Vertisols in the Central Clay Plain of the Sudan

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Vertisols in the Central Clay Plain of the Sudan

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Abstract

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The Central Clay Plain is situated between latitudes 16° and 10° North and longitudes 32° and 37° East, in the Republic of the Sudan. The parent materials of the clay soils which cover almost this entire area belong to two broad groups: alluvial, deltaic and paludal sediments from rivers belonging to the Nile system (aggradational clay plains), and colluvio-alluvial deposits derived from local rock weathering, pediplanation and short-distance transport (degradational clay plains). The soils are classified as Vertisols in three international systems.

Relationships between soil parent material, landform, climate, vegetation and soils were defined in the field. Field studies were supported by an analysis of mineralogical, chemical and physical soil data. The various landscapes that together make the Central Clay Plain were delineated on a 1:2 000 000 pedogeomorphic map. Hypotheses on the sedimentation history of the aggradational plains were tested against data on geology, palaeoclimatology and palaeobotany in the literature. Soils, vegetation and landforms show the degradational plains to be pediplains in an advanced stage of planation.

Special attention is given to soil classification, soil genesis, the process of pedoturbation, and the origin and impact of relatively small differences in soil morphology. It was found that the climatic north-south gradient has a stronger influence on soil properties than differences in parent material between aggradational and degradational plains.

free descriptors: swelling clays, soil morphology, soil classification, soil cartography, soil genesis, mechanical pedoturbation, sedimentation history, palaeopedology, landform evolution.

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Stellingen

1. Actuele sedimentatie en bodemvorming in de Gash delta, Kassala Provincie, Soedan, kunnen model staan voor processen die in het verleden de Gezira delta en Gezira bodems hebben gevormd.

dit proefschrift

2. Het lage chroma van de kleur van 'Pellic' Vertisols is gerelateerd aan de stabiliteit van smectiet.

dit proefschrift

3. Binnen het gebied dat wordt begrensd door de isohyeten van 150 en 1500 mm blijken de Vertisols van de centrale kleivlakte van de Soedan 'zonale gronden' volgens het concept van Dokuchaev: de belangrijkste differentiërende kenmerken worden bepaald door de bodemvormende factor klimaat.

dit proefschrift

4. 'Aquic conditions', zoals gedefiniëerd door ICOMAQ, kunnen in Vertisols niet voorkomen.

International Committee on Aquic Soil Moisture Regimes (ICOMAQ), Circular Letter 11, March 1991.
Soil Survey Staff 1992. Keys to Soil Taxonomy, Fifth edition.

5. Het in 1960 in de Amerikaanse bodemclassificatie geïntroduceerde onderscheid tussen Vertisols met een oppervlaktemulch ('grumic') en Vertisols met een oppervlaktekorst ('mazic') is ten onrechte uit het classificatiesysteem verdwenen; het onderscheid is relevant voor bodemgebruik en levert karteerbare polypedons op.

Soil Survey Staff 1960. Soil Classification, a comprehensive system. 7th Approximation. SCS, USDA, Washington D.C..
Soil Survey Staff 1992. Keys to Soil Taxonomy, Fifth edition. SMSS Techn. monograph no. 19.

6. Multidisciplinair onderzoek wordt gedwarsboomd door monodisciplinair gerichte wetenschappelijke ambitie van de onderzoekers. Wanneer universiteiten dit onderzoek opdragen aan AIO's - voor wie het 'publish or perish' in hoge mate geldt - dienen zij te zorgen voor een intensieve begeleiding door onderzoekers die wetenschappelijk en maatschappelijk hun schaapjes op het droge hebben en tevens in staat zijn multidisciplinair te denken.

7. In een continue waarnemingsschaal voor visuele bodemstudies - van veldwaarneming via microscopie naar submicroscopie - zoals o.a. bepleit door Wilding en Flach, ontbreekt vaak de schakel loupe/stereomicroscoop tussen de macromorfologie (profielbeschrijving) en de micromorfologie (microscopische studie van slijpplaatjes); tegelijk groeit de toepassing van submicroscopische technieken explosief zonder dat deze in voldoende mate zijn geïntegreerd in de waarnemingsreeks.

Wilding, L.P. en K.W. Flach 1985. Micropedology and Soil Taxonomy. in: L.A.Douglas and M.L.Thompson (Ed.), Soil Micromorphology and Soil Classification. SSSA, Spec. publ. no.15, p.1-16.

Douglas, L.A. (Ed.) 1990. Soil micromorphology: a basic and applied science. Developments in Soil Science 19, Elsevier, Amsterdam, 716 p.

8. Fundamenteel onderzoek heeft ook in ontwikkelingslanden bestaansrecht, het kan en mag er geheel losstaan van direct ontwikkelingsgericht onderzoek. De wetenschapper die participeert in dit fundamentele onderzoek behoeft geen slecht geweten te hebben.

Wagenings Universiteitsblad, 19/11/92, Wageningse Desert Storm in de Sahel.

NRC Handelsblad, 26/11/92, Op zoek naar regen.

9. De watersnoodramp van 1953 dreigt anno 1993 het Nederlandse rivierenlandschap te vernietigen.

10. Wie op gevorderde leeftijd promoveert, zou kunnen wijzen op de fabel van de krekel en de mier, ware het niet dat hij ook wist van de vos en de druiven.

Jean de La Fontaine, Fables
La Cigale et la Fourmi
Le Renard et les raisins

W.A. Blokhuis
Vertisols in the Central Clay Plain of the Sudan
Wageningen, 12 januari 1993

In herinnering aan mijn moeder, die mij leerde pianospelen,
en aan mijn vader, die mij inleidde in de bosbouw

Preface

Since the day that I first set eyes on the dull greyish-brown cracked bare surface coming towards us as the small plane that had brought me from Khartoum approached the landing strip at Wad Medani, the study of Vertisols has accompanied me, occupied me, inspired me and sometimes exhausted me. This was in 1959 - and I had no idea what kind of soils were below the cracked surface. In the following years, 1959 to 1963, during several soil surveys in the east-central Sudan, I learned to recognize these soils as 'black cotton soils' . This familiar name, widely used in the Sudan, was gradually replaced by 'Vertisols', introduced as the name for a Soil Order in the 1960 draft (the '7th Approximation') of the new USDA soil classification system, that later became known as Soil Taxonomy. I had the unique opportunity to study parts of the immense Central Clay Plain of the Sudan in detail, and to travel over most of its area.

In 1963 I joined the Department of Soil Science and Geology of the Agricultural University, Wageningen, and worked with Dr P. Buringh, the first professor in tropical soil science. In Wageningen, other activities both within and outside the Department demanded much attention, but the work on Vertisols continued, notably thin section studies, optical mineralogical investigations and lectures. Although I had the basic field data for a comprehensive study on the Vertisols of the Central Clay Plain of the Sudan, it was many years before I could find either the time, or the concentration to embark on such long-winded work as this study was promised to be.

In 1965 R.Dudal edited his 'Dark clay soils of tropical and subtropical regions', an FAO monograph. This was the first world-wide survey of Vertisols. In the years that followed, Vertisols received a great deal of international attention, and I was in the fortunate position to be able to broaden my study of Vertisols of the Sudan to Vertisols in general. This led the way to the International Committee on Vertisols (ICOMERT), that was to advise on the classification of Vertisols in the US soil classifcation system, Soil Taxonomy, and to several scientific meetings.

My studies on Vertisols in general are listed below; they stand apart from the regional study of the Central Sudan Clay Plain reported in this doctorate thesis. The Vertisols of the Sudan mark both the beginning and (more or less) the end of my work on Vertisols.

General papers on Vertisols:

Blokhuis, W.A., 1982. Morphology and genesis of Vertisols. Invited paper. In: Vertisols and rice soils of the tropics, Symposia papers 2, p. 23-47. Trans. of the 12th Intern. Congress of Soil Science, 8-16 February 1982, New Delhi, India.

______, 1985. Relationships between morphological properties and drainage in Vertisols. Invited paper. In: Taxonomy and management of Vertisols and Aridisols, Proceedings of Fifth Intern. Soil Classification Workshop, Sudan, 2 to 11 November 1982. Part I: Papers, p.231-242. Soil Survey Administration, Khartoum, Sudan.

______, 1989. Vertisols of the semi-arid tropics. Invited paper. In: Management of Vertisols for improved agricultural production. p. 37-43. Proceedings of an IBSRAM Inaugural Workshop, 18-22 February 1985. ICRISAT Center, India.

______, M.J.Kooistra and L.P.Wilding, 1990. Micromorphology of cracking clayey soils (Vertisols). Invited paper. In: L.A.Douglas (ed.), Soil Micromorphology: a basic and applied science. p. 123-148. Proceedings of the VIIIth Intern. Working meeting of Soil Micromorphology, San Antonio, Texas, July 1988. Developments in Soil Scienc 19, Elsevier, Amsterdam etc.

______, L.P.Wilding and M.J.Kooistra, 1991. Classification of vertic intergrades: macromorphological and micromorphological aspects. In: J.M.Kimble (ed.), Proceedings of the Sixth Intern. Soil Correlation Meeting (VI ISCOM): Characterization, classification and utilization of cold Aridisols and Vertisols, August 6-18, 1989. p. 1-7. USDA Soil Conservation Service, National Soil Survey Center, Lincoln, NE.

This thesis could not have been written without the scientific and technical cooperation and moral support of many.

First of all I wish to thank Dr Piet Buringh, who was to be my promotor. He guided my study with much skill and patience, and commented on an earlier version of this thesis. Unfortunately, university regulations do not permit an emeritus professor to act as promotor after five years of retirement.

Dr Johan Bouma accepted the thankless task of undertaking the role that his predecessor had almost completed. For the agreeable way he undertook this task, and for his critical comments on various aspects of the thesis, I am very grateful.

Soil genesis may be included in the same Commission of the International Society of Soil Scienc as soil survey, soil morphology and soil classification, for many a soil surveyor soil formation is a terrain full of pitfalls, especially when handling chemical, physical and mineralogical data. Dr Nico van Breemen, my second promotor, guided me expertly through this terrain. His comments prompted me to reconsider and rewrite parts of Chapters 8 and 9, an arduous but essential task.

Dr Leendert van der Plas accepted my request for him to read the sections on mineralogy. He scrutinized the manuscript and taught me how to use the wastepaper basket.

Dr Salle Kroonenberg showed tremendous interest in the chapters on geology, geomorphology and the history of the Nile river system in the Sudan. During lengthy discussions he introduced new ideas, which helped in solving some of the questions on landscape formation.

Other staff members of the Department have contributed to this thesis in one way or another. I would like to mention the following:

- Dr Boet Slager, who introduced me to the rewarding field of micromorphology;
- Dr Michel Mulders and his students, who assisted in processing and interpreting satellite images.
- Dr Dick Nota, who commented on the optical mineralogical investigation of sand and silt, and Jeanne Bakker, who instructed me on the techniques involved, and who undertook a substantial number of microscopic analyses;
- Dr Rienk Miedema, Tom Pape and Toine Jongmans of the morphology laboratory, who helped in interpreting the thin sections;
- Ed Meyer, who examined some of the mathematical sections of Chapter 8;
- The late Z. van Druuten, who did considerable photographic work in connection with the processing of satellite images and map compilation;
- Messrs. Buurman, Jeronimus and Versteeg, who drew most of the figures and maps.
- Members of the administrative staff who typed parts of the thesis.
- Norbert Lukkezen for financial and administrative guidance.
- Members of the technical staff of the mineralogy, granulometry, soil chemistry and soil morphology laboratories, who analyzed samples and prepared slides for microscopic study. I am grateful to Leo Begheijn and his co-workers for chemical analyses, to Jan van Doesburg for X-ray diffraction of clay samples and their interpretation, to Ton Engelsma for granulometric analyses and slide preparation for optical mineralogical investigation. Thanks are also due to Rudi Schoorl, a former member of the technical staff of the Department, for mineralogical investigation of clay fractions, and to Ab Jonker, who earlier in his career was engaged in the laboratory for mineralogy.

I am indebted to the following persons and institutions outside the Department of Soil Science and Geology.

- International Land Development Consultants (ILACO) and Netherlands Engineering Consultants (NEDECO), for permitting me to use some of the data collected during the Southern Gedaref soil surveys;
- The Director of Agriculture, Republic of the Sudan, who authorized the use of data collected when I was in the Sudan Government's service.
- The technical assistants in soil survey, in the period 1959-1963: Ahmed Musa, Babikr Suleiman, Hassan Fadl, Khalid Khalil, Siddig, Osman Abdel Rahim en Osman Geismalla; the drivers Fadl, Mohammed el Obeid, Omer el A'as, Abdel Bagie and others, and the Fellata labourers Musa Isa, Baqr and others. They were capable, untiring, reliable and good-humoured companions during many a lengthy 'trek'.
- My colleagues at the Soil Science Section of the Gezira Research Station, Wad Medani, Sudan: Louk Ochtman, Dr Arnold Finck and Dr Karl-Hermann Peters, for stimulating discussions and joint 'treks'.

- Dr Maya Kooistra, of the Winand Staring Centre, for her critical reading of Chapter 7. It was a pleasure to work with her and Dr Larry P. Wilding, on two papers on the morphology of Vertisols.
- Hugo Bijloo, who typed most of the tables;
- Wouter Bohmer of ISRIC for map drawing;
- The photographic laboratory at the Centre for Crop Protection for processing the photographic illustrations;
- Ann Chadwick, who corrected the English text;
- Roel Siebrand, for the layout of text and illustrations, typography and other aspects of desktop editing. The appearance of the thesis is entirely his work.

Three soil scientists who always showed a keen interest in my work on Vertisols are no longer with us:

Dr C.H.Edelman, professor of soil science, and Dr Jödes van Schuylenborgh, senior lecturer, both of the Department of Soil Science and Geology, and Dr Ernst Schlichting, professor of soil science at the University of Hohenheim, Germany.

I remember with gratitude the stimulating discussions we had. Ernst Schlichting visited his former student Karl-Hermann Peters in the Sudan in 1962, and the three of us made an interesting excursion over the Butana, the Gash delta and into Eritrea.

Finally, this work would never have come to an end without the distracting presence of my wife, Anneke.

CONTENTS

CHAPTER 1

Introduction

The east-central Sudan is largely a country of vast, flat and almost featureless clay plains, known collectively as the Central Clay Plain. This plain comprises relatively minor surfaces of a different nature, viz. the present valleys and recent terraces of the White Nile, Blue Nile and tributaries; flat to gently undulating surfaces of the Nubian Sandstone Formation (Mesozoic); basalt ridges (Tertiary); isolated rock outcrops (inselbergs) and rocky hills with fringing pediments, developed in Precambrian rocks of the Basement Complex.

The fine-textured sediments from which the clay plains are built appear to be very similar in granulometric composition and in clay mineralogy; clay percentages are between 60 and 80 and there is a dominance of smectite clay minerals.

The climate varies from arid in the northwest to sub-humid in the southeast; over most of the plain it is semi-arid. Annual rainfall is between about 150 mm (Khartoum) and 900 mm (Gallabat). There is one rainy season, increasing in length from two months (July and August) in the north to five months (May to September)in the south-east. Temperatures are high throughout the year (mean daily temperatures averaged over the year are from 27 to 30°C.).

The vegetation ranges from semi-desert grassland to savannah woodland. *Acacia*-species are dominant among the scrubs and trees of the savannahs and savannah woodlands.

The monotony of the landscape and the uniformity of the sediments tend to obscure the fact that the Central Clay Plain onsists of several geographic units, related to differences in origin of the sediments. These can be roughly divided into two broad categories: alluvial, deltaic and paludal deposits brought in from the Ethiopian highlands by rivers, and colluvio-alluvial material weathered from local rocks during pediplanation and transported over relatively short distances. The terms aggradational and degradational (Ruxton 1956; Ruxton and Berry 1960; 1978) have been used to differentiate between the two major types. Williams et al. (1982) use the terms depositional lowland clays and residual upland clays. We prefer the terminology used by Ruxton and Berry.

In the present study relationships are drawn between soil morphology, soil parent material, geomorphology, climate and vegetation, and, subsequently, the various landscapes, that together make the Central Clay Plain, are defined.

A comparative study of soil profiles from various parts of the clay plain is made to elucidate to what extent the soil characteristics are determined by soil parent material, or by other soil-forming factors, notably climate, relief and age. Attention will be focussed on differentiating characteristics rather than on common features, although the latter are far more obvious. Broadly speaking there is but one genetic soil type present, with a characteristic morphology and resulting from a specific combination of soil-forming factors. In soil classification systems these soils form a class at the highest level of abstraction: Order in the US Soil Taxonomy (Soil Survey Staff 1975), 'Classe' in the French system (CPCS 1967), and Major Soil Grouping in the FAO/ Unesco-system (FAO 1988). In all three systems the same name is used: Vertisols.

Vertisols have a distinct morphology, showing wide and deep cracks in the dry season, wedge-shaped structural aggregates with polished faces, slickensides, and other features derived from the swelling and shrinking of smectite clays, and the resulting movements in the soil due to shear failure. Within this one genetic type there are gradual, but distinct, variations with the amount of rainfall and the duration of the rainy season, and this zonality is more evident than the variations related to landscape formation and parent material.

In a chapter on geography (Chapter 2) general information on the Republic of the Sudan is given, and the physical environment (relief, drainage, climate), natural and semi-natural vegetation, and land use are described. The stratigraphical history of the clay plain and adjoining areas gives an insight into the nature and origin of the soil parent materials (Chapter 3). Palaeoclimatological evidence and archaeological finds support hypotheses on the sedimentation history of the aggradational plains (Chapter 4). The origin and landform evolution of the degradational plains are the subject of Chapter 5. Chapters 6, 7 and 8 deal with the soils: the geography of the soils of the clay plains and adjoining areas (Chapter 6), profile morphology and physical aspects of selected profiles (Chapter 7), and the mineralogical and chemical properties of these profiles (Chapter 8). Aspects of soil formation are discussed in a concluding chapter (Chapter 9).

The Central Clay Plain was studied by the author between 1959 and 1963, and during the winter of 1965/1966, when he was engaged in soil surveys for the Sudan Government and for International Land Development Consultants, Netherlands, respectively. General knowledge of soils and landscape was acquired during many journeys over the clay plain. During these trips observations of relief, landform, vegetation, land use and soil surface features were made, and soil investigations from borings and profile pits (see the geographic map, Appendix 3).

Twenty-seven soil profile pits, representing various landscapes of the Central Clay Plain, were studied in detail. Field observations were made on site characteristics and soil morphology, laboratory investigations on granulometric composition, on chemical and mineralogical properties, whereas micromorphological features were studied in thin sections by microscope.

Detailed information was obtained from soil survey areas, notably north of Khashm el Girba along the river Atbara westbank - at present a gravity irrigation scheme - and two locations in Southern Gedaref District (Umm Simsim and Umm Seinat) which were surveyed with a view on mechanised crop production under dryland conditions (Mechanised Crop Production Schemes or MCPS). Additional information on the geography of soils was obtained from the reports by MacDonald and partners / Hunting Technical Services (1963/1967) (Roseires Soil Survey), from the reports of an UNDP/FAO/Ministry of Agriculture, Sudan Government, joint project, and from reports published by the Soil Survey Administration (formerly the Soil Survey Division) and by the Research Division of the Ministry of Agriculture, both in Wad Medani, Sudan.

Much of the information in Chapters 2 to 5 is taken from published sources. In addition to articles in scientific journals, conference proceedings and the like, a number of comprehensive works deserve special mention. Whiteman (1971) gives a detailed account of the geology of the Sudan Republic. Butzer (1971) reviewed the palaeoclimates of the Sahara. Recent information on the quaternary environment in northern Africa has been compiled by Williams and Faure (1980), and in-depth studies on quaternary geology and biology of the clay plain between the two Niles have been edited by Williams and Adamson (1982). Ruxton and Berry (1978) reviewed the geomorphic history of the clay plain, and Berry and Whiteman (1968) the geography of the Nile in the Sudan. Buursink (1971) described the soils along the Blue Nile and (Main) Nile. For general reference on geography and agriculture, Barbour (1961) and especially Tothill (1948) have proved most valuable.

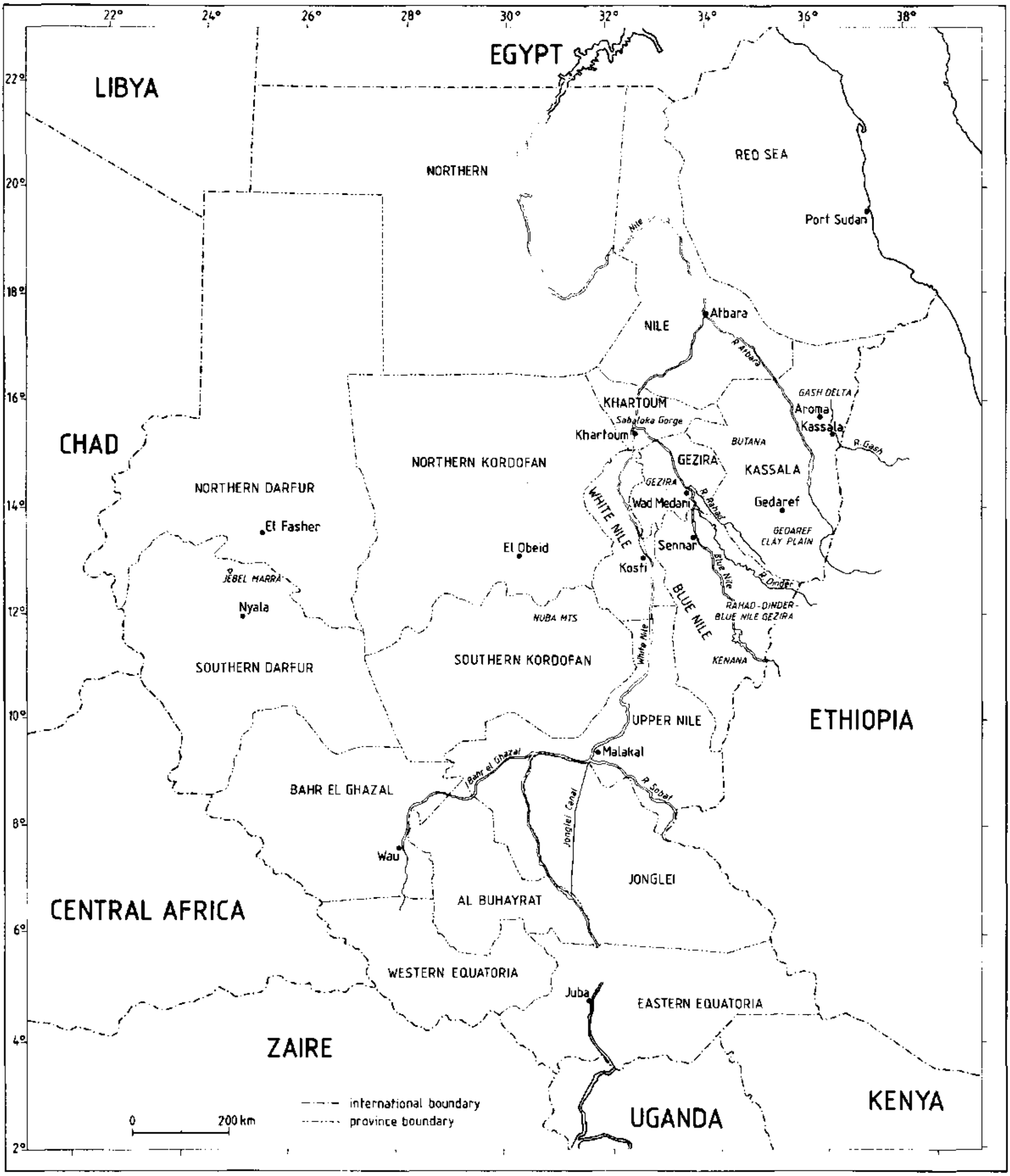

Fig. 2.1. The Republic of the Sudan, with provinces, main towns and rivers, and the geographic regions of the Central Clay Plain

Chapter 2

Geography

2.1 The Republic of the Sudan

Sudan, with its 2.5 million square kilometres, is the largest country of Africa. It stretches from 5° to 21° North, and occupies 8.3% of the African continent. Since 1980 it has been administratively divided into six regions that have, formally, their own legislative and executive power. The regions are: North, East, Central, Kordofan, Darfur, and South. The Southern region was established earlier, in 1973. Each region has two or three provinces, and there are fourteen provinces in all. Khartoum province stands apart (Fig. 2.1). Provinces are separated into urban or rural districts.

The Central Clay Plain occupies parts of the following regions and provinces: Central Region (with Gezira, White Nile and Blue Nile Provinces), Eastern Region (with Kassala Province), Southern Region (with Upper Nile Province) and Khartoum Province (Fig. 2.1).

The first census, in 1953, gave a population figure of 10.3 million. Based on the 1983 census, and an average population growth of 2.9% per annum, the population in 1986 was estimated at 22.4 million (Post 1987). The average population density is 8.2 per square kilometre, with extremes of 85.8 (Khartoum Province) and 2.3 (Northern Region).

One-third of Sudan's land area is desert. Another one-third is only suitable for grazing. This area is heavily used by a large livestock population: 14 million cattle, 16 million sheep, 11 million goats and 2 million camels. The total area of cultivated land in 1983/84 was estimated at 6.9 million hectares, less than 3% of the land area (World Bank 1985). Of these 0.9 million were under irrigation, 2.5 million under mechanized rainfed farming, and 3.5 million under traditional rainfed farming.

About 80% of the population earns a living in traditional farming, either smallholder cultivation or animal husbandry, or a combination of both. The average size of a smallholder farm was under one hectare in 1981 (Post 1987). The modern sector in agriculture consists mainly of an extensive system of mechanized rainfed crop production (mainly Sorghum) and of more intensive systems of irrigated agriculture. Most of the mechanized rainfed farming is on the Central Clay Plain, whereas irrigated agriculture is found along the rivers of the Nile system.

2.2 The Central Clay Plain: concepts, location and geographic regions

The terms Central Clay Plain and Southern Clay Plain are well-known to anyone familiar with the Republic of the Sudan. Barbour (1961) delineated these as geographic units, mainly on physical grounds, whereas Jewitt (1955a) used a soil criterion: predominance of dark cracking clays. Worrall (1961) published a soil map of the Sudan on a scale 1:5 000 000. Nine legend units of this map come under the general heading 'clay plain'. Four of these (the Gezira, the Butana, Nuba Mountains, the Fung) are grouped under the sub-heading 'clay, grey/brown, alkaline, with calcium carbonate concretions, sometimes gypsum'. These geographic areas taken together correspond well with the Central Clay Plain as defined by Jewitt and Barbour. Three other legend units of Worrall's map have in common : dominance of clay soils, and annual flooding or swampy conditions. These units cover the area generally known as the Southern Clay Plain. The remaining two legend units under the heading 'clay plain ' refer to smaller areas of non-flooded clay and loam soils in the southern Sudan.

There appears to be a reasonable consensus on the concepts of the two clay plains. Roughly, the division is one between a northern part (Central Clay Plain) with dark, cracking clays, not subject to prolonged annual flooding, and a southern part (Southern Clay Plain), where clays are predominant, but far less so than in the northern part, and where all land is subject to long periods of annual flooding or is permanently under marshy conditions.

The Central Clay Plain is situated between latitudes 10° and 16° North and longitudes 32° and 37° East (Appendix 3). In the north and northeast it merges with gravelly denudation plains developed in older geological formations; in the east and southeast the land rises towards the Ethiopian plateau; in the south, the Central Clay Plain merges with the annually flooded Southern Clay Plain, and in the west there is an irregular, sometimes gradual, sometimes abrupt boundary with the 'qoz'[1] , a landscape with sand sheets and stabilized sand dunes.

The Central Clay Plain stretches westward across the White Nile and in places merges with the Nuba Mountains clay plain. The Nuba Mountains[2] consist of inselbergs, granitic kopjes and rocky hills belonging to the Precambrian Basement Complex; these are interspersed with and surrounded by clay plains. The clays are weathering products of the local rock. The Nuba Mountains clay plain is a discrete physiographic unit, but has also been considered as part of the Central Clay Plain, for example by Jewitt (1955a) and Worrall (1961).

The area which forms the subject of the present study, comprises the following geographic regions (Fig. 2.1 and Appendix 3):

a. **The Gezira**, the triangular 'island' (Gezira in Arabic means: island) between the Blue and White Niles, south of their confluence at Khartoum to the Sennar-Kosti railway line.

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[1] English translations of Arabic words are in the Glossary.

[2] Geographic names are on the 1:2 000 000 geographic map (Appendix 3), and in several figures of Chapter 2, notably Figure 2.1.

b. **The Rahad-Dinder-Blue Nile Gezira,** situated between the rivers Rahad and Blue Nile. Towards the Ethiopian border this plain merges with undulating mountainous and rocky land. The Rahad and Dinder rivers are tributaries of the Blue Nile.

c. **The Butana,** situated between the rivers Rahad, Blue Nile, Nile and Atbara. South of approximately 15°30'N this is a very slightly undulating clay plain with some inselbergs and rocky hill groups. North of 15°30'N the Butana is a desert denudation plain. The Butana includes the alluvial clay plain on the west bank of the river Atbara, between latitudes 15° and 16° North. The Sennar-Gedaref railway line is usually considered to be the southern boundary (Barbour 1961).

d. **The Gedaref clay plain,** south of the Sennar-Gedaref railway line, between the rivers Rahad and Atbara. The clay plain stretches into Ethiopia.

e. **The Kenana or Fung,** the continuation of the Gezira towards the south. It merges with the Southern Clay Plain, and with undulating and rocky country on the Ethiopian border.

The river Gash, rising in the Eritrea Province of Ethiopia, has built an alluvial fan of sands, silts and clays, where it fades out in the desert. This fan, known as the Gash Delta, is situated east of the river Atbara. It does not belong to the Central Clay Plain, but the area is interesting by comparison, both from a sedimentological and a pedological point of view.

2.3 Relief and drainage

2.3.1 Relief

The Central Clay Plain gently dips from SE to NW. The aggradational plains slope with the rivers in the same general direction, whereas the degradational clay plains slope gently towards the main rivers. The Gezira plain is an alluvial fan with a slight slope towards the White Nile.

Degradational plains

In the northern Kenana (Fig. 2.2) the watershed between the White and Blue Niles is an ill-defined line running from the Manaqil ridge (Fig. 2.5) over Jebel Moya in a southerly direction, passing east of Jebel Dali, Jebel Bozi and Jebel Mazmum and, via Jebel Gerabin towards the Ingessana Hills. West of this divide, the northern Kenana slopes towards the White Nile, east of it towards the Blue Nile. In the Jebel Bozi/Jebel Abu Qurud area the contour pattern suggests the presence of (concealed) pediments. Jebel Dali has less, and Jebel Sureig no impact on the overall relief of the clay plain. Highest levels of the northern Kenana plain are at an altitude of approximately 490 m[3]. Slopes are gentle, generally less than 0.4%, except for the immediate proximity of inselbergs.

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3 Metres above sea level (Alexandria) at mean minimum discharge level of the river. Data are from Ministry of Irrigation and Hydro-Electric Power (1957).

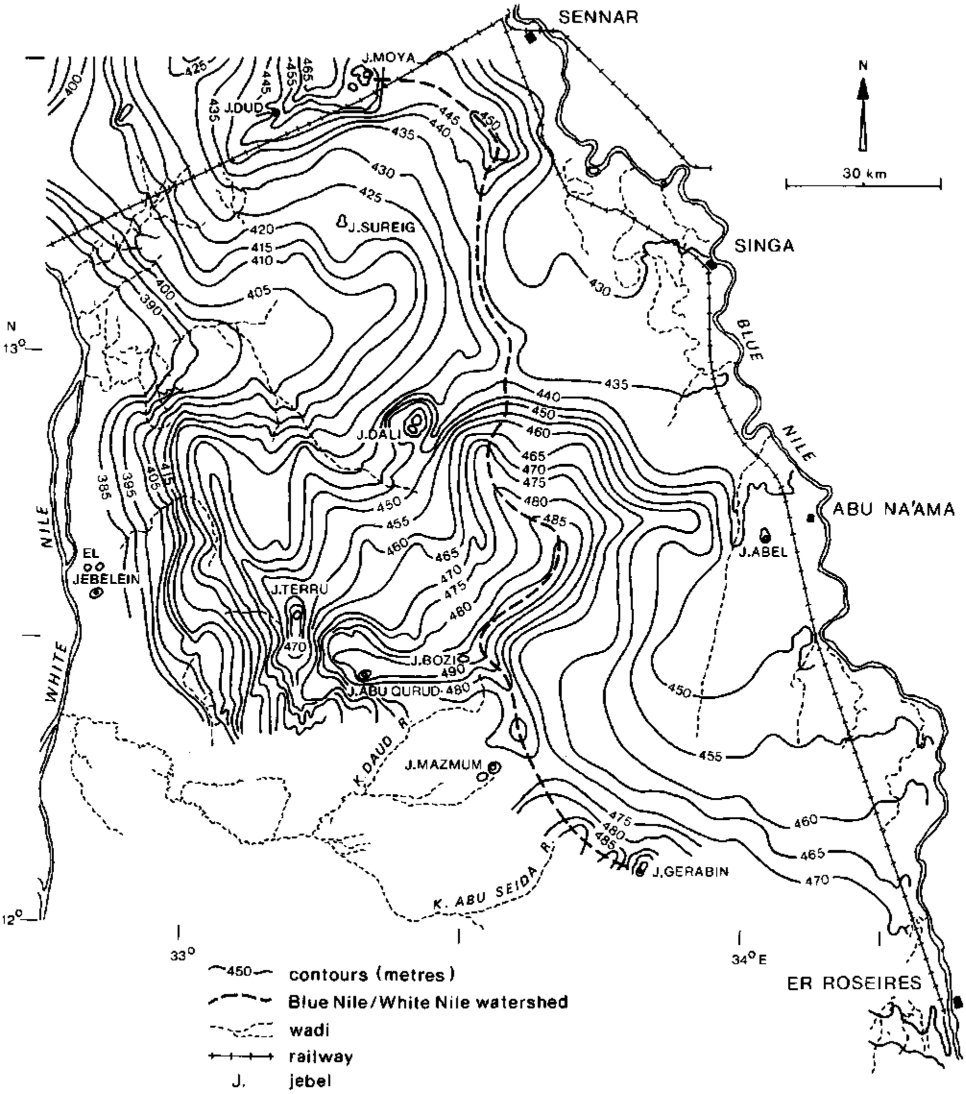


Fig. 2.2. Contoured map of the northern Kenana (after Sir Alexander Gibb & partners, 1954)

Relief is stronger and more irregular in the southern Kenana where hill groups are frequent. The relief is related to the inselbergs and other rocky outcrops. We have no contour maps of that area.

The divide between Rahad/Blue Nile and Atbara is a distinct terrain feature from Jebel En Nasla through Reira to El Husheib. Here the apparent flatness of the Butana clay plain is interrupted by a range of rocky hills and inselbergs with fringing pediments. The divide is situated approximately 50 m above the level of the aggradational plains at the same latitude (Van der Kevie and Buraymah 1976). From

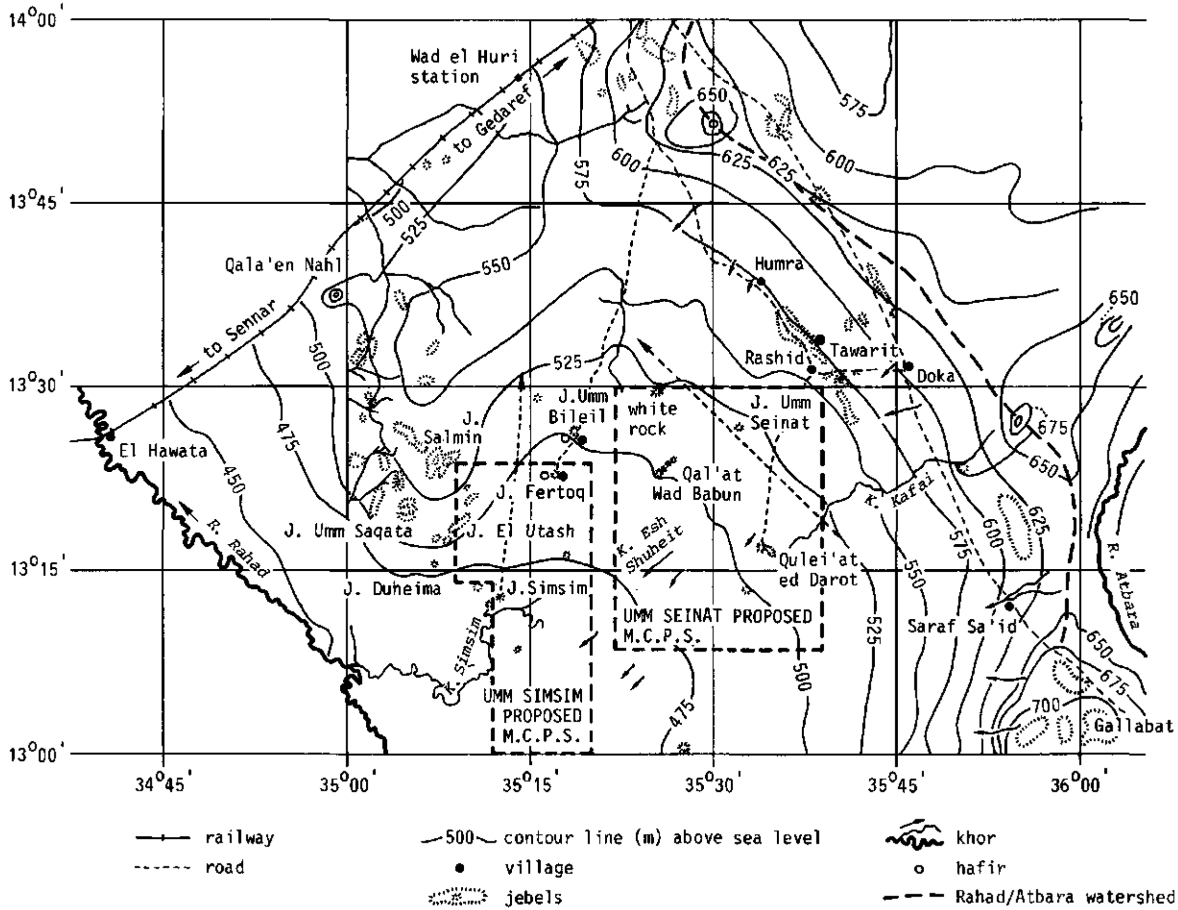


Fig. 2.3. Contoured map of part of the Gedaref clay plain (after Barbour 1961, and Nedeco/Ilaco 1966)

El Husheib to Gedaref the watershed is indistinct in the terrain. Beyond Gedaref and up to Gallabat, near the Ethiopian border, it is, again, distinct (Fig. 2.3).

The divide between the Atbara and the Nile runs from Jebel en Nasla westward to Jebel Qeili, and then in a northwesterly direction. The northern Butana, most of which is a desert denudation plain developed from Nubian sandstone, drains northwards towards either of these rivers.

Average slopes in the Butana are 0.5%. Individual slopes are seldom in excess of 1% except near rock outcrops (Worrall 1959). The Butana is a very gently undulating plain. The relief is characteristic of an old pediplain where hill slopes are graded towards local base levels (Chapter 5). Unfortunately, we have no contoured maps of the Butana. There is, however, a contoured map of part of the alluvial clay plain west of the river Atbara (the Khashm el Girba Soil Survey area; Fig. 2.4). The contours show a marked change in direction and density along a line that marks the boundary between the alluvial plain of the Atbara and the Butana pediplain (see also section 6.5.1).

The Gedaref clay plain has a gentle, regular slope (0.2% as an average) from the Gedaref-Gallabat ridge towards the river Rahad (Fig. 2.3). Ruxton and Berry (1978) consider it to be a classical pediplain. The basalt ridges and hills and several inselbergs make the relief locally stronger and deviating from the general pattern.

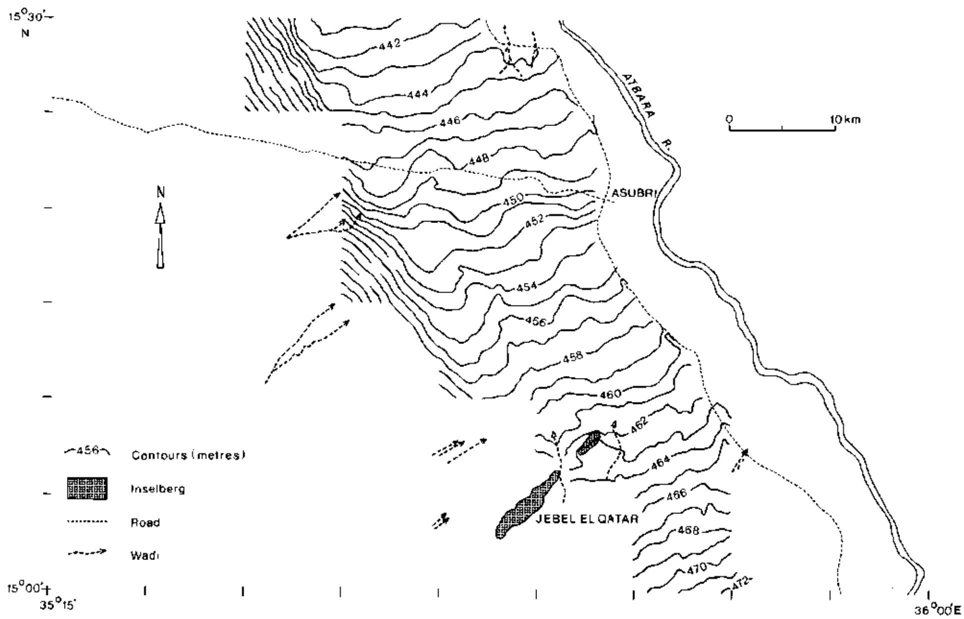


Fig. 2.4. Contoured map of the Khashm el Girb South soil survey area (adapted from 1:50,000 contoured maps of the Sudan Survey Department, Khartoum, 1960)

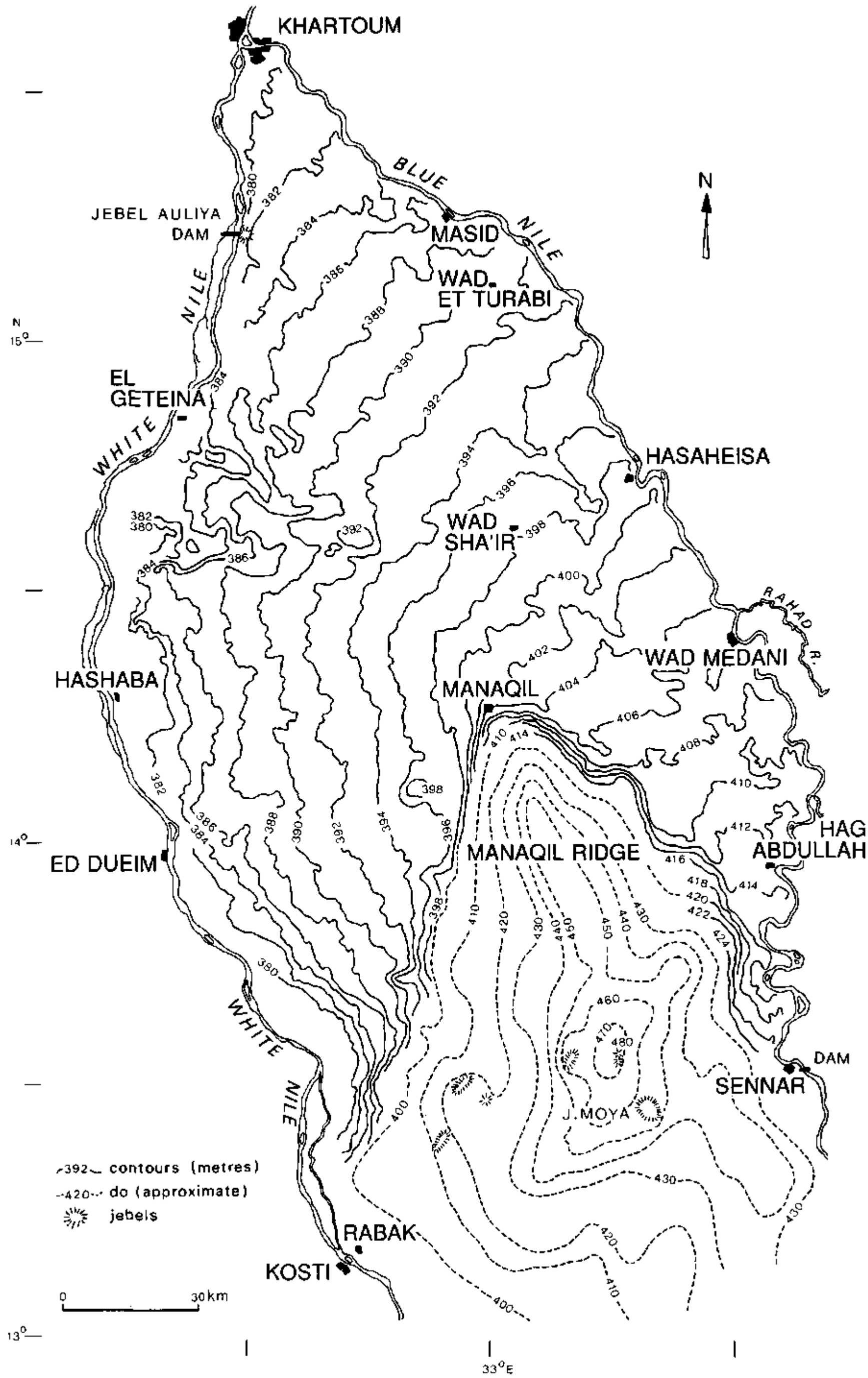


Fig.2.5. Contoured map of the Gezira (based on Sudan Topographical Survey data)

Aggradational plains

Slopes on the aggradational plains are usually less than on the degradational plains. The Gezira clay plain is graded northwest and west towards the White Nile valley (Fig. 2.5). The average slope in the Gezira is 0.02%. For comparison: in the Atbara alluvial plain, the average slope is 0.05%. In the Rahad-Dinder-Blue Nile Gezira, the general slope is with the river (Fig. 2.6). There is, in addition, the mesorelief of a river floodplain, showing levees, basin sites and silted-up meander channels. Such features occur only sparsely in other parts of the plain, for example west of Singa, in the Kenana.

2.3.2 Drainage

The Central Clay Plain is drained by the Nile river system which, in this area, consists of the White Nile, the Blue Nile and the main Nile, the semi-perennial rivers Dinder, Rahad and Atbara and a number of smaller and larger seasonal drainageways, wadis or (Arabic) 'khors'. The latter often originate at the foot of hills or inselbergs, but sometimes on the clay plain itself. Several 'khors' do not reach the rivers, especially in the lower-rainfall regions. In the Butana many of the 'khors' that drain the divide do not reach the Atbara, Blue Nile or Rahad, but fade out into the almost level clay plain.

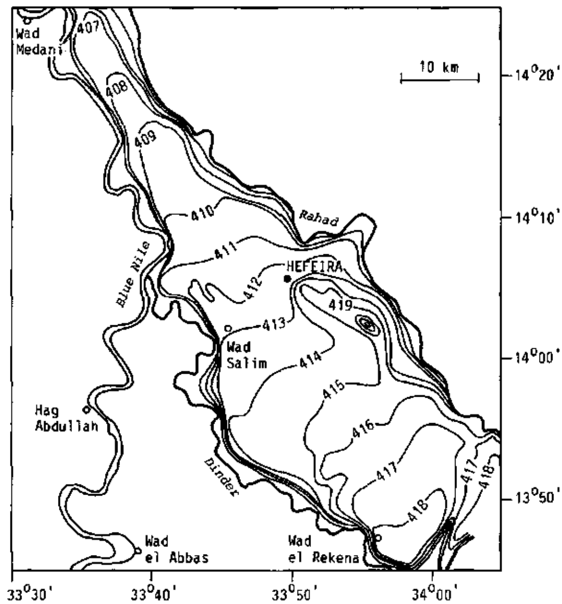


Fig. 2.6 Contoured map of part of the Rahad/Dinder floodplain (after Ruxton and Berry 1978)

2.3.3 River gradients and discharge

The Blue Nile enters the Sudan at Fazughli (altitude 473 m). From Er Roseires (438 m) to Khartoum (370 m), a length of 624 km, the average gradient of the river is 11 cm per km (between Er Roseires and Sennar (266 km) 12 cm per km, between Sennar and Khartoum (358 km) 10 cm per km). The Blue Nile has deeply incised into its deposits. Incision decreases progressively downstream, from 34 m at Er Roseires to 14 m at Khartoum (Ruxton and Berry 1978).

The gradient of the river Atbara between Khashm el Girba (432 m altitude) and its confluence with the Nile at Atbara town (349 m), a distance of 438 km, is 19 cm per km.

The gradient of the White Nile is much smaller. From Malakal (382 m) to Kosti (374 m), a length of 497 km, it is 1.6 cm per km, from Kosti to Khartoum, 314 km, it is 1.3 cm per km. At equal distances from their confluence at Khartoum, the minimum discharge level of the White Nile is at a much lower altitude than that of the Blue Nile: one compares for example Er Roseires (438 m) and Renk (382 m), or Sennar (405 m) and Kosti (374 m) (see also Appendix 3).

The Blue Nile is a highly seasonal river with a ratio of peak flow to low flow of 40:1. Before the completion of the Roseires Dam in 1965, the total amount of sediment contributed each year by the Blue Nile to the main Nile was 41 million tons (Table 2.1). At peak flow (August) the sediment concentration was 4000 mg/l, as against 100 mg/l at low flow (June) (Badri 1972, cited by Williams et al. 1982).

The White Nile flow strongly contrasts with that of the Blue Nile; the ratio of peak flow to low flow is only 5:2, and it contributes 2 million tons of sediment load to the main Nile at Khartoum. The White Nile's seasonality is strongly buffered by the 'sudd' marshes, and by the Jebel Auliya reservoir. Its relatively high level at low flow means that it contributes considerably (83%) to the main Nile low season flow.

Table 2.1: Present hydrological regime of the Nile (prior to 1965) (after Williams et al. 1982, adapted)

river	discharge into main Nile		ratio peak flow to low flow	% of peak flow	% of low flow	sediment load at confluence with main Nile (tons x 10^6)	% of sediment load
	km^3	%		at confluence with main Nile			
White Nile	27.5	30.2	5:2	10	83	2	3.5
Blue Nile	51.0	56.0	40:1	68	17	41	71.9
Atbara	12.5	13.8	n.d.	22	0	14	24.6

2.4 Climate

2.4.1 General characteristics of the climate of the Sudan

The Sudan lies entirely in the tropics, between latitudes 3 and 22° N. The country is, except for the Red Sea littoral and the eastern slopes of the Red Sea hills, landlocked, and the climate is of a continental nature.

Rainfall is determined by the annual advance and retreat of the Intertropical Front or Intertropical Convergence Zone (I.T.C.Z.) over the country, with the advance and retreat of the sun. The I.T.C.Z. is a dividing line between generally warm and dry, and cooler, moist air masses (Griffiths 1972). The prevailing wind directions are north-northeast in front of the I.T.C.Z. and southwest behind. The movement of the front is well-illustrated by the yearly shift of the 10 mm-isohyet over the country (Fig. 2.7), reaching almost to the Egyptian frontier.

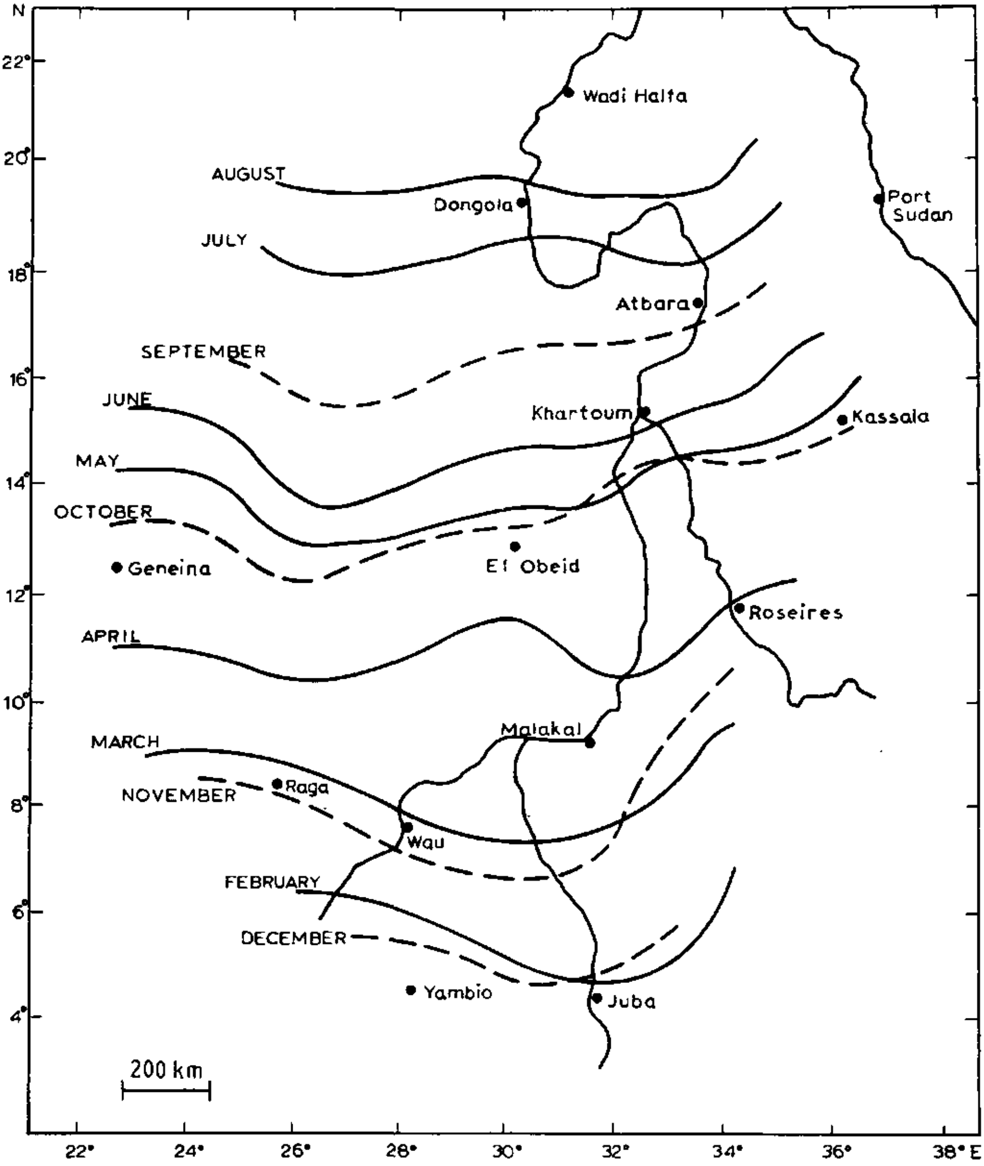


Fig. 2.7. Yearly shift of the I.T.C.Z., illustrated by the annual movement of the 10 mm-isohyet; average over the period 1931-1960 (after Griffiths 1972)

The pattern of isohyets (Fig. 2.8) conforms well to the yearly shift of the Intertropical Front. The general east-west course of the isohyets is, however, clearly influenced by the Ethiopian highlands, from where thunderstorm activity spreads over the Sudan plains, and by moist air masses from Zaire, flowing into the southwestern part of the Sudan (Griffiths 1972). Due to the extreme flatness of the country and the absence of large inland surface waters, local climatic effects are few;

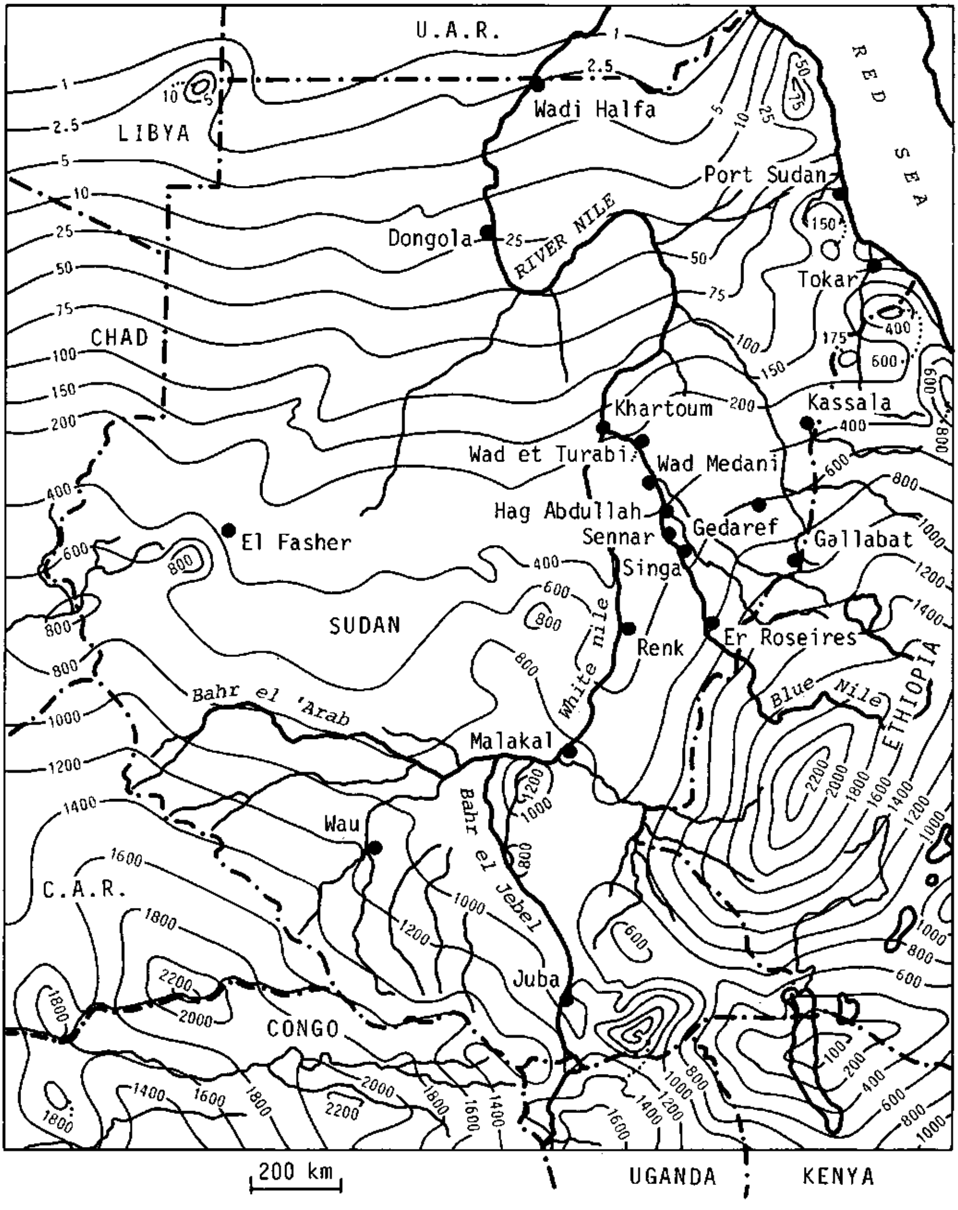


Fig. 2.8. Mean annual rainfall of the Sudan; isohyets in mm (after Whiteman 1971, based on Sudan Topographic Survey Map and Meteorological Department Data)

only the Marra mountains southwest of El Fasher, hill ranges southeast of Juba, and the swamp region south of Malakal (the 'sudd') give locally higher amounts of rainfall. A relatively dry area in the southeast, with rainfall as low as 400 to 600 mm, stretches into the Turkana desert of Kenya.

The yearly shift of the I.T.C.Z. brings a rainy season of variable duration in the summer, and a dry winter. The transitional spells between the dry and wet seasons have their own characteristics, and so four seasons can be distinguished: a relatively cool, dry winter; a hot, dry season with variable air humidity before the rains start; a cooler rainy season with high air humidity; a hot, still rather damp season at the end of the rains. From north to south the length of the rainy season and the amount of rainfall increase, the latter from 25 mm to almost 1600 mm per annum.

2.4.2 The climate of the Central Clay Plain

The climate of the Central Clay Plain reflects the general characteristics of the Sudanese climate, as discussed in 2.4.1. The rainy season varies both in duration (Khartoum has two months (July and August), Er Roseires five months (May to September) with over 50 mm rainfall), and in the amount of annual rainfall (Khartoum 163 mm, Er Roseires 808 mm).

According to Koeppen's (1936) classification, three climatic regions can be distinguished in the Central Clay Plain:

- Hot Desert (BWh), with less than 400 mm of rain per annum; (winter dry); mean annual temperature > 18°C.;
- Hot Steppe (BSh), with annual rainfall from 400 to 800 mm (winter dry); mean annual temperature > 18°C.; BSh covers most of the Central Clay Plain;
- Tropical Rainy Climate with a dry season in the winter(Aw), and with annual rainfall over 800 mm; mean temperature of coldest month at least 18°C.

This classification does not indicate the efficiency of the rainfall for plant growth; for example, the length of time that the soil moisture tension is above pF 4.2 (15 bar or 1500 kPa, at the permanent wilting point), and the length of time, if any, that there is a surplus of rainfall over evapotranspiration. Such data is also important for soil formation. When precipitation exceeds evapotranspiration and when the permeability of the soil material and the internal drainage of the site permit, leaching processes are possible. But even if there is never a surplus as calculated from monthly averages, severe rainstorms may cause short periods of leaching that have a cumulative effect over the years, even if such surplus situations occur only during a few days each year.

Thornthwaite (1948) takes both monthly rainfall and monthly potential evapotranspiration (PE) into account. His approach will be discussed in the next section. The US Soil classification system (Soil Survey Staff 1975) uses soil moisture and soil temperature regimes for the definition of taxa. The length of time that a soil is moist (above permanent wilting point) is an important diagnostic criterion on the second highest level of classification. The soil moisture and soil temperature regimes will be discussed in section 2.4.4.

2.4.3. Rainfall and potential evapotranspiration; the classification of Thornthwaite

Thornthwaite (1948) has defined indices of humidity and aridity, and an overall moisture index. The relation between water surplus and water need constitutes an index of aridity, Ia, or an index of humidity, Ih. Expressed as percentages these indices are

$$Ih = 100s/n, \text{ and } Ia = 100d/n,$$

in which s = rainfall less potential evapotranspiration (surplus); d = potential evapotranspiration less rainfall (deficiency), and n = water need, considered to be equal to potential evapotranspiration (PE).

The overall moisture index (Im) for a station is then (Thornthwaite and Mather 1955):

$$Im = Ih - Ia = 100(s-d)/n = 100(s-d)/PE$$

Satakopan (1965, cited by Oliver 1969) made calculations of PE following Thornthwaite's method. These are given in Figure 2.9. There are some differences between Satakopan's PE-values and our calculations based on data from Ireland (1948). The differences may be due to the period of observation chosen, and/or the fact that we did not correct PE-values for season or latitude. Satakopan's map shows that over the entire Central Clay Plain the mean annual evapotranspiration is between 1750 and 1850 mm.

Thornthwaite's climatic types have been mapped by Oliver (1969) and these are shown in Fig. 2.10. The map units are based on the annual moisture index, Im; values of Im for a number of stations are shown on the map. Over the entire Central Clay Plain moisture indices are negative; the classes are arid and semi-arid.

For two stations, one with low rainfall (Wad Medani), and one with relatively high rainfall (Er Roseires) mean monthly data are given for temperature, rainfall, PE, d and s (Table 2.2). Wad Medani has no month with a surplus, Er Roseires has three months with a surplus.

In Table 2.3 annual data on rainfall, temperature, PE, s and d are given for a number of stations in the Central Clay Plain, and the months when there is a water surplus, and the amount of that surplus. Climatic types according to some classifications that are based on such data, are added; Koeppen (1936) recognizes three classes, Thornthwaite (1948) two classes in the Central Clay Plain area.

The data of Table 2.3 can be used to assign the stations of the Central Clay Plain to four different groups:

- Khartoum to Wad Medani: rainfall up to 400 mm; in general no water surplus;
- Wad Medani to Singa: rainfall 400 to 500 mm; there is no water surplus, or only a slight surplus for one month;
- Singa represents a zone with a rainfall of 500 to 800 mm in which insufficient

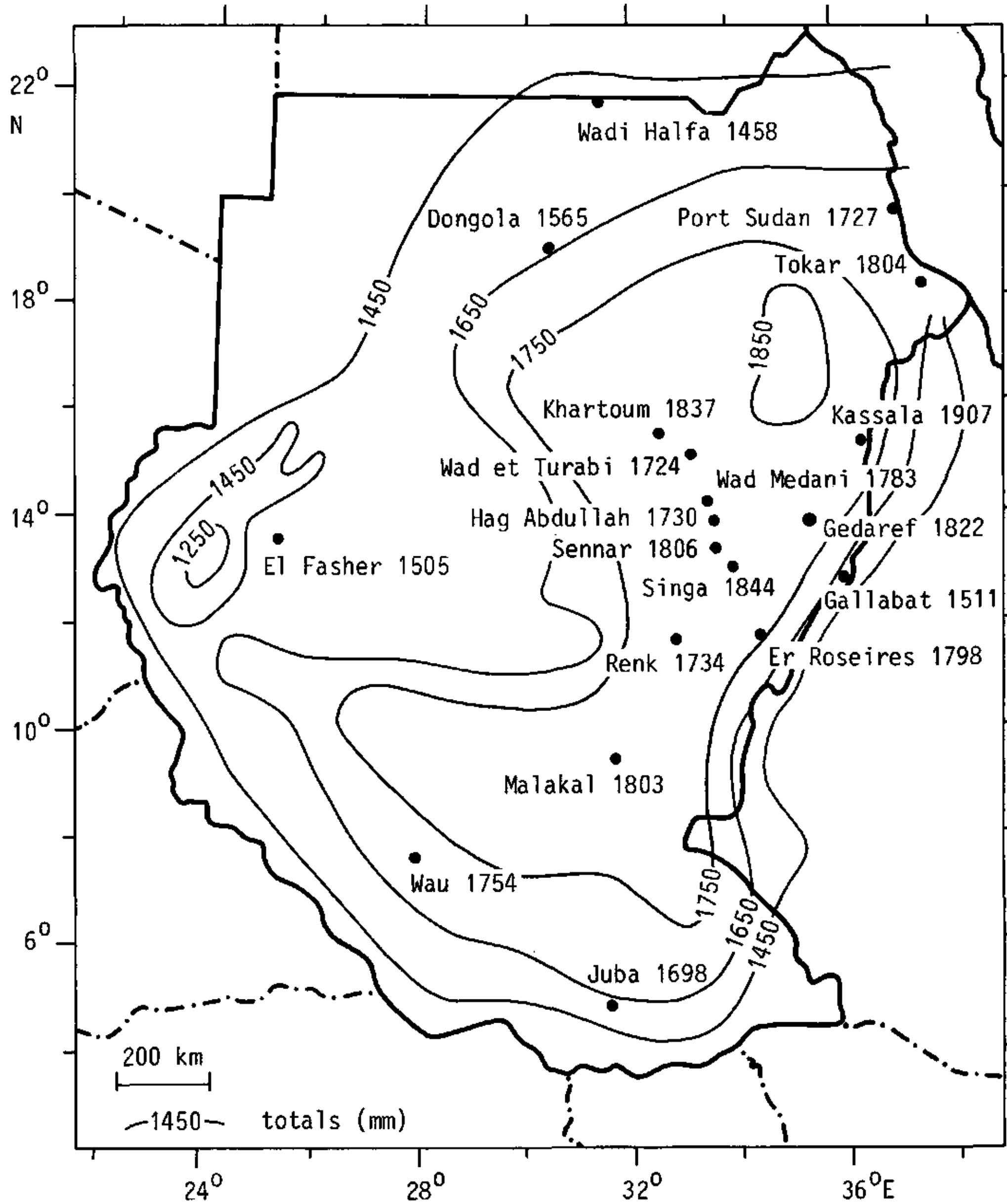
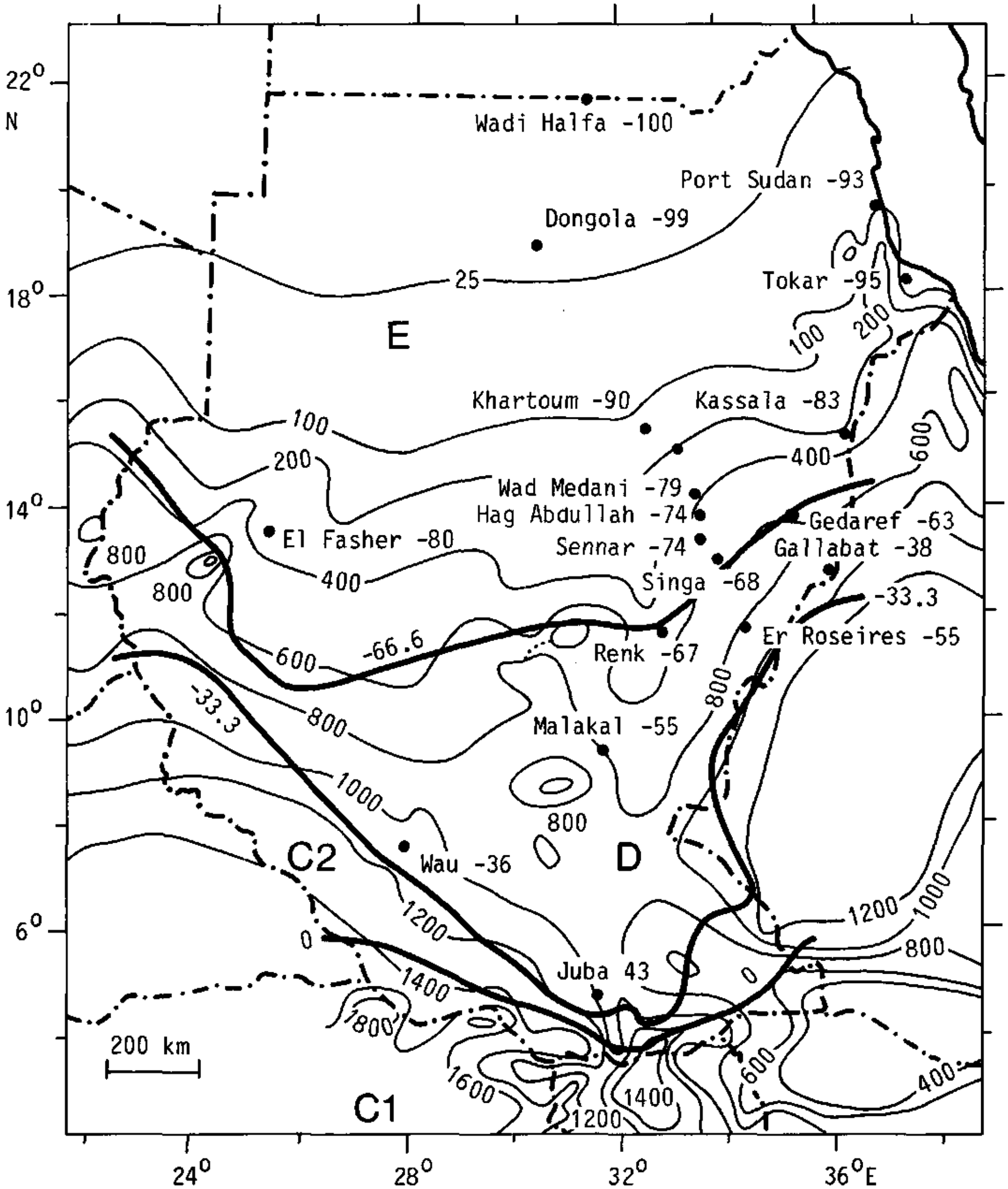


Fig. 2.9. Annual potential evapotranspiration in the Sudan according to Thornthwaite's (1948) method (after Satakopan 1961, cited by Oliver 1969)



Moisture indices

	20	
C1		moist sub humid
	0	
C2		dry sub humid
	-33.3	
D		semi arid
	-66.6	
E		arid
	-100	

-600- isohyets (mm)

Fig. 2.10. Rainfall and moisture regimes; moisture indices (Im) are given for meteorological stations (after Oliver 1969)

Table 2.2.: Meteorological data of two stations in the Central Clay Plain, Sudan

Wad Medani (14°24'N - 33°29'E)					Er Roseires (11°51'N - 34°23'E)					
month	mean daily temperature (°C)[1]	mean monthly rainfall (mm)[1]	PE (mm)[2]	d (mm)	month	mean daily temperature (°C)[1]	mean monthly rainfall (mm)[1]	PE (mm)[2]	d (mm)	s (mm)
January	24.2	0	120	120	January	26.2	0	130	130	
February	25.2	0	125	125	February	27.5	1	144	143	
March	28.2	0	149	149	March	29.8	2	160	158	
April	31.0	4	168	164	April	31.6	16	171	155	
May	32.5	11	175	164	May	31.0	62	168	106	
June	31.9	36	173	137	June	28.6	128	152	24	
July	29.1	135	156	21	July	26.8	186	138		48
August	27.8	143	146	3	August	26.4	222	134		88
September	28.9	59	155	96	September	26.9	155	139		16
October	30.2	12	163	151	October	28.0	31	148	117	
November	27.7	1	145	144	November	27.8	5	146	141	
December	25.0	0	125	125	December	26.5	0	135	135	
Year	28.5	401	1800	1399	Year	28.1	808	1765	1109	152

d= deficit

s= surplus

PE = potential evapotranspiration

[1] after Ireland (1948)

[2] calculated cf. Thornthwaite (1948) after data by Ireland (1948)

Table 2.3: Meteorological data of thirteen stations in the Central Clay Plain area, Sudan

station	location		annual rainfall (mm) [1]	mean annual temp. (°C) [1]	year			number of months with rainfall >50 mm	months in which there is a surplus, and quantity of the surplus (mm)				number of months with rainfall >50 mm	climatic type	
	North	East			PE (mm) [2]	surplus (mm)	deficit (mm)		June	July	August	Sept.		Köppen (1936)	Thornthwaite (1948)
Khartoum	15°37'	32°32'	163	29.6	1699	0	1715	2					2	Hot Desert (BWh)	arid
Wad et Turabi	15°05'	33°03'	251	28.1	1771	0	1620	2					2	do	do
Wad Sha'ir	14°42'	33°17'	273	27.6	1726	0	1453	2					2	do	do
Kassala	15°28'	36°24'	327	29.2	1855	0	1528	3					3	do	do
Rabak	13°11'	32°43'	399	28.5	1798	8	1407	4			8		4	do	do
Wad Medani	14°24'	33°29'	401	28.5	1800	0	1399	3					3	Hot Steppe (BSh)	do
Hag 'Abdullah	13°57'	33°34'	449	28.0	1766	22	1339	3			22		3	do	do
Sennar	13°33'	33°37'	454	28.7	1818	17	1381	4			17		4	do	do
Renk	11°45'	32°47'	513	27.9	1747	0	1234	4					4	do	do
Singa	13°09'	33°57'	574	28.6	1807	63	1296	4		14	49		4	do	do
Er Roseires	11°51'	34°23'	808	28.1	1765	152	1109	5		48	88	16	5	(Aw)[3]	semi-arid
Malakal	09°33'	31°39'	826	28.0	1758	93	1025	6		41	52		6	do	do
Gallabat	12°58'	36°10'	907	26.6	1647	277	1017	5	28	83	132	14	5	do	do

[1] after Ireland (1948).

[2] calculated cf. Thornthwaite (1948) after data by Ireland (1948).

[3] Tropical Rainy, winter-dry

stations are recorded. There is a slight water surplus in one month and a distinct surplus in a second month.

- Er Roseires to Gallabat: rainfall 800 to 1000 mm; there is a distinct water surplus for two to four months.

The data of Tables 2.2 and 2.3 should be read with some reserve. Efficiency of rainfall is influenced by factors such as nature of the soil, vegetation cover, solar radiation, wind force and air humidity. Thornthwaite's figures for potential evapotranspiration are based on the assumption that a continuous canopy of actively growing vegetation, freely supplied with water, is present; under these conditions the rate of transpiration is thought to be controlled by the climate alone and not by the nature of the vegetative cover or the soil. For the open, grass-savannah type of vegetation in the northern part of the clay plains this situation exists more or less during the rainy season. In the dry season, however, the actual evapotranspiration is much less than the PE because of the sparse vegetation.

In the southern parts of the clay plain,on the other hand, actual evapotranspiration may exceed PE as water may remain on the soil surface for long periods. This is well illustrated in some extremely high Piche evaporation values, e.g. Khartoum 3.016 mm, Kassala 2.027 mm, Wad Medani 2.758 mm (Oliver 1965). Low air humidity during most of the year and the generally strong winds will, no doubt, greatly increase evaporation from a free water surface.

Another aspect of rainfall distribution is important in this respect. Over much of central and eastern Sudan, a large proportion of the rain falls during the night, between 1800 and 0600 hrs (Khartoum 78%; Wad Medani 65%; Kassala 78%) (Oliver 1965), when the energy available for evapotranspiration is much lower than during the day. Actual evapotranspiration then falls short of potential evapotranspiration. The greater effectiveness of rain is, for example, shown in harvestable Sorghum production at a rainfall of 200 mm, and non-irrigated cotton at a rainfall of 400 mm (Oliver 1969).

Two remarks should be made to these general statements by Oliver. Firstly, surface flooding is not restricted to the higher-rainfall clay plains, water stagnates on the surface of clay plains in the lower-rainfall areas as well; the lower effective rainfall on clay plains compared with sandy soils is reflected in different vegetation types (section 2.5). Secondly, Sorghum on clay plains with a rainfall of 200 mm or less is usually cultivated on small plots surrounded by earth dams ('terus') which allow for the storage of some additional moisture (section 2.6).

2.4.4 Soil moisture and soil temperature regimes

In the US Soil Taxonomy (Soil Survey Staff 1975) soil moisture conditions and soil temperatures throughout the year are diagnostic criteria at the second level of generalization, the suborder (section 6.3). We will consider here the relevance of 'soil moisture regimes' and 'soil temperature regimes' cf. Soil Taxonomy for a zonal differentiation of the Central Clay Plain.

Soil moisture regime refers to the presence or absence of either ground water or water held at a tension below 15 bar (1500 kPa), over defined lengths of time and periods of the year, in a specified section (control section) of the soil profile. Soil temperature regime refers to the soil temperature at a depth of 50 cm; criteria for the definition are the average annual temperature (Ta), the average summer temperature (Ts) (the three warmest months), and the average winter temperature (Tw) (the three coldest months). By definition,Ts in the northern hemisphere refers to June, July and August, Tw to December, January and February.

Van Wambeke (1982) calculated the soil moisture and soil temperature regimes of Africa, using a mathematical model developed by F.Newhall of the Soil Conservation Service in 1972. Newhall used monthly air temperature and rainfall data as inputs in a computation model that was designed for areas with limited availability of climatic data; for example only on a monthly basis. Interpretation of relevant data on the Sudan (Tavernier and Van Wambeke 1982) is shown in Fig. 2.11, and data on Central Clay Plain stations in Table 2.4.

Table 2.4: Soil moisture regime, tentative subdivision of soil moisture regime, and soil temperature regime of some stations in the Central Clay Plain (after Van Wambeke 1982)

station	soil temperature regime	soil moisture regime	tentative subdivision of soil moisture regime
Ed Dueim	isohyperthermic	aridic	typic aridic
Gedaref	isohyperthermic	ustic	aridic tropustic
Kassala	isohyperthermic	aridic	typic aridic
Khartoum	hyperthermic	aridic	typic aridic
Kosti	isohyperthermic	aridic	typic aridic
Kurmuk	isohyperthermic	ustic	aridic tropustic
Malakal	isohyperthermic	ustic	aridic tropustic
Renk	isohyperthermic	aridic	weak aridic
Er Roseires	isohyperthermic	ustic	aridic tropustic
Sennar	isohyperthermic	aridic	weak aridic
Singa	isohyperthermic	ustic	aridic tropustic
Wad Medani	isohyperthermic	aridic	typic aridic
Wad et Turabi	isohyperthermic	aridic	typic aridic

The Central Clay Plain soils have aridic and ustic soil moisture regimes. In a proposed subdivision of the four moisture regimes in freely drained soils (aridic, xeric, ustic, udic), the Central Clay Plain classes are: typic aridic, weak aridic and aridic tropustic.

The soil temperature regime is usually isohyperthermic: Ta 22°C. or >; Ts-Tw < 5°C.; in the northern part it is hyperthermic: Ta 22°C. or >; Ts-Tw > 5°C. The boundary between the iso- and the non-iso temperature regimes is indicated in Figure 2.11. The representative profiles Jebel Qeili (nr. 6) and Hadeliya (nr. 8) have a hyperthermic soil temperature regime, all the other representative soils (Table 6.1) an isohyperthermic regime.

The iso/non-iso boundary in Figure 2.11 must be regarded with some caution. Comparison of Newhall's measurements and calculations with measurements by Oliver (1966) show differences (Table 2.5). And even Oliver's data are - in his own words - open to criticism: the data are averages from three daily observations, whereas continuous records would have given a more precise indication of the thermal range.

Table 2.5: Mean annual soil temperature (Ta), mean summer soil temperature (Ts) and mean winter soil temperature (Tw) at 50 cm depth at Khartoum, according to Oliver (1966) (measured[1]) and to Newhall's model (after Tavernier and Van Wambeke 1982)

	Ta (°C)	Ts (°C)	Tw (°C)	Ts-Tw (°C)	soil temperature regime
According to Oliver (1966)	34.0	36.5	29.6	6.9	hyperthermic
According to Newhall's model	31.2	32.3	27.2	5.1	hyperthermic

[1] averages from three daily observations, at 0800, 1400 and 2000 hrs.

Soil moisture regimes are devised for soils that are freely drained and in which moistening and desiccation of the soil take place along a horizontal plane that moves vertically in the soil. Soil moisture regimes have some meaning for silty, loamy and sandy soils, but cannot be applied to smectite clays, where infiltration is unequal due to the presence of desiccation cracks, and where hydraulic conductivity vertically is very slow, and laterally almost nil. In most orders of Soil Taxonomy, the soil moisture regimes are diagnostic at the suborder level. In Vertisols the soil moisture regime terms used in naming the suborders are the same as those used for freely drained soils, but they are defined differently, viz. on the lengths of time and periods of the year that cracks are open or closed. However, if we compare the taxonomic names of Vertisols of the Central Clay Plain (Table 6.1) with the overall soil moisture regimes in that area, we find a discrepancy: all Vertisols are classified as 'ustic' (both Chromusterts and Pellusterts), whereas calculated ustic soil moisture regimes (in well-drained soils) are only found south of approximately the 600 mm isohyet (cf. Figures 2.8 and 2.11).

The climatic zonality in the Central Clay Plain, whether expressed as soil moisture regime or as climatic type, has a distinct bearing on a zonality in vegetation (section 2.5) and on soil characteristics (Chapters 6, 7 and 8). In all climatic zonations

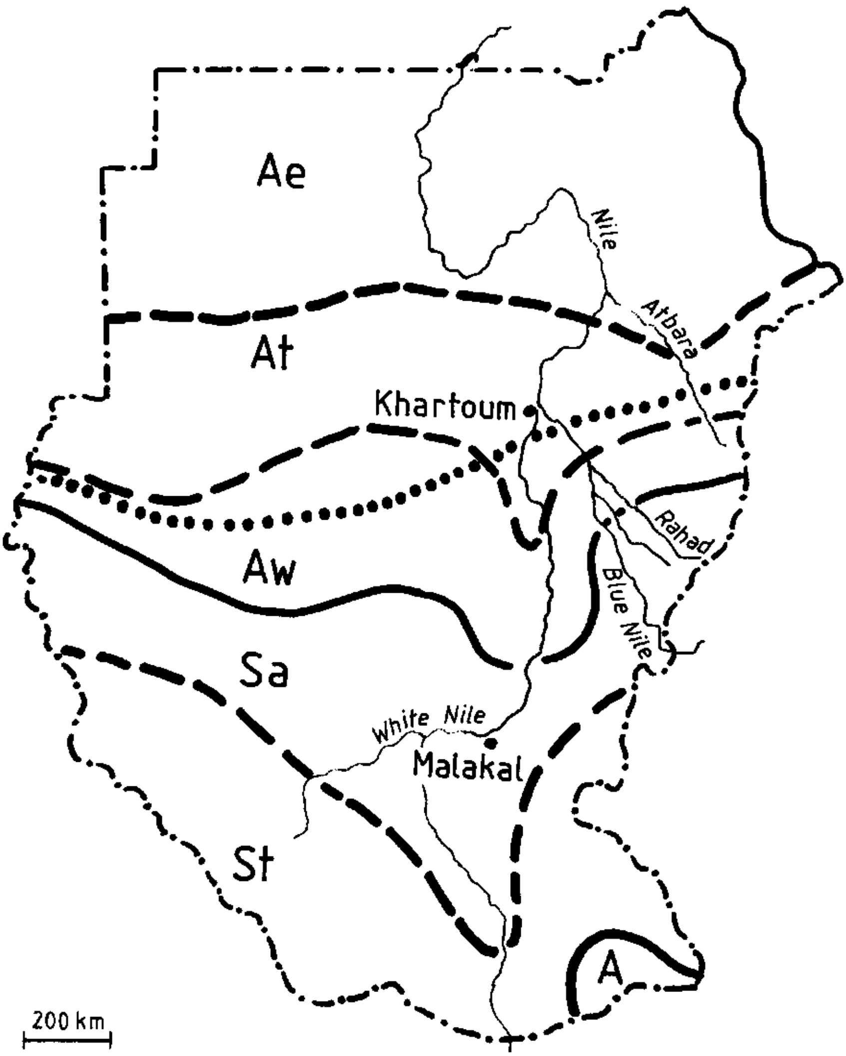


Fig. 2.11. Soil moisture regimes, tentative sub-divisions of soil moisture regimes and soil temperature regimes (after Tavernier and Van Wambeke 1982)

Ae extreme aridic
At typic aridic
Aw weak aridic
Sa aridic tropustic
St typic tropustic

Soil temperature regimes in the Sudan are hyperthermic north of the iso/non-iso boundary (....), and isohyperthermic south of it.

discussed above, the Central Clay Plain emerges as mainly an arid plain. Vegetation types, land use and soil characteristics are, however, for the major part of the clay plain, more characteristic of a semi-arid to sub-humid climate.

2.5 Natural and semi-natural vegetation

2.5.1 Classification and cartography

The first classification and cartographic representation of the vegetation types of the Sudan was by Andrews (1948). His approach was floristic rather than ecological. The first ecological classification was by Smith (1949), who made a study on the impact of rainfall and soil type on the distribution of tree species. Harrison and Jackson (1958) published a vegetation map 1:4 000 000 of the Sudan, in which they gave special attention to the differences in vegetation between 'qoz' sands and clay plains within the same climatic belt. Rattray (1960) compiled the knowledge on the grass cover of Africa and made a classification of the major grass associations. His map 1:10 000 000 shows the grassland-types - named after one characteristic or dominant genus - and the associated steppe, savannah or woodland, if present. On Rattray's map, the Central Clay Plain forms part of two units: A11 north of about 15° North latitude, and SO1 for the southern part of the plain. 'A' refers to *Aristida* grassland, 'SO' to *Sorghum*, associated with savannah. The numbers refer to specific regions in Africa. Rattray's units show a great deal of parallelism with the units of Harrison and Jackson.

Since 1958, descriptions of the vegetation of the Sudan have followed the classification of Harrison and Jackson (1958): Lebon (1965), Barbour (1961), Buursink (1971). In detailed studies, local classifications of the vegetation have been used, for example by Bunting and Lea (1962) and in various soil survey reports.

In this section, the vegetation will be described in rather general terms and only the more important or characteristic species will be mentioned. The information is drawn from Harrison and Jackson's map and accompanying brochure, from our own observations and from other sources. More detailed information on the vegetation of specific areas, and on the distribution of plant species or vegetation types in relation to environmental factors (soil, hydrology, slope, climate) is given in Chapter 6, which deals with the geography of the soils and their environment.

Plant species are named according to 'The flowering plants of the Anglo-Egyptian Sudan' (Andrews 1950-1956); this also applies to the nomenclature used in other chapters, notably Chapter 6.

2.5.2. Vegetation, climate and soils; some general remarks

In the 75 to 300 mm rainfall zone there is a striking difference between the vegetation of sandy soils ('qoz') and that of clay soils receiving the same amount of rain. In this climatic belt, the 'qoz' sands show an open growth of trees and shrubs and a partly bare, partly grass-covered surface, whereas the clay plains are virtually devoid of trees, but have a cover of varying density of annual herbs and grasses. Examples are the 'semi-desert grassland on clay' (Photo 1) and two 'desert scrub' types on sand, *Acacia tortilis - Maerua crassifolia*[4] (Photo 2) and *Acacia mellifera - Commiphora.*

Smith (1949), in his study on the factors governing the distribution of tree species, came to the conclusion that a species '... which requires 3n inches on clay soils requires less than 2n inches of rain on sands'. As an example he mentioned the occurrence of *Acacia senegal*, the small tree that yields gum arabic. This species is widespread on 'qoz' sands along the 450 mm isohyet, and is found on level clay plain sites receiving a rainfall of about 650 mm.

The differences in vegetation can be understood from the different behaviour of sandy soils and montmorillonitic clays through the seasons. When the rains start, the deeply and widely cracked soil of the clay plains is not wetted equally: the surface soil and the soil around cracks are thoroughly wetted, but the moisture hardly penetrates any further, either laterally or vertically. As soon as the cracks close, hydraulic conductivity is reduced to almost nil, and further rainfall causes flooding. In Gezira clay, the moisture penetration is limited to the upper 75 cm of the soil; below that depth there is hardly any variation in moisture content throughout the year (see e.g. Crowther 1948 ; Farbrother 1972). After the rainy season, the soils dry out and vertical cracking promotes evaporation. In a short time the stage of physiological drought is reached; the permanent wilting point correlates with a moisture percentage of about 20 (Zein el Abedine et al. 1969). The conditons of moisture distribution and availability on the clay plains are adverse to the growth of deep-rooting species (trees and perennial grasses), but they favour a rapid, but short-lived, growth of annual grasses and herbs.

In the permeable soils of the 'qoz' that often have sand percentages of over 90, rainwater penetration is deep and there is no flooding. In the dry season the surface soil dries out rapidly but, owing to restricted capillarity, soil water remains stored in the subsoil. Conditions are favourable to deep-rooting plants: a soil enabling deep root penetration, a moist subsoil, and a high percentage of soil water available to plant roots. The growth of shallow-rooting plants is restricted as the surface soil dries rapidly, hence the often sparse growth of annual species.

In the semi-desert rainfall zone, deep clays produce a treeless vegetation climax (Harrison and Jackson 1958); grass savannah would, therefore, be a natural feature in this climatic belt. Barbour (1961) suspects a man-made origin because the grass savannahs are bounded on vegetation types with woody species. Rattray (1960), in his

4 There is considerable confusion over the botanical identity of the two species Acacia tortilis (Forsk.) Hayne and Acacia raddiana Savi, and the names used are apparently different between Harrison and Jackson (1958) and Andrews (1948; 1950-1956).

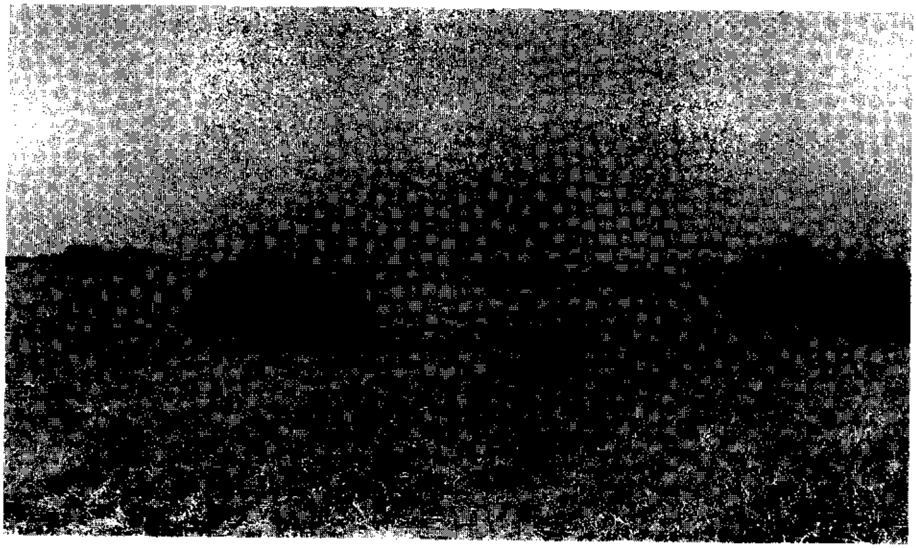


Photo 1: Semi-desert grassland on clay with scattered Acacaia mellifera *and short and medium grasses (*Setaria spp, Chloris spp *and others). Butana.*

Photo 2: Acacia tortilis - Maerua crassifolia *on sand. Butana, east of Khartoum.*

review of the grass cover of Africa, states that the presence of true climax grasslands is doubted by many ecologists. In the northern Butana, we observed that a vegetation type with widely scattered trees and bushes (*Acacia tortilis - Maerua crassifolia* desert scrub), borders abruptly on a treeless semi-desert grassland, and this change coincides with one from a sandy desert detritus surface to a clay plain. In this area, both vegetation types could well be natural features as their boundary is an ecological one.

In slightly higher rainfall areas of the semi-desert zone, tree/grassland boundaries on the clay plains, and density and species composition of the vegetation have probably been influenced by man over considerable areas (see, for example, the Acacia - Grassland cycle, to be discussed below).

In areas with an annual rainfall of more than 300 mm, the hydrological differences between sands and clays are becoming less manifest; both clay plains and 'qoz' areas are covered by woodland savannah with, however, characteristic differences in floristic composition and density of grass cover. We may conclude that, in addition to an edaphic differentiation between 'qoz' and clay plain, there is a climatic zonality. The latter is most distinct on the clay plains, as these cover an area where relief and drainage are fairly uniform over a wide climatic range.

Large areas of the Gezira, the northern Kenana and the Gedaref clay plain are under cultivation, and there are only traces of the natural vegetation left. The same applies to land bordering the rivers that is extensively used for both irrigated and dryland farming. In areas not regularly cultivated, the vegetation has often changed and deteriorated due to human activity: shifting cultivation, (over)grazing, wood chopping, grass and bush fires. Often, the biotic factor has reduced the vegetation to a type that is somewhat similar to one occurring under natural conditions in a lower-rainfall belt.

2.5.3 Vegetation classification by Harrison and Jackson (1958)

The major divisions of Harrison and Jackson's classification are the following:

I. Desert
II. Semi-desert
III. Woodland Savannah
IV. Flood Region
V. Montane Vegetation.

The sub-divisions relevant to the Central Clay Plain belong to the major units II and III, viz. (Fig. 2.12):

- II. Semi-desert
  - b. Semi-desert grassland on clay (1)
- III. Woodland Savannah
  - A. Low Rainfall
    - 1. On clay
      - a. *Acacia mellifera* thornland, alternating with grass areas (2)
      - b. *Acacia seyal* - *Balanites* savannah alternating with grass areas (3)
      - c. *Anogeissus* - *Combretum hartmannianum* savannah woodland (4)
    - 3. Special areas
      - b. Hill Catena (5)

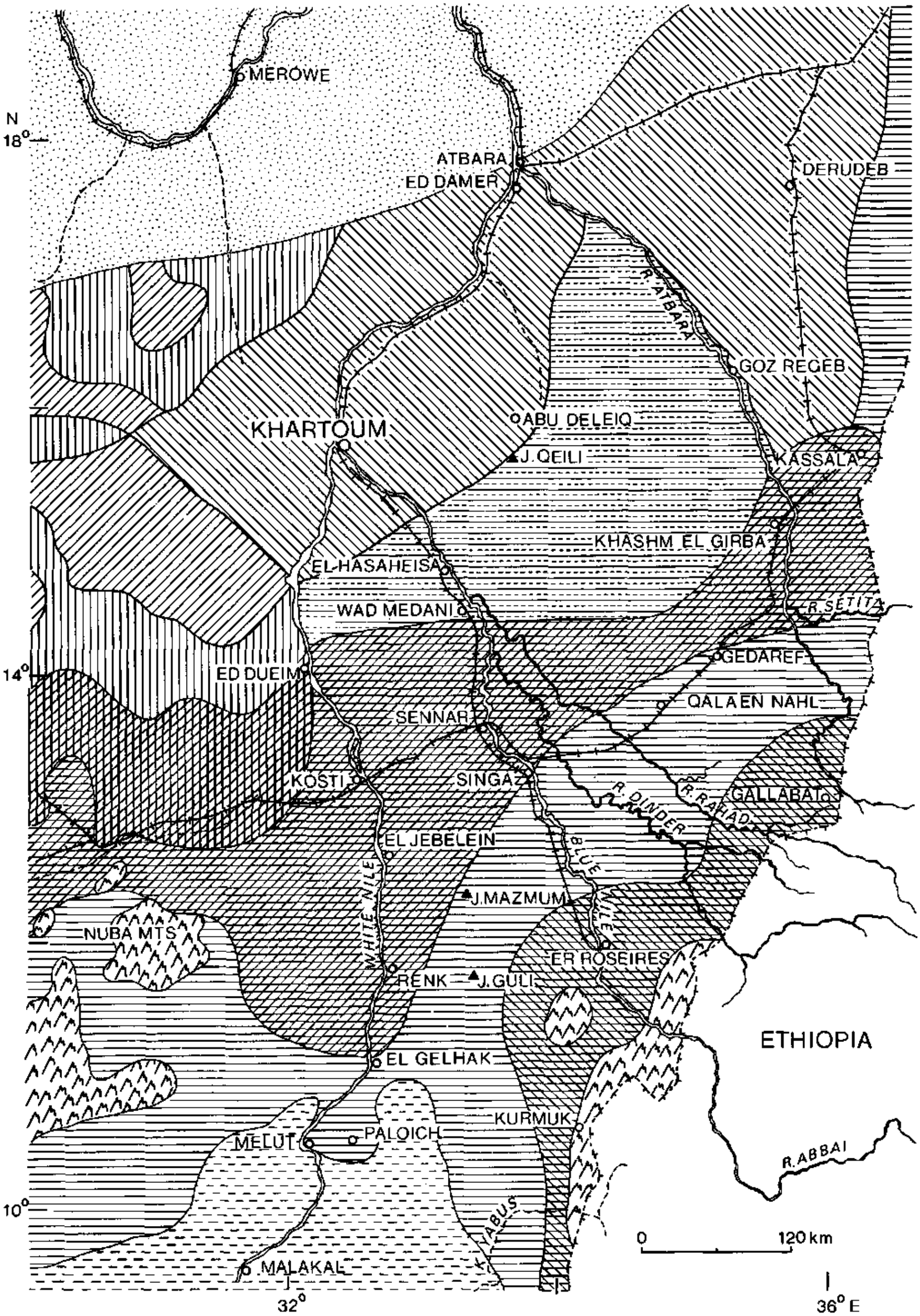


Fig. 2.12. Vegetation types of the Central Clay Plain and adjoining areas (after Harrison and Jackson 1958)

DESERT

SEMI - DESERT

Acacia tortilis - Maerua crassifolia desert scrub

Semi - desert grassland on clay (1)

Semi - desert grassland on sand

Acacia mellifera - Commiphora desert scrub

WOODLAND SAVANNAH

Low rainfall, on clay

Acacia mellifera thornland, alternating with grass areas (2)

Acacia seyal - Balanites savannah, alternating with grass areas (3)

Anogeissus - Combretum hartmannianum savannah woodland (4)

Low rainfall, on sand

Acacia senegal savannah

Special areas of low rainfall woodland savannah

Hill Catena (5)

FLOOD REGION

▲ jebel: inselberg or small group of inselbergs

railway

The numbers between brackets refer to vegetation types that are described below.

The vegetation types described as Semi-desert have a 'varying mixture of grasses and herbs, either without any woody vegetation at all or, more frequently, with a variable scatter of scrub bushes up to about 2 m high interspersed with bare areas' (Harrison and Jackson 1958, p.5). Grass growth is generally insufficient to reach the stage where fires are an annual possibility, and grass fires never play a major part in deciding the species composition of the vegetation.

The vegetation types with an open growth of trees and bushes, never attaining closed canopy, belong to the major division Woodland Savannah, of which the following description is given: "Woodland savannah includes any mixed type of vegetation composed of grass with bushes or trees or both in which the very variable proportion of grass to bushes or trees is determined by the frequency and intensity of fires. It is the type of vegetation characteristic of the dryish tropics with a monsoon rainfall confined to a few months, followed by a long hot, dry season. The bushes or trees do not give sufficient shade to prevent the development of a strong grass growth which, when it dries out in the dry season, makes fires an annual possibility. Thus all plants occurring are species with some degree of fire tolerance" (Harrison and Jackson 1958, p.9).

1 Semi-desert grassland on clay

The semi-desert grassland on clay covers the northern and central Butana clay plain and the central part of the Gezira clay plain.

The northern Butana clay plain has a vegetation of short grass species, mainly *Setaria* ssp., with *Schoenefeldia gracilis, Aristida* ssp., *Chloris* ssp. and others. Grass areas alternate with areas covered by annual herbs (*Ipomoea* ssp., *Ocimum basilicum* and many others), often mixed with some grasses.

Southwards tall annual grasses, mainly *Sorghum* ssp. and *Cymbopogon nervatus,* often form pure stands and are found next to areas dominated by *Setaria* ssp. or, sometimes, annual herbs.

The Butana grass plains show a characteristic pattern : grassbands alternate with almost bare stripes, and these form a pattern roughly parallel to the contours. These patterns, first described by Worrall (1959), will be discussed in Chapter 5. The grass savannahs are not completely without trees; the scrub *Acacia mellifera* occurs along 'khors' and on on-flow sites near rock outcrops.

2 Acacia mellifera thornland on dark cracking clay, alternating with grass areas

At about the 400 mm isohyet there is a gradual transition towards *Acacia mellifera* thornland. This *Acacia* species forms dense, almost pure thickets with little grass or herb vegetation (Photo 3). Associated with the *Acacia mellifera* are other scrubs such as *Cadaba glandulosa* and *Cadaba rotundifolia, Capparis decidua* and *Boscia senegalensis.* Within this vegetation type, treeless grass plains occur, with mainly tall annual species such as *Sorghum* ssp., *Cymbopogon nervatus, Sorghum purpureo-sericeum, Hyparrhenia pseudocymbaria* and *Sehima ischaemoides.*

Acacia mellifera thornland is well represented in the southern Butana and the northern, central and southwestern Kenana, extending westward of the White Nile. It also occurs in the southern Gezira and the northern part of the Rahad-Dinder-Blue Nile plain, but here it has often changed beyond recognition due to cultivation and habitation.

In both the *Acacia mellifera* thornland and the *Acacia seyal - Balanites* savannah (to be discussed next), areas with a more or less dense tree or bush cover alternate in time and space with treeless grass plains in what appears to be a well-defined cycle. This Grassland-*Acacia* cycle was first described by Hancock (1944) and has since been the subject of study and speculation by various authors (Harrison and Jackson 1958; Smith 1949; Thomson 1946; Moir 1954; Bunting and Lea 1962; Blokhuis 1963). It has been ascribed to the influence of rain-deficient 'mahal' years, to fire, to termite activity, to nitrogen accumulation and depletion cycles, and to combinations of these factors.

3 Acacia seyal - Balanites savannah

Where the rainfall exceeds 600 mm, the *Acacia mellifera* thornland merges with the *Acacia seyal - Balanites* savannah. Rattray (1960) sets an upper rainfall boundary of 760 mm for this savannah where it occurs on datum sites - sites neither receiving water from, nor draining excess water off to adjoining surfaces - or in slight depressions. The soil would not be able to absorb more than 760 mm rain. More rain would cause flooding, and the woodland savannah would then give way to edaphic *Hyparrhenia* grassland, which characterizes the 'toich' regions of the southern clay plain. However, we found *Acacia seyal - Balanites* savannah on datum sites receiving an even higher rainfall, up to 1000 mm. Widespread flooding occurs over the clay plain, even in lower-rainfall areas, but only prolonged flooding - we do not know for how long - prevents tree growth.

The dominant tree species in this vegetation type is *Acacia seyal*; it is generally accompanied by the evergreen tree *Balanites aegyptiaca* (Photo 4). Pure stands of *Balanites* represent sites of present or former cultivation; *Balanites* is often preserved as a shade tree and is, moreover, almost fire-resistant. In depressions subject to prolonged flooding, *Acacia fistula* is dominant or forms pure stands, but this tree is also found on datum sites in higher-rainfall areas. *Acacia senegal* occurs in a belt around the 650 mm isohyet.

Under the open tree canopy, is a ground cover of tall grasses, mainly *Sorghum* ssp., *Sorghum purpureo-sericeum*, and *Hyparrhenia pseudocymbaria. Cymbopogon nervatus* is limited to the drier parts of this vegetation unit.

Treeless grasslands alternate with woodlands, and it appears that the Grassland - *Acacia* cycle described above, occurs here as well. Distinct depressions are treeless because of prolonged flooding (see above).

The *Acacia seyal - Balanites* savannah covers the larger parts of the Gedaref clay plain, the Rahad-Dinder-Blue Nile Gezira and the southeastern Kenana.

4 Anogeissus - Combretum hartmannianum savannah woodland (Photo 5)

This savannah woodland is found on non-flooded or slightly flooded clay plains with a rainfall of over 800 mm. Most of the clay plains in this rainfall belt are degradational plains with a slightly undulating relief. Clay-covered plains alternate with sandy, gravelly and rocky areas. Land subject to flooding has a vegetation that is transitional to the *Acacia seyal - Balanites* savannah, and it may even be dominated by *Acacia* species.

Of the two typifying species *Anogeissus schimperi* occurs on sandy and gravelly areas, whereas *Combretum hartmannianum* is found on both coarse-textured and fine-textured soils in the Gedaref clay plain and west of Er Roseires. *Anogeissus* is also a typifying species for another vegetation type which occurs mainly on sand.

The dominant grasses are the perennials *Hyparrhenia pseudocymbaria, Hyparrhenia rufa, Andropogon gayanus* and *Setaria incrassata*, an indication that "... annual grasses of the drier clay plains to the north give way to the perennials of the Flood Region and High Rainfall Woodland Savannah (Harrison and Jackson 1958, p.14). The grasses occur in association with the woody species; there are no treeless grassplains.

It is of interest to note, that inside the *Acacia seyal - Balanites* savannah, *Anogeissus schimperi, Combretum hartmannianum* and other broad-leaved tree species occur on and around inselbergs and other rocky outcrops, whereas they are not found on the clay plains. In the higher-rainfall areas such a clearcut difference between the vegetation of the clay plains and of the inselbergs is not found. This observation clearly shows that with increasing rainfall the edaphic factor is of lesser importance for the distribution of tree species (cf. section 2.5.2).

5 Hill catena (Photo 6)

Under the name Hill Catena, the vegetation types occurring on inselbergs with fringing pediments and similar sites are grouped together. Hill catenas occur under widely varying rainfall conditions, from 600 mm in the Jebel Marra area (Darfur Region), to over 1200 mm in Equatoria Province. There are large variations within this unit, but in general it represents sites with moister conditions - due to on-flow from rock surfaces - than the surrounding plains. Often, there is a marked zonality from hilltop to clay plain, with *Anogeissus - Combretum hartmannianum* savannah woodland forming a transitional zone.

The Hill Catena appears as a unit on the map only where hilly areas are extensive, for example the Ingessana Hills and foot slopes of the Ethiopian massif. The Hill

Photo 3: Acacia mellifera *thornland on dark cracking clay, with tall grasses. Track from Gedaref to Jebel El Fau, in 1962.*

Photo 4: Acacia seyal - Balanites *savannah, with* Acacia *(left) and* Balanites *(right). Track from El Gelhak to Khor Yabus, southern Kenana.*

Photo 5: Anogeissus - Combretum hartmannianum *savannah woodland. Ingessana Hills, southern Kenana.*

*Photo 6: Hill catena, with 'tebeldi' (baobab) trees (*Adansonia digitata*) in the centre of the photograph. Jebel Umm Seinat, Gedaref clay plain.*

Catena vegetation type is not found in the semi-desert vegetation zones; in this rainfall belt rocky areas carry a vegetation similar to low-rainfall vegetation types on sand.

Several small areas in the Central Clay Plain carry a vegetation that differs from any of the above five types. Generally, these have a physiography distinct from that of the surrounding clay plains, but they are too small to be represented on the 1:4 000 000 vegetation map.

The areas concerned are:

a. inselbergs and hill groups too small to be mapped;
b. flat-lying outcrops of the Nubian sandstone formation;
c. the 'kerrib' land along the main rivers;
d. recent river terraces and alluvial islands; these are often cultivated;
e. cut-off meanders and point bars along the Blue Nile and tributary rivers. These are ponded sites ('maiyas') where the large tree *Acacia arabica* is characteristic.
f. dunes east of the White Nile, in the El Geteina area;
g. marshy land along the White Nile.

2.6 Land use

The information for this paragraph is drawn from Tothill's Agriculture in the Sudan (1948), Post (1987), ILO/UNDP (1976), World Bank (1979; 1985), from several unpublished reports and from own observations. A comprehensive survey of land use in the Sudan was made by Lebon (1965). As both irrigated agriculture and mechanized crop production have increased tremendously in the last twenty years, the latter source is outdated as far as the Central Clay Plain is concerned.

The larger part of the Central Clay Plain is still being used for nomadic grazing by cattle, sheep, goats and camels, and it carries a semi-natural grassland or savannah type vegetation. Forests in the southern part of the clay plain produce firewood and wood for charcoal burning. The small tree *Acacia senegal* produces gum arabic, an important export product.

For succesful production of rainfed crops, a rainfall of at least 300 to 400 mm is required. On lesser rainfall areas, water supply to fields is increased by the impounding of rainwater against low earth banks ('terus'). A form of shifting cultivation known as 'hariq' is practised in tall grass areas in the savannah woodlands.

Economically most important are the rainfed mechanized crop production schemes (MCPS) and the irrigation schemes, most of which are irrigated by gravity flow: the Gezira Scheme, with the Manaqil extension, the New Halfa or Khashm el Girba Scheme, the Rahad Scheme, and the irrigated land of the Kenana Sugar Corporation. Along the Blue Nile and the White Nile and the lower reaches of Dinder and Rahad are numerous pump schemes. The largest of these are Guneid and Es Suki, both irrigated with water from the Blue Nile (Fig. 2.13).

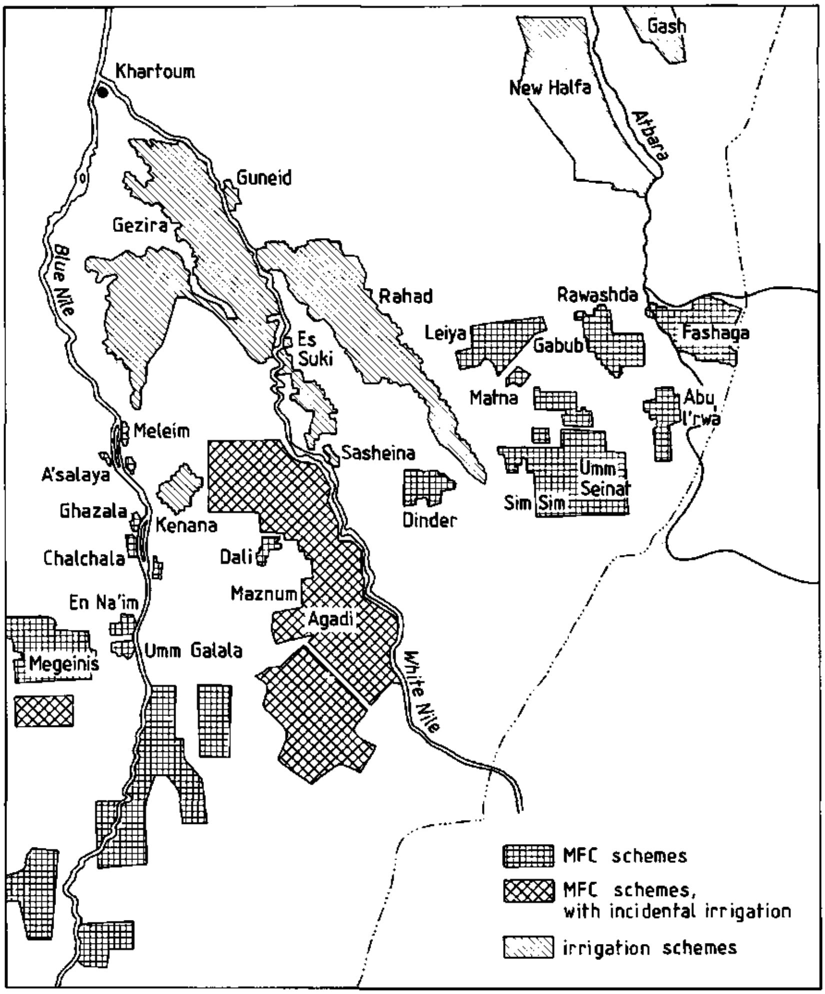


Fig. 2.13. Irrigation Schemes and Mechanized Crop Production Schemes (MCPS) in the Central Clay Plain area (from various sources)

2.6.1 Irrigated agriculture

The oldest and most well-known of the gravity irrigation schemes is the Gezira Scheme (Photo 7) with an area of almost 470 000 hectares. The Scheme is irrigated from a reservoir in the Blue Nile at Sennar (Photo 8). The Sennar dam was built in 1925. Between 1958 and 1962, the Scheme was enlarged by the Manaqil extension and Gezira Phase V, that together cover an area of 400 000 ha. For many years, the main cash crop in the Gezira-Manaqil was cotton (Photo 9), mainly long-staple varieties, but in the last decades there has been a shift towards medium-staple cotton in response to increased demand, and towards food crops such as wheat and

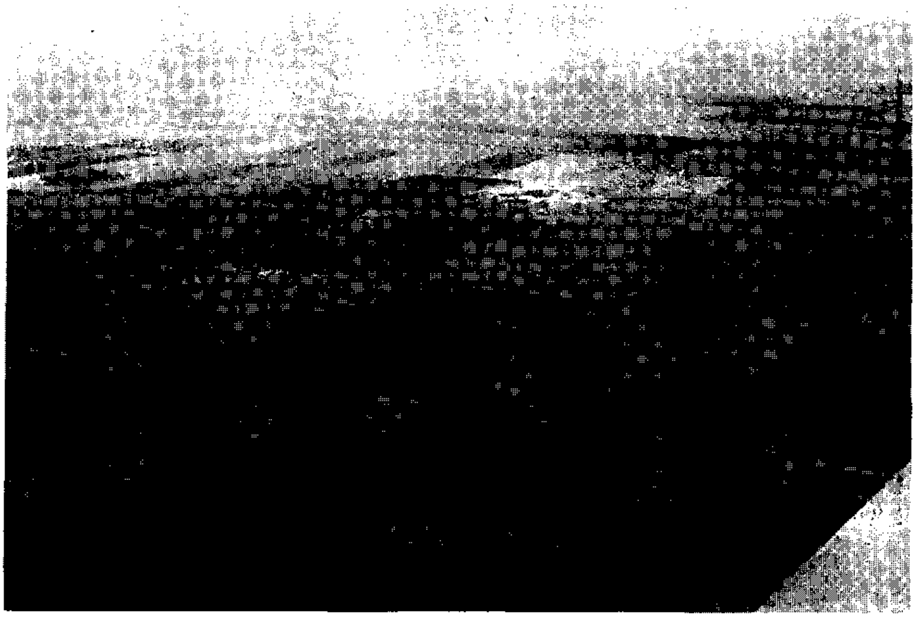


Photo 7: Aerial view of the Gezira Scheme. Dark-grey fields are cotton, medium-grey fields are 'dura' or 'lubia', light-grey fields are fallow. Villages interrupt the regular pattern of fields.

Photo 8: Inlet of the main irrigation canal for the Gezira Scheme.

groundnuts. Traditionally, cotton was cultivated in rotations including the food crop 'dura' (*Sorghum vulgare*, great millet), the fodder crop 'lubia' (*Dolichos lablab*), and fallow years. The Gezira-Managil Scheme is under the management of a tripartite partnership: the Sudan Gezira Board, the Sudan Government and the tenant farmers (ILO/UNDP 1976).

The Guneid pump scheme, on the Blue Nile east bank opposite the Gezira, is under the same management as the Gezira-Manaqil Scheme. It has an area of almost 36 000 hectares. The main cash crop is sugar cane.

The New Halfa or Khashm el Girba Scheme is irrigated by a reservoir in the Atbara river above the town of Khashm el Girba. Irrigation of the first phase of the Scheme was started in 1965; at present some 200 000 ha are irrigated. Over most of the irrigable area, cultivation is in rotations similar to those of the Gezira-Manaqil, but there is also large-scale cultivation of sugar cane.

The Roseires Dam Project, which is now being implemented, will ultimately provide for the irrigation of extensive areas in the Rahad-Dinder-Blue Nile Gezira, along the Blue Nile and Rahad east banks, and in the northern Gezira from a reservoir in the Blue Nile above Er Roseires.

In the northern Kenana, the Kenana Sugar Corporation includes an integrated sugar plant and factory with a planned capacity of 350 000 tonnes, and an irrigated area on the clay plain that will ultimately have an extent of 120 000 hectares. The high capital coefficient, as well as organizational and logistic problems, throw doubts on the ultimate profitability of this gigantic enterprise (Oesterdiekhof 1982).

Another large enterprise in the Roseires project is the Rahad Scheme, on the east bank of the river Rahad. In 1985 an area of 120 000 hectares was irrigated. Irrigation from a barrage in the Rahad is restricted to August, when the river is in spate; otherwise irrigation is by water from the Blue Nile, pumped from a site near Meina el Mek, from where it is led over a distance of 80 km by a canal (Jansen and Koch 1982). The two main crops are medium-staple cotton and groundnuts.

On both banks of the Blue and White Nile are numerous pump irrigation schemes. These schemes were started by private enterprise, but were nationalized in 1968 and are now managed by the Agrarian Reform Corporation (ARC). In 1975 (ILO/UNDP 1976) the ARC was responsible for 62 schemes, with a gross area of almost 120 000 ha along the Blue Nile between 40 km north and 20 km south of Sennar, and for 186 schemes, with a gross area of 175 000 ha along the White Nile, over a length of 380 km upstream from Jebel Auliya.

Along the Blue Nile, and on islands in the river, there is intensive cultivation of vegetables, food and fruit crops during the dry season. These fertile lands, known as 'gerf', are flooded annually when the river is in spate (Photo 10).

2.6.2 Rainland cultivation

Extensive mechanized crop production schemes (Fig. 2.13) have been developed by private entrepreneurs (often traders at nearby market places) and by the

Photo 9: Picking cotton in the Gezira.

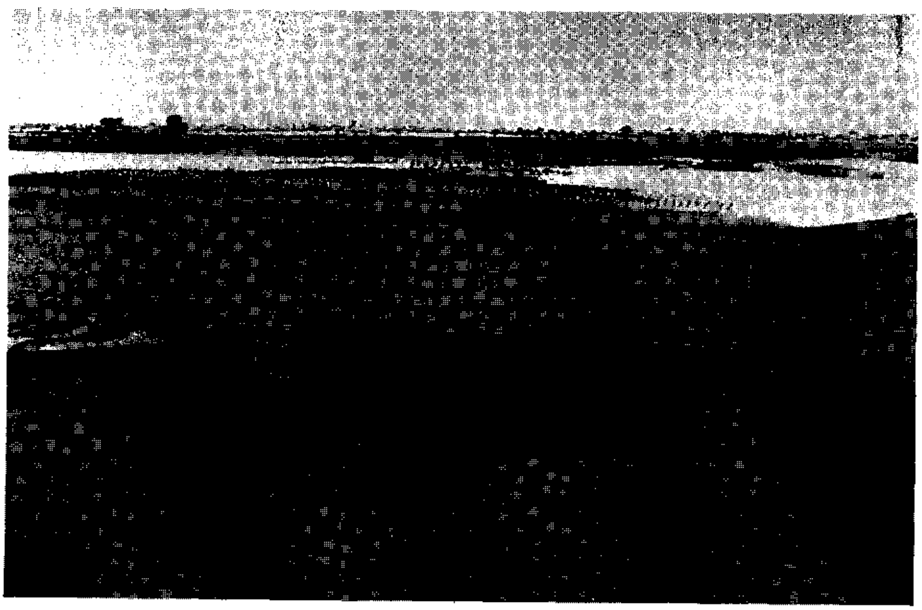


Photo 10: 'Gerf' cultivation along the Blue Nile near Wad Medani. Vegetables are cultivated in the dry season on land flooded when the river is in spate.

Mechanized Farming Corporation (MFC). They are largely confined to the clay plains of the 500 to 800 mm rainfall zone, notably the Central Clay Plain area. In 1968 the MFC, an autonomous body inside the Ministry of Agriculture, was given the responsibility for all mechanized farming projects in the country. In 1985 2.5 million hectares were under mechanized rainfed cropping by about 4000 large farmer/ merchants (Land Resources Development Centre 1987; FAO/WFP Multidonor mission 1986).

Sorghum has always been the main crop. Over one million tons of sorghum, about half of the Sudan's total production, is cropped on the mechanized farms (Land Resources Development Centre 1987). Sesame (*Sesamum orientale*, 'simsim) and short-staple cotton are minor crops. In 1979 Sorghum covered 80% of the cropped land, sesame 15% and short-staple cotton 5%. The MFC recommends a rotation with 60% of the land in Sorghum, 7% in sesame, and 33% in fallow.

Subsistence agriculture on the lower-rainfall clay plains is confined to places in the vicinity of villages - mainly near the rivers - in flooded wadi beds or near inselbergs and hills. The main crop is Sorghum (Photo 11). Another food crop, bullrush millet (*Pennisetum typhoideum*, 'dukhn'), occurs locally; it is the typical grain crop of sandy areas. In the higher-rainfall areas sesame is cultivated in addition to Sorghum, for example, in the Gedaref clay plain.

A system of shifting cultivation known as 'hariq'is practised in tall grass areas. It is described by Burnett (1948) as follows: "The normal procedure is to allow 2 to 4 years' growth of grasses to form a rank dense matted growth. After the first heavy rains in the year chosen for cultivation and when the new growing grass has sprouted and is showing green, the matted growth is fired. If taken at the right time the heat generated from the burning grass is sufficient to kill off the new young grass. The resultant clean land can then be sown, and if the burning has been succesful no subsequent hoeings should be necessary". The grass most suitable for 'hariq' cultivation is *Sorghum purpureo-sericeum*, 'anis'. 'Hariq' cultivation is often seriously threatened by uncontrolled grass fires.

Where the rainfall is insufficient for the production of crops, additional water supply is obtained by building low earth banks ('terus') across and with the slope of the land, leaving the upslope side open (Photo 12). 'Terus' cultivation is practised on the gently sloping aggradational clay plains in the 250 to 300 mm rainfall zone (Burnett 1948), seldom far from the river where most villages are found.

2.6.3 Other forms of land use

In some areas the collection of gum arabic is an important activity. The best quality gum is produced by *Acacia senegal*; gum of lesser quality is obtained from *Acacia seyal*. Charcoal burning is a local industry in some parts of the Kenana.

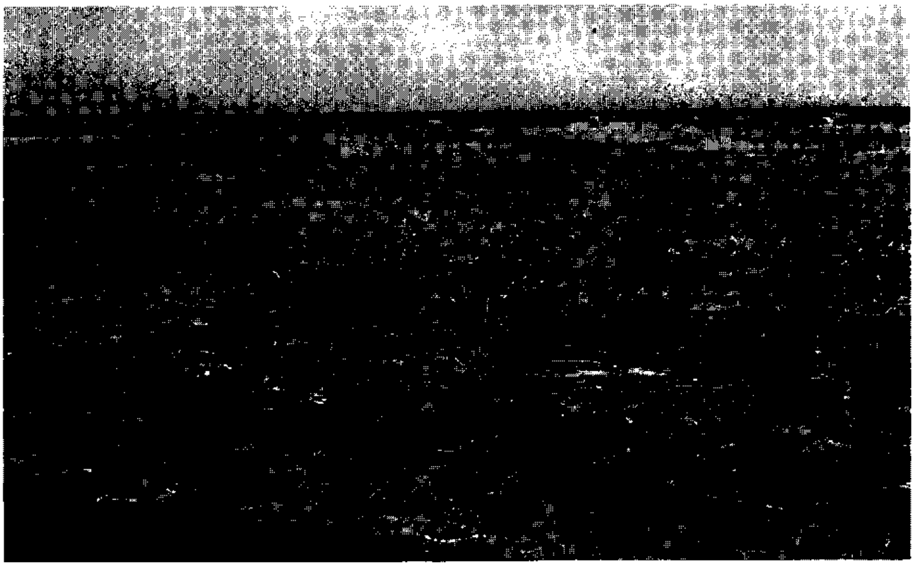


Photo 11: Subsistence rainland cultivation. Field near Sennar with stubble of 'dura'.

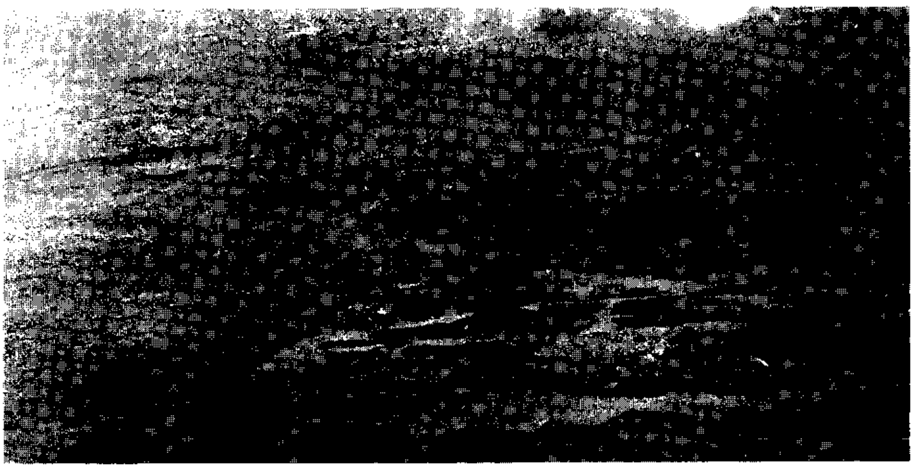


Photo 12: Aerial view of the Atbara river (left) with bordering 'kerrib' land, and the clay plain with 'terus' cultivation.

Livestock husbandry is widespread over most of the clay plain (Photos 13 and 14). Grazing has affected the natural vegetation in most areas, and the land around villages and close to the rivers is often overgrazed, whereas large areas with good grass cover but without a water supply remain relatively unused (Jewitt 1955a; Jackson and Shawki 1950). The effects of overgrazing are most evident in the semi-desert climatic belt, where villages have wide fringes of almost bare land.

Both grazing and cultivation can be extended towards remote areas if there is a supply of drinking water. On the clay plains rain-water can be efficiently stored in

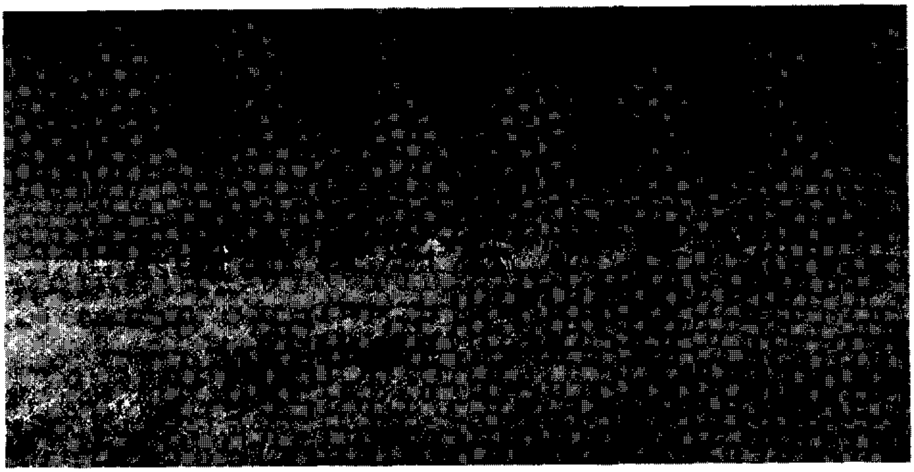


Photo 13: Shukriya nomads and camels on the Butana grass plain.

Photo 14: Cattle on the Central Clay Plain.

pools ('hafirs') that collect the water from runoff of nearby areas (Photo 15). Privileged sites for 'hafir' building are near inselbergs, where rain-water from the hill slopes is collected.

The creation of two large irrigation schemes on the eastern and western fringes of the Butana - Khashm el Girba and Rahad - has strongly affected pastoralism and nomadism in the area. These schemes have absorbed part of the natural pasture lands, and many nomads have settled as contracted tenants. The irrigation schemes give supplementary fodder (crop remains) to the nomad tenants, and thus diminish the risk of drought and failure of natural pastures. There is also a shift from single-animal herding to multiple-type herding, mainly combining sheep, cattle and goats (Abu Sin 1982).

Photo 15: 'Hafir' and cattle near Jebel Ghadambaliya, Butana.

2.6.4 Soil degradation

The irrigation schemes, but particularly the mechanized rainfed crop production schemes, have considerably reduced the land available for smallholder farming and for grazing. Demands on both arable land and grazing areas tend to be too heavy, and physical and chemical soil deterioration are serious threats (Post 1987). In the mechanized rainfed areas there is a continuous near-monoculture of Sorghum, without any fertilizer being used. Over the years Sorghum yields have dropped from 1900 to 700 kg/ha with continuous cultivation. Farmers tend to react by illegally opening further blocks of land, abandoning depleted areas with no attempt being made to rehabilitate them (Land Resources Development Centre 1987). Soil degradation is evident in many of the mechanized schemes (World Bank 1979; Musnad and El Rasheed 1979; Thimm 1979), but there is little information available on the precise nature of this degradation.

2.7 Summary

Apart from small areas with inselbergs or hill groups, the Central Clay Plain has slopes below 1% and qualifies to the category 'level' of the FAO site classification (FAO 1977). Contour maps reveal the differences between aggradational and degradational plains.

The aggradational plains have formed from Pleistocene and Holocene alluvial deposits of the Nile river system. The very different regime, now and in the past, between the White Nile and the Blue Nile, has had - and still has - a strong impact on the nature of the alluvial deposits. The formation of the aggradational clay plains will be dealt with in Chapter 4.

It is important to the formation of the degradational plains, that many of the minor waterways that sprout at the foot of hills or begin on the clay plain itself, do not reach major drainage ways but fade out in a lower part of the plain. This situation has probably existed for most of the time of planation. The formation of the degradational plains is the subject of Chapter 5.

Climatic differentiation of the Central Clay Plain is based on precipitation and evaporation data, temperatures not being much different from North to South. A sub-division into four regions appears most appropriate:

- rainfall up to 400 mm; no month with a water surplus.
- rainfall 400 to 500 mm; slight surplus for one month.
- rainfall 500 to 800 mm; slight surplus for one month; distinct water surplus in a second month.
- rainfall 800-1000 mm; distinct water surplus for two to four months.

To what extent this climatic zonality is matched by differences in soil characteristics, will be discussed in Chapters 6, 7 and 8.

Four vegetation units in the classification of Harrison and Jackson (1958) cover the Central Clay Plain. Their boundaries are roughly parallel to the 400, 600 and 800 mm isohyets. Edaphic factors, and especially the differences between clay soils on one side, and sandy, rocky and stony areas on the other, are particularly important in the lower-rainfall part of the clay plain. Differences in vegetation have been used extensively in soil mapping, on all scales from semi-detailed to exploratory (Chapter 6).

Irrigated agriculture is practised extensively in areas that are commandable from the Nile waters. Rainfed agriculture is practised in areas with an annual rainfall of 400 mm or above, largely in Mechanized Crop Production Schemes (MCPS), and to a smaller extent as subsistence agriculture in a system of shifting cultivation. In combination with flooding ('terus'-cultivation) a much lower rainfall is adequate for annual crops. Livestock husbandry is widespread over most of the Central Clay Plain.

Chapter 3

Geological sequence

3.1. The Central Clay Plain on geological maps

The data on geology are mainly drawn from three sources. Firstly, Andrew's (1948) 'Geology of the Sudan', in Tothill's (ed.) 'Agriculture in the Sudan'. Most stratigraphical terms now in common use are still those introduced by Andrew and earlier workers. Secondly, Whiteman's (1971) comprehensive monograph 'The Geology of the Sudan Republic', in which earlier work is summarized and a considerable amount of new material presented. A third source was Vail's (1978) 'Outline of the geology and mineral deposits of the Democratic Republic of the Sudan and adjacent areas'.

The geological sequence, from Precambrian up to and including Tertiary, is shown schematically in Table 3.1. The Quaternary will be dealt with in this Chapter as well, but aspects of it are treated in more detail in Chapters 4 and 5.

Additional information was drawn from geological maps. The now outdated Geological Map of the Sudan, 1:4 000 000 (1963) gives the 'superficial deposits' as a hatching superimposed on the 'geological reference'. The boundaries of the deposits were to be regarded as 'provisional'. The area mapped as 'clays predominant' comprises both the central and the southern clay plains. In 1952, a more detailed map was published of sheet 55, Khartoum, of the 1:1 000 000 topographic series. Whiteman (1971) included a general geological map, on a scale of about 1:9 000 000 with his work on the geology of the Sudan. Whiteman used the litho-stratigraphical term 'formation' instead of the time-stratigraphical term 'series' which was in common use, notwithstanding the uncertainty of age of much of the Sudan's geology. The term 'formation' is also used on the newest geological maps, both on a scale of 1:2 000 000: the much improved edition of the Geological Map of the Sudan, published by the Geological and Mineral Resources Department, Khartoum (1981), and a map that is attached to Vail's (1978) monograph.

The most useful geological map from the soil scientist's point of view would be a combination of the two recent 1:2 000 000 maps. Vail's map is strongly biased towards surface formations, but with little differentiation therein. The clay plains of the east-central Sudan come under two headings: (1) alluvium, wadi fill and swamp deposits (Quaternary), and (2) unconsolidated superficial sediments, mainly sands, gravels and clay; precise age uncertain (Tertiary-Quaternary). Relevant to the clay plain area is also unit (3) blown sands, fixed dunes (Qoz), and superficial deposits. Unit (1) covers the Rahad-Dinder-Blue Nile Gezira and the White Nile valley, whereas unit (2) covers the remaining part of the Central Clay Plain. The Southern Clay Plain is made up of units (1) and (2).

Table 3.1: Geological sequence, Precambrian through Tertiary, Sudan Central Clay Plain area; after Whiteman (1971), Berry and Whiteman (1968), Barbour (1961) and others

Time-scale		Formation	Tectonics	Sedimentation and denudation	Occurrence in Central Clay Plain (and some other areas)
TERTIARY	Pliocene	Umm Ruwaba and El Atshan Formations; lower members of Gezira Formation	gentle warping with uplift of eastern Sudan, accompanied by faulting; rise of Ethiopian plateau and Red Sea hills; Red Sea formed; downwarping along present line of Nile Valley; formation of Sudan basin	deposition into subsiding basin, continuing into Pleistocene	formations generally covered without uncorformity by a homogeneous surface deposit of alluvial-lacustrine clays
	Miocene	— ironstone phase in Mid-Tertiary — (part of iron-rich deposits is probably Pleistocene)	volcanicity, starting in Palaeocene and continuing into Miocene; development African Rift System		pea-iron gravel and laterite cappings in Gedaref district; ferruginous capping on Nubian Sandstone Formation? / planation of Basement Complex surface through Tertiary and Quaternary
	Oligocene	Gedaref crinanites and basalts		extrusion of lava flows on Gedaref Sandstone Formation	plateau-ridges in Gedaref area
	Eocene	no deposits		predominantly a period of erosion	
	Palaeocene				
MESOZOIC	Cretaceous	Nubian Sandstone Formation		probably fresh-water sediments deposited in a series of fans and playas	underlies Gezira Clay plain and adjoining parts of Butana and Rahad-Dinder-Blue Nile Gezira; outcropping as desert denudation surface in northwest Butana and, locally, along Blue Nile eastbank Khartoum to Wad Medani
	Jurassic	Gedaref Sandstone Formation		marine (Jurassic sea) or fresh-water deposit	forms erosion surface in Gedaref area on which Tertiary basalts have been extruded; partly covered by Quaternary sediments (clay plain); outcrops as inselbergs
	Triassic	absent		period of erosion (post-Carboniferous to pre-Nubian)	absent
PALAEOZOIC		absent		Palaeozoic sedimentation possible, but, if so, deposits subsequently cleared by erosion	absent
PRECAMBRIAN		Basement Complex	large-scale folding, orogeny and metamorphism and	extended periods of denudation	inselbergs, or hill groups and rocky land; Nuba Mountains Ingessana Hills

On the 1963 Geological Map of the Sudan, 1:4 000 000, all sediments that have infilled the Tertiary basin in southern and east-central Sudan are mapped as Umm Ruwaba series. The delineation of the deposits has been much refined in the 1981 1:2 000 000 edition, and this map gives a good indication of which parts of the Sudan clay plain-at-large are underlain by (coarser-textured) unconsolidated deposits. These roughly correspond with the aggradational plains. In the new edition, the northern part of the Rahad-Dinder-Blue Nile Gezira and the Gezira fan are mapped as Gezira Formation, whereas the southern part is still assigned to the Umm Ruwaba Formation. The other infillings of the Sudan basin have been mapped either as Umm Ruwaba Formation (Tertiary to Quaternary), or as 'alluvium, wadi fill, terraces, delta and swamp deposits (Recent)'. Of the remainder of the clay plain area - the degradational plains - the underlying rocks are mapped: Basement Complex, Nubian Sandstone Formation and Basic volcanics, mainly basalts.

Whiteman (1971) separates the Rahad-Dinder-Blue Nile Gezira from the Umm Ruwaba formation as El Atshan formation, following Ruxton (1956). The other parts of the Central Clay Plain are mapped according to the underlying solid geology, mainly Basement Complex and Nubian Sandstone Formation.

Vail (1978) does not make the distinction between clays overlying coarser-textured unconsolidated strata, and clays overlying (weathered) rock, be it conformably or unconformably, and so he refrains from any statement on the origin of the clays. As this latter aspect is a major issue in our study, and an important criterion for the differentiation of pedogeomorphic mapping units (Chapter 6), we have largely adhered to the Sudan Government map, but not without consulting Vail's. On a reduced scale and somewhat simplified, the Sudan Government map is reproduced here as Figure 3.1.

The unfortunate aspect of the Sudan Government geological map is that there is no explanatory note accompanying it. Some of the boundaries are questionable. Firstly, the one between the Gezira formation and the Basement Complex in the southern Gezira. The contour map (Fig. 2.5) or the delineation of the 'upland clays' by Williams et al. (1982) gives a better indication of where the latter boundary should be situated. Secondly, the boundary between the Umm Ruwaba and Gezira formations divides the Rahad-Dinder-Blue Nile Gezira into two parts for reasons unknown to us. Vail's separate mapping of the Rahad-Dinder-Blue Nile Gezira as 'alluvium, wadi fill and swamp deposits' at least treats this clay plain as one and the same unit. In his monograph, Vail acknowledges that this area was mapped as the El Atshan formation by Whiteman (1971), and that the sediments were said to be similar to the Umm Ruwaba and Gezira formations, and therefore belonging to 'the same broad group as the other unconsolidated sands and clays'. He uses, however, the term 'alluvium' for the Rahad-Dinder-Blue Nile Gezira, because of the occurrence of annual flooding by the main rivers, causing overspill and temporary inundations locally. Indeed this part of the Central Clay Plain differs from most of the remainder in showing the features of a recent river floodplain.

The term 'old alluvium' has been used for the coarse-textured unconsolidated

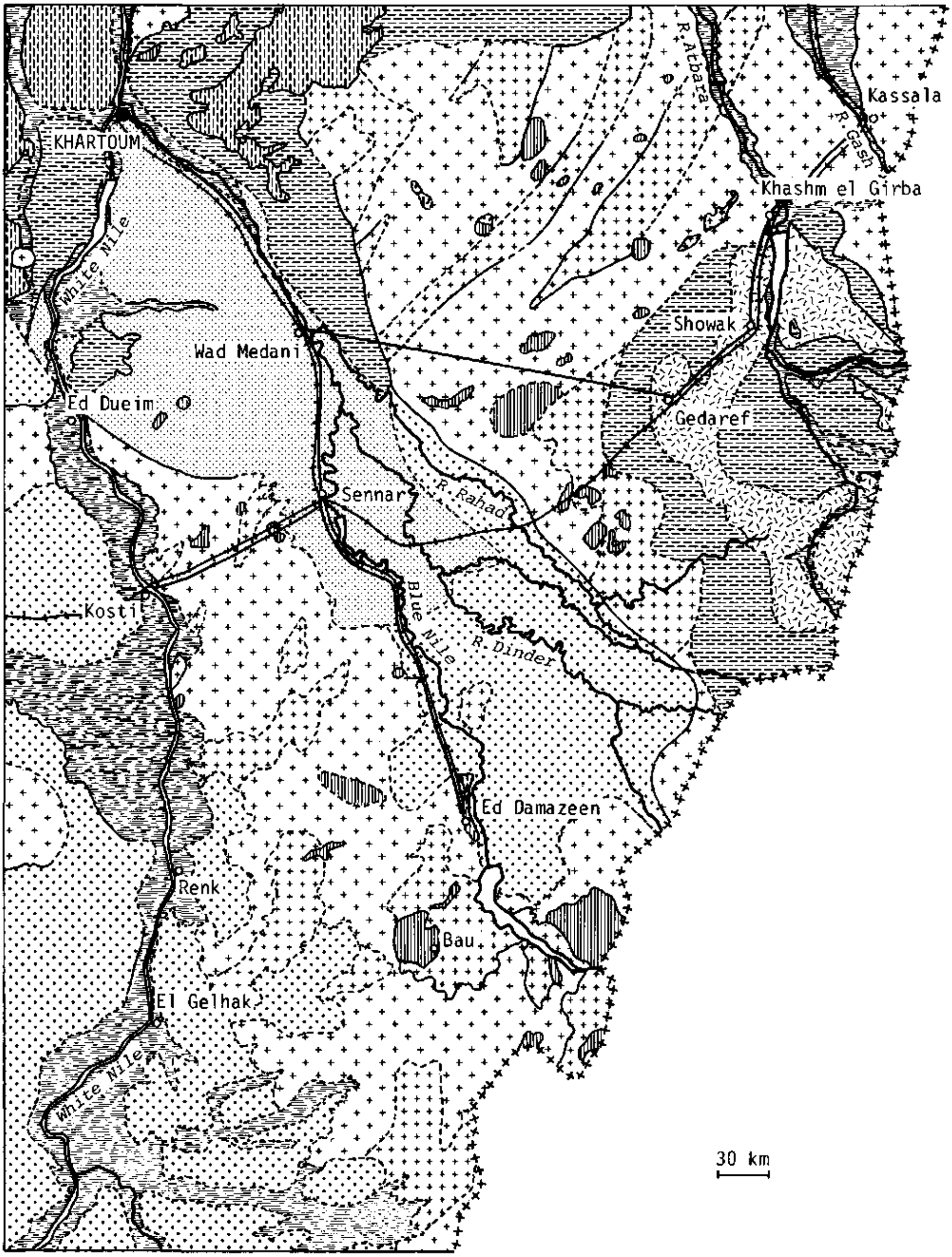


Fig. 3.1. Geological map of the Central Clay Plain area, Sudan (from Geological Map of the Sudan, Geological and Mineral Resources Department, Khartoum 1981)

LEGEND

RECENT		Alluvium, wadi fills, delta and swamp deposits
TERTIARY to QUATERNARY		Gezira Formation: unconsolidated clays, silts, sands and gravels
		Umm Ruwaba Formation: unconsolidated sands, with some gravels, clays and shales
MESOZOIC to TERTIARY		Basic volcanics, mainly basalts
		Acidic and intermediate volcanics, mainly rhyolites and trachytes
CRETACEOUS	a) b)	Nubian Sandstone Formation: continental clastic sediments including sandstones, siltstones, mudstones and conglomerates (a, outcrop; b, non-outcrop)
PRECAMBRIAN		Undifferentiated Basement Complex
		Undifferentiated Schist Group: metasediments, marble, quartzites and graphite and mica schists
		Intrusive rocks
		railway
		road

sediments of the Sudan basin that underlie the clays (Umm Ruwaba, El Atshan and Gezira formations), (Whiteman 1971; Vail 1978). This is a most useful term as the three formations are laterally continuous, and similar in age and composition.

There are differences in thickness: the Umm Ruwaba formation attains a maximum thickness of 335 m in the Kordofan Region, whereas the Gezira formation varies in thickness between 4.5 and 111 m (Whiteman 1971, pp. 90 and 125). Ruxton and Berry (1978) include alluvial fill deposits along the Atbara and the Gash rivers with the 'old alluvium'. Their concept of 'old alluvium' is, apparently, that of alluvium which is above or outside present deposition levels or areas.

In the following, the relevant formations of the Central Clay Plain area will be discussed, their chronology, stratigraphy and the nature of the rocks. The formations are: Basement Complex Group (mainly Precambrian), the Gedaref Sandstone Formation (Jurassic), the Nubian Sandstone Formation (probably Late Cretaceous), volcanic and intrusive rocks, mainly lavas (Mesozoic to Tertiary), and the Umm Ruwaba, El Atshan and Gezira formations (Pliocene and Pleistocene).

The clays of the plain are discussed in Chapters 4 and 5 with regard to their origin and age. They are mainly Pleistocene to Recent. Other Quaternary formations include the White Nile alluvium and the 'qoz' sands; these are discussed in this Chapter. Local details of the geology are discussed in Chapter 6, together with vegetation, landform and soils.

3.2 Precambrian

The Precambrian Basement Complex Group consists of volcanic, metamorphic and sedimentary rocks, varying in chemical composition from acid to ultra-basic (Photo 16). Igneous activity in the Sudan has probably extended from the earliest Precambrian times to the present day. In the Basement Complex group, the evidence is in a variety of extrusive and intrusive rocks (Vail 1978). Most of the Basement Complex is mapped as 'Undifferentiated Basement Complex', 'Undifferentiated Schist Group' and 'Undifferentiated Gneiss Group'. The 'Undifferentiated Schist Group' in the Butana is also known as the 'green series' (Geological Map Khartoum, 1:1 000 000, 1952; Whiteman 1971), whereas Vail (1978), considering its grade of metamorphism, describes it as a 'greenschist facies'. The Basement Complex rock outcrops appear as hill groups (Photo 17) or inselbergs (Photo 18). The inselbergs often consist of younger intrusive rocks which appear as stocks, bosses, plugs and batholiths, and the rock types include granites, pegmatites, granodiorites, syenites, gabbro, ultrabasic rocks and serpentinites. The Ingessana Hills in the southern Kenana are an intrusive body of ultrabasic and basic rocks. Jebel Qeili in the northern Butana is an igneous ring complex, consisting of granite, syenite, gabbro and rhyolite (Vail 1978).

3.3. Palaeozoic

Palaeozoic sediments are absent from most of the Sudan, Egypt, Ethiopia, East-Africa and Saudi-Arabia. In the Sudan, the development of the Basement Complex structures was followed by pediplanation, which lasted until early Carboniferous, or even late Jurassic times (Whiteman, 1971, p.52). The few Palaeozoic rocks which have been recorded in the Sudan are outside the Central Clay Plain. Widespread Palaeozoic sedimentation may have occurred but, if so, the deposits have been cleared by erosion. Possibly some of the rocks included in the Basement Complex are of Palaeozoic age.

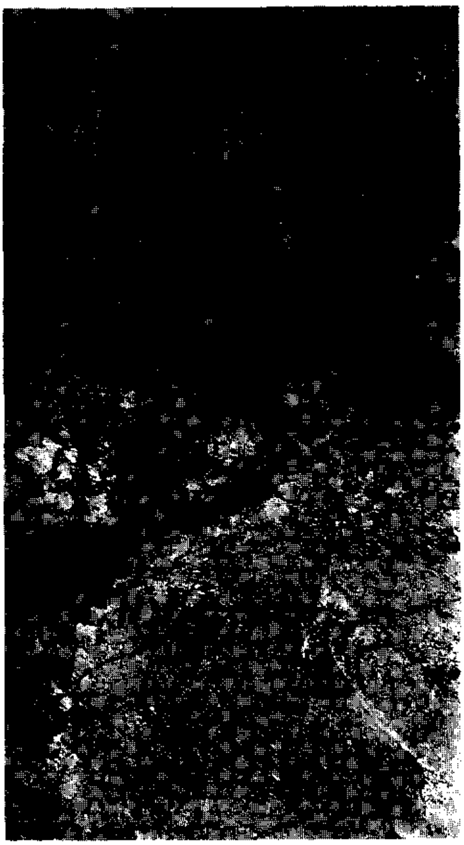


Photo 16: Saprolite ('rotten rock') of granite, exposed in a dry sandy wadi bed near Kurmuk, southern Kenana.

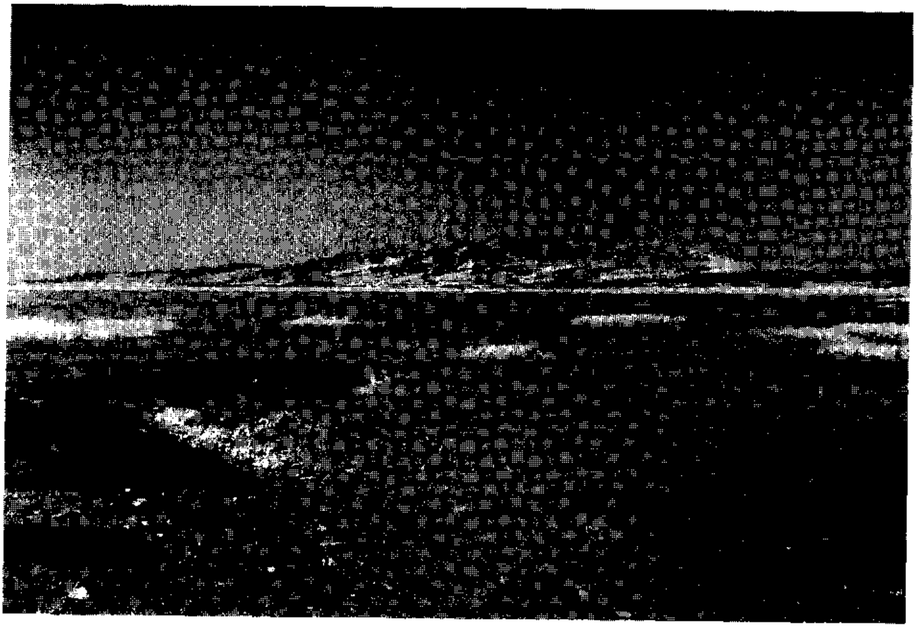


Photo 17: Basement Complex hills south-east of El Husheib, Butana. These hills form part of the Blue Nile/Atbara watershed.

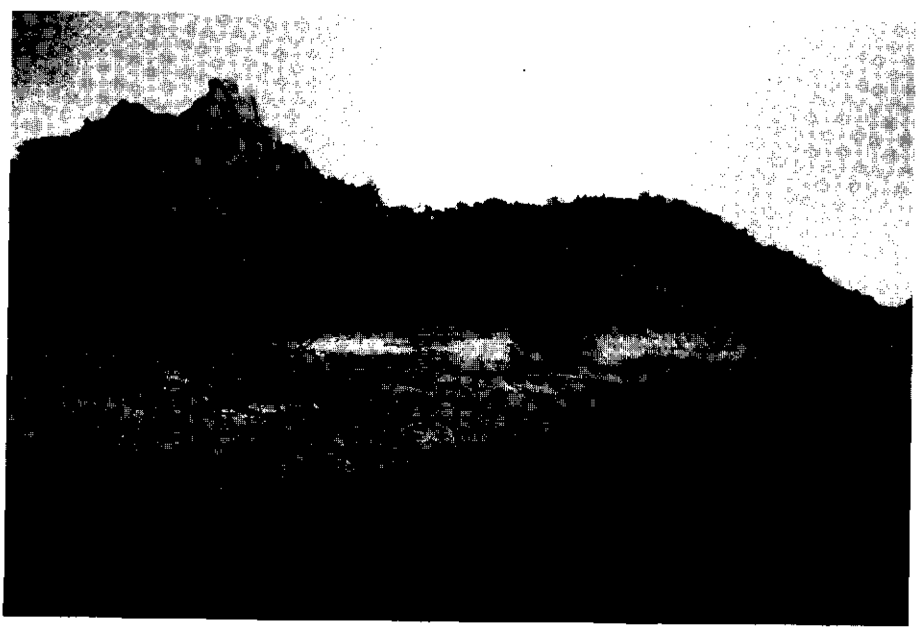


Photo 18: Jebel Geradin, a granitic inselberg in the central Kenana.

3.4 Mesozoic

The Mesozoic formations overly with marked unconformity the Basement Complex surfaces formed in the Palaeozoic. By far the most important of the Mesozoic formations in the Sudan, and the only one occurring in the Central Clay Plain area, is the Nubian Sandstone Formation. Its occurrence in the Sudan is continuous with outcrops in Libya and Egypt, and it covers most of north central Sudan, with tongues extending southwards into Kordofan and Darfur, the western Gezira and the western Butana. Another occurrence, around Gedaref, was named the Gedaref Sandstone Formation by Whiteman (1971). It is continuous with the Adigrat Sandstone Formation in Ethiopia, which is probably Jurassic. Because of the difference in age, Whiteman separated the (?Jurassic) Gedaref Sandstone Formation from the (Late Cretaceous) Nubian Sandstone elsewhere in the Sudan. The Gedaref Sandstone Formation is not in the legend of the 1:2 000 000 geological map of 1981.

The variable thickness of the Nubian Sandstone Formation reflects the irregularity of the rock floor on which it was deposited. The formation consists of mudstones to sandstones and pebble conglomerates, mostly occurring in horizontal bedding. Silicified beds occur near the base, whereas ferricrete or highly ferruginous sandstones are common in outcrops. The ferricrete sandstones may reflect a 'laterization stage' or ironstone phase (Andrew 1948) in the Mid-Tertiary as will be discussed below.

The Nubian Sandstone Formation in the Central Clay Plain is mostly covered by alluvial sediments of the Blue Nile, or, in the Butana pediplain, colluvio-alluvial sediments. The Formation outcrops in parts of the Managil ridge, and as slightly elevated surfaces of varying size on the Blue Nile east bank between Khartoum and Wad Medani. These latter outcrops are covered by a veneer of iron-coated sands, loamy sands and gravels. North of about latitude 15°30'N the Formation forms a desert denudation surface with sandy and gravelly detritus.

The outcropping Nubian Formation in the north of the Sudan is continuous with the main aggradational basins in the east-central and southern Sudan (the 'old alluvium'-infilled basins, referred to earlier). The continuity indicates a warping along NNW-SSE axes (Ruxton and Berry 1978; Whiteman 1971). According to Vail (1978, p. 26), the sandstones and mudstones of the Nubian Formation are 'subaqueous continental deposits laid down relatively rapidly under changing facies conditions, probably in braided river systems debouching into delta fans or across flood plains'.

The Gedaref Sandstone Formation resembles, at least superficially (Vail 1978), the Nubian formation. The sediments are often silicified to such an extent that they approach quartzites, e.g. Jebel Umm Bileil (Fig. 2.3) and other inselbergs in the Gedaref clay plain. These rocks are very resistant to weathering and the inselbergs have probably produced little weathering material from which the clays of the surrounding plain could have formed.

3.5. Tertiary

The Eocene period was mainly a period of erosion. Large areas which were covered by Nubian sandstone were swept clean and a new weathering cycle could develop on Basement Complex rocks. The present degradational clay plains have probably been Basement Complex weathering surfaces since the Tertiary.

Most of the Tertiary was a period of major faulting and warping in East Africa. An important phase of upward movement, volcanic activity and Rift formation occurred during the Miocene, and again in the Pleistocene until today (Holmes 1965). The Ethiopian plateau and the Red Sea hills rose and the Red Sea was formed. The height of the plateau was further increased by great volcanic activity during Oliogocene-Miocene, producing mainly plateau lavas. The upwarping of the Ethiopian massif and the Red Sea hills was accompanied by downwarping in Central Sudan and Egypt along a NNW-SSE axis. It created the central plain of Egypt and the Sudan in which the Nile system has developed.

Tertiary formations are few in the Central Clay Plain area. In the Gedaref-Gallabat area there are outcrops of fine-grained basalts which have probably formed as lava flows extruded onto the Gedaref Sandstone Formation (Whiteman 1971, p.104). They are continuous with the main outcrops of the Ethiopian Trap Series, described by Mohr (1963). Hills and small domes of solvsbergite[1] occur in the Gedaref district, for example, around Jebel Simsim.

Andrew (1948) recognizes an ironstone phase in the Mid-Tertiary during which time the lateritic crusts on plateau sites in Equatoria Province would have formed. Sandford (1933, p.222, cited by Andrew 1948, p. 102) related ironstone outcrops in the northwestern Sudan to a Middle Pleistocene lateritic phase. Whiteman (1971, p.108) concludes that both the origin and the age of the various forms of laterite cappings, pea-iron gravel (Photo 19) and ferruginized sandstone are uncertain. Some of the latter belong to the Nubian Sandstone Formation (see above).

Sandford (1935, p. 366-9, cited by Whiteman 1971, p. 108) ascribes the formation of laterite and other superficial iron concentrations in central and northern Sudan to a period with high annual rainfall and annual dry seasons. Edmonds (1942), however, observed that red ironstone concentrations in northern Sudan are only found in sandstones and intercalated shales and have nowhere affected igneous rocks (contrary to 'normal' laterization). He ascribed the iron concentration to evaporation processes under continuous desert or semi-arid conditions, rather than assuming temporary wetter periods.

The contrasting opinions may refer to different situations. A distinction must probably be made between humid climatic conditions which enabled the formation of laterite, now capping sandstone outcrops, and semi-arid conditions, that gave rise to

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[1] A fine-grained, holocrystalline, hypabyssal rock. Gary et al. (1972) recommend the term trachyte, but in the geological literature on the Sudan the name solvsbergite is commonly used.

ironstone precipitations in sandstones. Such concentrations of ferric iron are also found in well-drained soils of the northern Sudan, giving a red iron coating on sand grains as, for example, in the 'qoz' sands of Kordofan and Darfur Provinces. Staining or cementation by ferric iron is an actual soil-forming process in the present semi-arid central Sudan[2], but true laterite found in this region is certainly fossil and must be related to a climatic period wetter than today. This need not be a Tertiary climate, but could equally well be a pluvial period during the Pleistocene (Whiteman 1971, p. 109).

Laterites and ferruginous concretions occur in the Gedaref area at the base of the Gedaref formation, at the base of the basalt, and on the basalt (Ruxton and Berry 1978). Exposed pea-iron terraces were frequently found in the Umm Simsim soil survey area (Gedaref clay plain), notably where Khor Simsim had incised into the alluvial sediments (see also section 6.5.2 and Fig. 6.3).

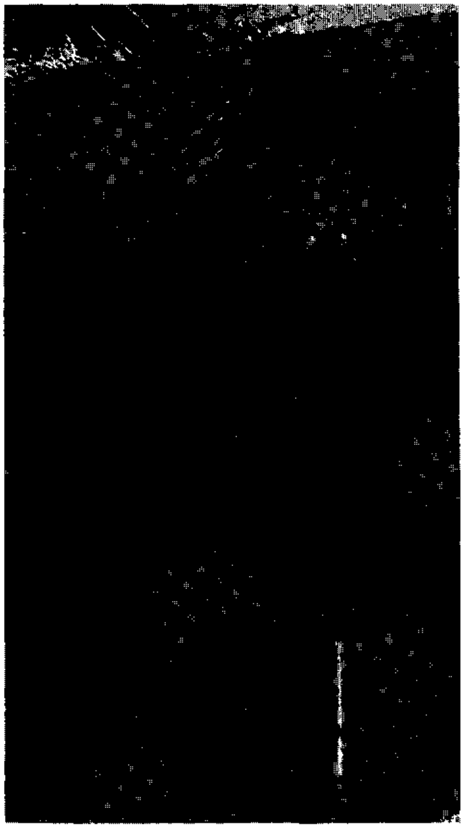

Photo 19: Lateritic gravel in an exposure near the Sennar dam.

The Umm Ruwaba and El Atshan Formations of unconsolidated sediments form the first stage of infilling of the Sudan basin. Sedimentation probably started in Late Tertiary (Pliocene) and extended until Mid-Pleistocene or later. The Gezira Formation is probably Pleistocene to Recent.

3.6 Quaternary

The infilling of depressions in the Tertiary Sudan basin, that began in Pliocene times with the Umm Ruwaba formation has continued until the present day. It was little affected by post-Mesozoic tectonic movements, and periods of continuous and

[2] Finck (1963, p. 63) ascribed the surficial iron accumulation to a kind of 'reversed podzolic process', by which free iron-oxides are moved to the surface by capillary rising water. The pedological process of the reddening of a surface soil is more generally known as 'rubefaction'.

extensive erosion, entirely removing older sediments have been absent. The Quaternary history of the present aggradational clay plains is one of deltaic, floodplain or semi-lacustrine deposition, in each stage the mode of sedimentation and the nature of the sediments being defined by variations in river regime and base level that were largely controlled by climatic variations, both in the source areas of the rivers debouching onto the Sudan plain and in the Sudan plain itself. In this section the sediments are described. The sedimentation history of the Nile basin in the Sudan is discussed in Chapter 4, with due emphasis on Quaternary climatic changes and their effects on erosion and sedimentation.

3.6.1 The Umm Ruwaba, El Atshan and Gezira Formations

The Umm Ruwaba Formation consists of unconsolidated sands, sometimes gravelly, clayey sands and clays and is often poorly sorted. Berry and Whiteman (1968) suggested that the deposits were laid down in a series of land deltas similar to the Gash delta of Kassala Province and to the present 'sudd'. The Formation consists of sediments derived from the East African mountains and the hills and plateaus in the southern Sudan, the Nuba Mountains, Basement Complex outcrops in the clay plains (for example, the Ingessana Hills) and - to a minor extent - the Ethiopian volcanic plateau (catchment area of the Sobat river). Sedimentation has continued until today in what is now the Southern Clay Plain, but has come to a standstill in most of the Central Clay Plain area. The northwestern lobes of the formation have been covered by aeolian sands ('qoz').

The El Atshan deposits (Whiteman 1971), more or less covering the Rahad-Dinder-Blue Nile Gezira, have much in common with the Umm Ruwaba sediments, but have in addition some specific constituents, like pebbles of agate, ironstone nodules and calcrete. In the upper part of the Formation there is a sudden influx of basaltic minerals, such as titan-augite and calcic plagioclase, sometimes with zeolites. Beds of calcrete are most commonly found in the border zone between the Formation and the overlying clays.

The basaltic minerals and the geographic location of the Formation indicate that the alluvium was deposited by rivers draining the Ethiopian basaltic plateau. Most of the sediments are derived from the Trap series, mainly flood basalts (Mohr 1963).

The Gezira Formation is similar to and perhaps continuous with the El Atshan Formation. The Gezira sediments are laid down by the Blue Nile and its tributaries and the sediments are derived from a variety of rocks from Ethiopia and east-central Sudan. The formation consists of unconsolidated clays, silts, sands and gravels. Ghubshan (near Manaqil, Fig. 2.5) is regarded the type locality; here the Formation is 61 m thick and rests unconformably on Nubian sandstone. The thickness of the Formation varies from 1.5 m near Manaqil village (close to the Manaqil ridge), and over 180 m in the centre of the Gezira (El Boushi and Abdel Salaam 1982).

Three lithological units are recognized (Berry and Whiteman 1968):

- Upper Clay member ('Gezira clay'): mainly clay, varying in thickness from 7 to 45

m. It is 24 m thick near the Blue Nile and decreases to 3 m in the centre of the Gezira and near the White Nile (El Boushi and Abdel Salaam 1982).

- Lower Sandy member: sand, often clayey and calcareous, with occasional gravels, silts and clay lenses, varying in thickness from 20 to 60 m. Individual gravel lenses are between 1 and 30 m thick and may extend for distances of up to 24 km; they usually thin out towards the present Blue Nile channel (Abdel Salaam 1966, cited by Whiteman 1971).
- Mungata member: this unit is only recognized in the southern Gezira. It consists of clays, but silts, sands, grits and gravels also occur; locally it may contain salt beds.

Rapied facies changes are common in the two lower units and this is in marked contrast to the uniformity of the 'Gezira clay'. This indicates an altogether different way of deposition of the upper member compared with the lower members. At Ghubshan, the 'Lower Sandy member' consists of gravelly sand (9 m), passing upwards into clayey sand (35 m); the 'Upper Clay member' consists of dark clays and silts (17 m) (Whiteman 1971, p.125).

At the Gezira Research Station at Wad Medani a 20 m deep pit showed, below 1,5 m of dark-coloured clays, a homogeneous brown clay substratum with a soil profile (slickensides and an apparently pedogenic accumulation of lime and gypsum).

The aggradational clay plain of the Atbara west bank, north of Khashm el Girba, probably belongs to a formation similar to the El Atshan and Gezira formations, considering the homogeneous surface cover of clays, underlain by coarser-textured sediments at varying depths (Blokhuis et al. 1964) and the similarity in soil profile morphology between the Khashm el Girba and Gezira clay plains (Chapter 7). Radiocarbon age determinations of the surface clays showed that Gezira and Khashm el Girba clays were deposited in the same period. However, Ruxton and Berry (1978) consider the Khashm el Girba clay plain to be younger than the Gezira on mineralogical grounds and also because sandy and silty layers occur at shallow depth (see also section 6.5.1).

3.6.2 The 'qoz' sands

The 'qoz' sands cover extensive areas west of the White Nile, especially in Kordofan and Darfur Provinces. The 'qoz' consists of fixed sand dunes and gently undulating sandy surfaces (Photo 20). The material is derived from weathering of Nubian sandstone outcrops in the region, mainly from the Libyan desert. Part of the 'qoz' may be reworked sandy material from the Umm Ruwaba formation. The sands are mainly well-rounded quartz grains; on the surface and at shallow depth the grains are reddish due to iron-staining (section 3.5).

The 'qoz' sands represent climatic conditions during the Pleistocene and probably also during the Holocene that were drier than at present (Grove and Warren 1968; Whiteman 1971, p.139). The sand cover is now fixed by vegetation and by a thin

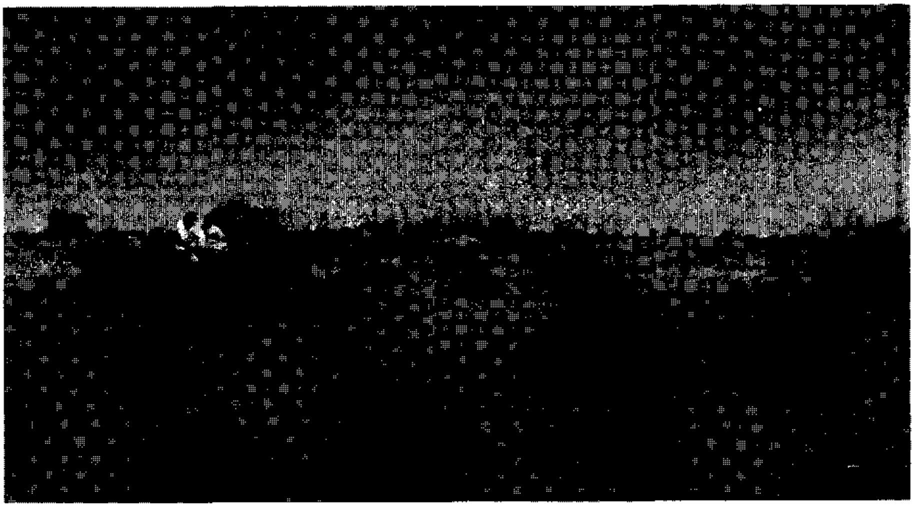

Photo 20: 'Qoz' sand ridges (background) alternating with clay flats (foreground). White Nile westbank near Kosti.

surface crust which is slightly cemented by iron. The relative age of the 'qoz' sands and the Pleistocene clay deposits is discussed in Chapter 4.

'Qoz'-like deposits are also found on the White Nile east bank between El Geteina and Hashaba, where they form sand dunes. Williams (1966) suggested that the material of these dunes is derived from sandy distributaries of a proto-Blue Nile (Chapter 4).

3.6.3 White Nile alluvium

White Nile floods during Late Pleistocene and Early Holocene have created sandy beach ridges at 386 and 382 metres above sea level, which now appear as terraces (Berry 1962). A White Nile lake or high level White Nile river probably existed at the 382 m level some 12 000 to 8 000 YBP (Williams 1966; Williams and Adamson 1974). The present White Nile is at a 6 to 7 m lower level (Williams and Adamson 1973).

The 386m terrace has been found in the Khartoum area and near Jebel Auliya. South of Kosti the terrace is a continuous feature. From Kosti to Melut it forms a narrow 1 to 2 km wide flat in the north, but widens to the south. From Melut to Malakal a terrace at 387 to 388 m level can be related to the 386 m levels in the north.

The 382m terrace has also been recognized near Jebel Auliya (Berry 1962). On the east bank of the river the terrace is more than 8 km wide just south of Kosti, and 17 km wide near El Jebelein. It is well-defined south of El Jebelein to Melut, where it disappears.

The terrace levels do not rise appreciably upstream. Berry (1962) and Berry and Whiteman (1968) associated the 382m level with a lake, dammed back by a plug of silt laid down by the Blue Nile. Backflooding by the Blue Nile flood may also have impounded the White Nile upstream of their confluence (Chapter 4). The area of the White Nile terraces is now a clay plain with soils that differ from the clay soils of the adjoining Gezira and Kenana.

3.6.4 Recent formations

In the Central Clay Plain, recent formations are limited in extent. They comprise sand dunes along the White Nile east bank and recent river alluvium and wadi fill.

Since the formation of the aggradational plains, the rivers of the Blue Nile system have incised. The clay plains now form the highest river terrace or Er Roseires terrace (Buursink 1971, p.56). The recent deposits of the Blue Nile cover discontinuous strips of land along the river, some hundred metres wide and 6 to 10 m above low water level. The alluvium has also built up islands in the Blue Nile, which are flooded annually. Similar deposits are found along the Rahad, Dinder and Atbara rivers. The sediments are fine micaceous sands, silts and clays.

Recent wadi fill consists of gravelly, sandy, silty or clayey material, depending on the catchment area and on stream velocities. Wadis draining the clay plains often originate from these plains or rise at the foot of inselbergs; such wadis carry only fine-textured sediments. Other wadis fade out in flat or depressed locations on the clay plain.

In the valley of the White Nile, downstream of Malakal, a fairly stable condition existed due to the level terrain and the high escape level at Khartoum (Andrew 1948). Stability was further enhanced by the building of the Jebel Auliya dam in 1937, which has given the river the characteristics of a storage lake. The backwater effect of the impounding can be felt 600 km upstream (Ministry of Irrigation and Hydro-Electric Power 1957). Under these conditions, the rate of deposition is low and recent alluvium is of limited extent. Moreover, most sediment is trapped in the 'sudd' marshes south of Malakal.

In the 'sudd' area, and eastwards in the Sobat marshes, slow aggradation is proceeding. These marshes form part of the Southern Clay Plain where present sedimentation follows the Umm Ruwaba deposition without unconformity.

The Gash delta, east of the Atbara river and outside the Central Clay Plain, is an alluvial delta, built by the river Gash which rises as the Mareb south of Asmara in Eritrea. The Gash flood is short in duration, but very intense. The heavily swollen river carries gravel, sand, silt and clay, but the amount of water is insufficient to reach the Atbara river. An inland delta is formed, graded in a northerly direction, with a marked succession from sandy through loamy to clayey deposits. At Aroma, the 'upper alluvium' of the delta has a thickness of 62 m, and is underlain by a thick layer of 'old alluvium' (Ruxton and Berry 1978). Tothill (1948, p. 137) describes the deposit underlying the 'upper alluvium' as 'cracking clay' probably of the same age as the Gezira clay. The 'old alluvium' is underlain by basalt or crinanite[3] (Ruxton and Berry 1978).

3.7 Summary

The following aspects of the geological sequence are most relevant to the sedimentation history and the geomorphology of the Central Clay Plain.

The degradational clay plains are overlying, and have formed from Precambrian Basement Complex rock, and, in parts of the Gedaref clay plain, from Tertiary formations, mainly basalts. Locally, the mineralogy and the textural composition of the clay plain soils have been strongly influenced by inselbergs and rocky hills (e.g. in the southern Kenana); some of these are younger intrusions of Precambrian rock (for example, the Ingessana Hills).

The Mesozoic Nubian and Gedaref formations, consisting mainly of sandstone, produce hardly any clay upon weathering. Sandstone outcrops and the associated sandy soils occur as islands in the clay plain.

Laterization occurred during wet periods in the Mesozoic and Tertiary. Pea-iron gravel found on the surface or at shallow depth (for example, along Khor Simsim, in the Gedaref clay plain) is probably derived from the weathering of lateritic sheets, and subsequent transport of debris.

The geological differentiation Umm Ruwaba, El Atshan and Gezira Formation is relevant to a pedogeomorphic sub-division of the aggradational clay plains (Chapter 6).

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[3] An olivine-analcime diabase in which the ophitic texture is well-developed. Gary et al. (1972) recommend the name teschenite.

Chapter 4

Pleistocene and recent history of the Nile system in the Sudan basin

4.1 Palaeoclimates, erosion and sedimentation

The variety of Pliocene to Recent unconsolidated sediments that have infilled the Sudan basin reflect variations in the regime of the rivers that debouch into this basin. These rivers rise in East Africa: Bahr el Jebel or White Nile, Central Africa: Bahr el Arab, and Ethiopia: Great Abbai or Blue Nile and its tributaries, Atbara, with its tributary Tekezze or Setit,and Sobat, tributary of the White Nile (Fig. 4.1).

Several authors have related variations in river regime to variations in climate, and so various palaeoclimatic sequences have been devised. Such sequences have also been inferred from the moraines of former glaciations, as in Ethiopia (Nilsson 1940), and from stratigraphical, archaeological and palaeontological evidence, notably in East Africa (Leakey 1936; Wayland 1934). Several attempts have been made to correlate sequences based on Pleistocene cultures, on palaeontological and palaeobotanical finds, and on stratigraphical evidence (Bishop and Clark 1967).

More recent research, including radiocarbon dating, has clarified a number of controversial points but has also shown that the palaeoclimatic sequence in Africa is far more complex than previously realized, and that the classical differentiation into pluvial and interpluvial periods or phases can no longer be held upright. Butzer (1971; 1972) proposed abandoning the term 'pluvial' once and for all, and, instead, differentiate between morphodynamic periods - with active denudation, erosion and sedimentation - and morphostatic periods - with slope stability and soil formation.

The concept of alternating periods of geological activity and stability was first introduced by Erhart (1956), who used the terms 'rhexistasie' and 'biostasie' for periods of geological instability and of biological balance, respectively. The recognition that periods of 'rhexistasie' alternate with periods of 'biostasie' is, according to Erhart, essential to stratigraphical studies; it also implies that knowledge of processes of pedogenesis is required to understand the nature of the sediments. Rohdenburg (1970) was the first to use the terms morphodynamic and morphostatic. He suggested that both an increase and decrease in rainfall may give rise to an increase in erosional force,and that, similarly, such changes in rainfall may cause a decrease in erosional force. Changes in morphodynamics, in Rohdenburg's concept, are not simply the result of an increase or decrease in rainfall, but of changes in rainfall regime, probably of regimes that differ from any of those occurring today. Alimen (1971) also recognized the difficulty of relating Pluvial/Arid cycles with erosion/sedimentation cycles. She suggested that two types of Pluvials are feasible, one with

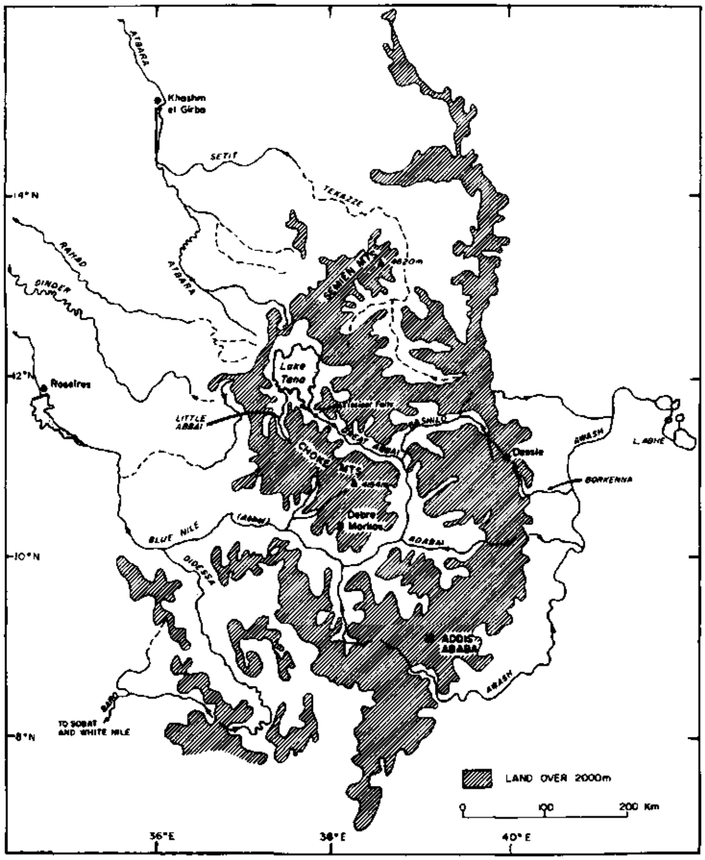

Fig. 4.1. The Blue Nile headwaters (after Williams et al. 1982)

geomorphological activity (erosion and sedimentation), and one with geomorphological stability (soil formation).

Langbein and Schumm (1958) showed that a precipitation of 250 to 400 mm per annum, typical of semi-arid to sub-humid grasslands in the USA, produced maximum denudation rates. With lower precipitation, fluvial denudation decreases, as less water is available. With higher precipitation a vegetation cover becomes effective in stabilizing slopes, and less denudation occurs in spite of increased runoff.

Rohdenburg's concept of morphodynamic and morphostatic periods has not received wide attention by authors studying the Nile system in the Sudan. In most of their papers, past climates are described by comparing them with present-day climates in the same regions. The climatic record, therefore, is generally given in terms of major or minor fluctuations in rainfall, with suggestions on temperature changes, seasonality of rainfall, and fluctuations in river discharge, bed load and suspended load. Of great importance to palaeoclimatic studies are lake level fluctuations. Both high and low lake levels were found to be coeval over the entire African continent north of the Equator, and this showed that climatic variations have occurred on a regional scale. Relevant to our study is that periods with high rainfall in the main catchment areas of the Nile system (Ethiopia and East Africa) were also periods with relatively high rainfall in the Sudan basin where a considerable proportion of the Nile sediments accumulated.

In this Chapter, the depositional history of the aggradational plains in the east-central Sudan will be discussed under three main headings:

1. Late Quaternary climates in the headwaters of the rivers that brought down the sediments, notably the Blue Nile and its tributaries, and the Atbara.
2. Late Quaternary climates in east-central Sudan, important to soil formation.
3. Development of the Nile system and the erosional and depositional regime of the river during Late Pleistocene and Holocene, with special emphasis on the Blue Nile in the Sudan.

Climatic variations have an effect on erosion in the catchment areas, on the nature and amount of bed load and suspended matter, on the total discharge, and on the discharge pattern over the year. Deposition in the Sudan basin is not, however, only a consequence of environmental conditions in the headwater regions of the Nile rivers, but is also influenced by climatic conditions and vegetative cover in the plain of sedimentation.

In Table 4.1 an attempt is made to correlate Quaternary events in the Central Clay Plain area, and relate them to occurrences elsewhere in eastern Africa.

4.2 Late Quaternary climates in Ethiopia and East Africa

The Late Pleistocene was, in general, a cold and dry period, whereas the transition to the Holocene was marked with gradually warmer and wetter conditions. The maximum extension of the land ice in Europe was reached at about 20 000 to 18 000 BP[1], but it was not before 12 000 BP that the ice caps started to melt away rapidly (Van der Hammen 1979). The warming up of the oceans was very rapid from 12 000 BP onwards (Berger et al. 1977).

Past climates have been related to the levels of several African lakes. Dating of these levels, by radiocarbon analysis of fossil shells from beach deposits, by geochemical and pollen studies, and by other methods, has supplied valuable information not only on palaeoclimates, but also on the regime of rivers that run through lakes, like the White Nile, or that orginate from the overflow of a lake, like the Blue Nile (from Lake Tana in Ethiopia).

Butzer et al. (1972) gave radiocarbon dates of East African lakes. Before 20 000 BP several lakes were greatly expanded, whereas prior to 12 000 BP lakes were much smaller. In the period 10 000 - 8 000 BP the lakes were again large; the rise in levels began about 12 000 BP and there was a minor recession around 10 000 BP. In the period 8 000 BP to the present day some relatively short-term lake expansions

[1] BP or YBP: years before present

occurred; for example, from 6 000 to 4 000 BP at Lakes Rudolf, Nakuru and Chad.

Geochemical and pollen studies have shown that Lake Victoria was a closed basin from at least 14 500 BP until about 12 500 BP, and probably again for a short period around 10 000 BP (Livingstone 1980). Livingstone found a tendency for early Holocene lake levels - that were generally high - to be interrupted by a transitory dry period about 7 000 BP.

Van Zinderen Bakker and Coetzee (1972) found evidence of a brief dry interlude about 10 500 to 10 000 BP from dated lower levels in Lakes Victoria, Rudolf, Chad and Afrera. After about 10 000/9 500 BP there was a wet period, with slightly drier conditions or a more seasonal rainfall after 6 000 BP.

From past levels of the Lake Victoria basin Kendall (1969) has inferred a dry period from before 14 500 to 12 500 BP, a moderately wet period from 12 500 to 10 500 BP, with a moderately dry spell from 10 500 to 9 500 BP. This was followed by a wet period from 9 500 to 6 500 BP. After 6 500 BP the climate became slightly drier and the rainfall more seasonal. A major event was the overflow of Lake Victoria that began towards 12 500 BP and ended towards 11 300 BP. This resulted in higher and less seasonal floods of the White Nile in the central Sudan. Dry periods were usually cold, wet periods warm. Kendall found a strong correlation between coolness and aridity on the East African plateau over the past 15 000 years.

Street (1979) studied past levels of Ethiopian rift-valley lakes. She calculated that precipitation during the Quaternary varied by at least 25% above and below present levels. For the Ziway-Shala basin in southern Ethiopia she found a reduction in precipitation of 9 to 23% during terminal Pleistocene, followed by an abrupt increase in the Early Holocene to at least 28 to 74% above present volumes. The Ziway-Shala basin is outside the Blue Nile catchment area, but Street's estimates tally with those from other basins in East Africa.

From lake levels in the Ethiopian rift and the Afar, Gasse et al. (1980) concluded that high lake levels occurred from 27 000 or earlier until 20 000 BP or later; this was followed by an extremely dry period from 17 000 to 12 000 BP.

It appears from these studies that palaeoclimates in East Africa and Ethiopia were similar. In both regions a warm and wet period occurred from 27 000 BP or earlier until 20 000 BP or later. A relatively dry and cold period occurred from 18 000/17 000 BP until 12 000 BP. From 12 000 to 8 000 BP there was a distinct warm and wet period, with a dry interval around 10 500 to 9 500 BP. The evidence for the period 8 000 to the present time is conflicting. The Holocene, until approximately 4 000 BP, was wetter than terminal Pleistocene and than the present climate, but there were dry intervals, dated by some investigators to be around 6 000 to 4 000 BP.

4.3 Late Quaternary climates in the Sudan plain

Warren (1970) postulated a series of shifts in the climatic record of the Sudan, based on the orientation of dune systems, the 'qoz' sands, in the Kordofan province.

Warren's dating was correlated by Wickens (1975) with an updated chronology given by Grove (1973). Four periods were distinguished (Fig. 4.2):

Period I, from 20 000 to 15 000 BP was a very dry period, in which the isohyets shifted 450 km south of their present positions, and arid conditions extended to 10° N. The dunes of the 'Low Qoz' were formed, probably partly from sands of the Umm Ruwaba Formation (Grove and Warren 1968).

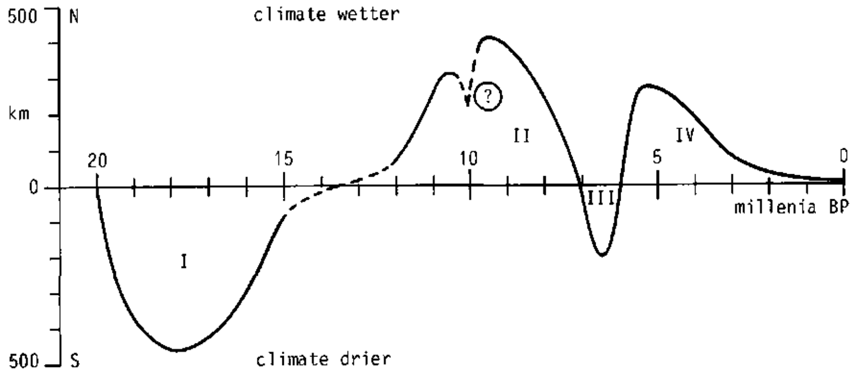

Fig. 4.2. Climatic shifts in the Sudan from 20 000 BP to the present (after Wickens 1975). The Y-axis shows the shift northwards and southwards of the isohyets during this period, compared with their present position at O-level.

Period II, from 12 000 to 7 000 BP was a very wet period, with the isohyets shifted about 400 km north of their present positions. Mean flow levels of the White Nile in Early Holocene were at least 4 m above recent levels prior to the construction of the Jebel Auliya dam (Williams and Adamson 1980). Evidence of a wet period in east-central Sudan is also supplied by the occurrence of small lake basins west of the White Nile valley near Jebel Auliya, that have been dated at between 8 500 and 7 000 BP (Williams and Adamson 1973; 1980). These lakes were 20 to 40 m above the highest Holocene flood level of the White Nile, confirming that there was a period of high rainfall in the Sudan coeval with high levels of the Nile.

The dunes of the 'Low Qoz' were stabilized; the dune sands weathered and, according to Grove and Warren (1968) soils with an illuvial clay horizon formed.

Period III, from 7 000 to 6 000 BP was a dry period, or a series of repeated phases that were drier than at present. The isohyets were about 200 km to the south of their present positions (Wickens 1975). Renewed dune formation took place, and the 'High Qoz' were formed, distinct from the 'Low Qoz' in shape and orientation (Grove and Warren 1968). There are, however, no radiocarbon dates from the area, and there is no palaeo-ecological evidence (Wickens 1975). Evidence of a drier interval on a regional scale is that no high lake levels have been recorded (section 4.2).

Period IV, from 6 000 to 3 000 BP was a period of higher rainfall in the Sudan, but it was not as wet as period II. Warren (1970) concluded that isohyets were about 250 km north of their present positions. Biological evidence, however, indicates a smaller northward shift of the isohyets, about 100 km from their present positions.

From the occurrence of sub-fossil shells of the land snail *Limicolaria flammata*, Caill. in the upper 15 cm of Gezira clay, Tothill (1946) drew the conclusion that after clay deposition had come to an end, a climate with a rainfall higher than at present must have existed in the Gezira for some time (section 4.4.3). This climatic period was dated by Adamson et al. (1982) at between 8 500 BP and 5 000 BP. Today, *Limicolaria* is confined to *Acacia*-tall grass plains bounded by the 500 and 800 mm isohyets.

The general pattern that emerges is, first of all, of a parallel occurrence of wetter and drier periods in the east-central Sudan and in the headwaters of the Blue Nile and White Nile rivers. There are indications of one or more warmer and wetter periods before 20 000 BP. A dry and cold period occurred from 20 000 to 12 000 BP. The most important climatic change is towards an increase in rainfall at about 12 500 BP. Wet conditions continued until about 8 000 to 7 000 BP, after which time the climate became gradually drier until present conditions were reached around 3 000 BP. There were, however, fluctuations, and a relatively dry interval may have occurred between 7 000 and 6 000 BP.

4.4 Sedimentation in the Sudan basin

4.4.1 Development of the Nile river system in the Sudan

The Nile system in the Sudan developed through the linkage of several sections draining the western slopes of the Ethiopian plateau, parts of East Africa, and the south-western border zone of the Sudan.

De Heinzelin (1967) and Butzer and Hansen (1967) considered the main Nile in the Sudan to be a relatively young connection between a river system ('Lake Sudd'), blocked by the Sabaloka gorge, and an old, apparently headless, Plio-Pleistocene Nile in Nubia. Berry and Whiteman (1968) rejected this hypothesis; they found that the incision of the Sabaloka inlier started as early as Late Cretaceous times and that ultimately in the Pleistocene the gorge must have attained its present form. They considered the Nile and its tributaries to be an ancient system that attained its present geography in Late Cretaceous or Early Tertiary, except for the Bahr el Jebel and Albert-Victoria sections which are Late Pleistocene. Adamson (1982) related the Nile drainage to the rifting of Africa; this would imply that the Nile dates from the Tertiary.

The Blue Nile system in the Sudan consists of the rivers Blue Nile, Rahad and Dinder, which have roughly parallel courses. The Atbara, tributary of the Nile, has a similar course. Whiteman (1971, p. 167) considered this feature to be due to some overall structural control.

The regime of the White Nile has always been strongly influenced by overflow from Lake Albert and Lake Victoria (Williams and Williams 1980; Kendall 1969). Ponding of water in the Albert basin has occurred since Miocene times; it was related to drainage diversions in Uganda.

4.4.2 Models of erosion and sedimentation with special reference to the Blue Nile

Contradictory relations have been proposed by stratigraphical geologists, sedimentologists and palaeoclimatologists between climatic conditions, and the erosional and depositional action of rivers. This is well illustrated by palaeoclimatic models, devised to explain Late Pleistocene aggradation by the main Nile in Nubia, Upper Egypt (Williams and Adamson, 1974), where large accumulations of silt have formed terraces about 40 m above the present maximum flood level at Wadi Halfa.

According to Fairbridge (1964) these deposits 'represent a climatic phase when the flood energy must have been very greatly reduced; indeed from the present average annual discharge of 76 000 millions of tons a year, the flow must have been cut at times to the merest trickle.' Under these conditions sediment load was deposited far upstream of the delta.

Butzer (1959), however, in considering the formation of the Nubian silts, states that 'as the Nile mud today, silts will have been deposited by summer floods, although of considerable greater magnitude and reaching higher levels.' The floods would have resulted from periods of 'pluvial erosion in the summer rainfall belt of either Ethiopia and/or the southern Sudan' (Butzer and Hansen 1967). The term 'Wild Nile' was used by Butzer and Hansen (1968) to emphasize the catastrophic nature of the floods. The floods were the highest since 25 000 BP, and much higher than any recorded flood levels since Pharaonic times (Paulissen and Vermeersch 1989). Paulissen (1986) radiocarbon-dated charcoal samples and estimated the 'Wild Nile' silts to have been deposited around 12 500 BP, a date corresponding well with the onset of the Holocene wet phase in Eastern Africa.

De Heinzelin (1967) criticized Fairbridge's (1962) concept that 'maximum sedimentation-levels represent minimal fluvial discharge', and considered that the 'maximum sedimentation level (floodplain) is dependent on the maximum fluvial discharge.' Maximum fluvial discharge would occur when rainfall in the catchment areas is at a maximum. As under these circumstances the soil is protected by dense vegetation, erosion would be limited to fine-textured material only.

It is clear from the above discussion that there is no simple relation between climate in the headwaters, stream velocity, fluvial discharge and the relative amounts and grain size of the bed load and suspended load in a river (cf. Williams and Adamson 1974). The usual models, however, are more or less the following.

Unsorted sediments can be related to a succession of morphodynamic and morphostatic phases, or to a morphodynamic phase of varying intensity. In the Pluvial/Interpluvial concept, such conditions would be met during the waning phase of a Pluvial, with increased aridity, less but more torrential rainfall, and less protective vegetation cover (Butzer and Hansen 1967), or with the onset of a Pluvial period, when there is still insufficient vegetation to protect the surface. Erosion would be strong and deposition of eroded matter would be by braided rivers or by seasonal wadis running into inland deltas.

Fine-textured sediment load can be related to a period of morphostability, or - in the Pluvial/Interpluvial concept - to the maximum of a Pluvial with high rainfall, well distributed over the year or during a relatively long rainy season, and a luxuriant vegetation cover in the headwater regions of the rivers. Erosion would be limited and only fine-textured sediment would be deposited by slow rivers flowing at a relatively high level during long periods of the year.

These concepts may apply to the Blue Nile in the Sudan, but not necessarily to the White Nile - which has lost most of its sediment before its confluence with the Blue Nile - or to the Egyptian section of the main Nile. The catastrophic floods of the 'Wild Nile' and the related silt deposits in Nubia were dated at the onset of the Early Holocene wet period in Africa (Paulissen 1986). Earlier siltation phases at Nubia - with sedimentation entirely from the suspended load of the Nile, without notable contributions from local wadis - were dated at 17 000 to 12 000 BP, a period which from all available records was cold and dry in the headwaters of the Nile system, both in Ethiopia and in East Africa. Nubian siltation phases in this period would be in accordance with Fairbridge's (1962) concept.

If we take the date of deposition of the earlier Nubian silts as being correct, and the climate at that time in the headwaters region as cold and dry, then the problem is one of river regime in relation to climate. Adamson et al. (1982) offer the following solution: a relatively dry climate in Ethiopia and East Africa may have resulted in higher flood levels in Nubia, be it of shorter duration; during short periods, the Nile was a vigorous river capable of carrying a heavy load of fine-textured material over long distances.

The Late Pleistocene and Early Holocene Blue Nile models described by Williams and Adamson (1980) are in agreement with a morphodynamic and a morphostatic stage in the headwaters region of the Blue Nile, respectively. Emphasis on climatic changes to account for differences in erosion and sedimentation regime is considered justified by these authors as endogenic geological activity in this period and in this region was of no great importance.

The Late Pleistocene Blue Nile reflects conditions pertaining to around 18 000 BP, when the climate in Ethiopia was relatively cold and dry, which would have had the following consequences for erosion in the headwaters region and sedimentation in the Sudan basin:

- a high sediment yield because of strong erosion from bare slopes;
- a coarse-textured bed load and a much reduced suspended load because of the absence of a fine-textured weathering mantle and of sedentary soils;
- a high runoff because slopes were bare and seasonally frozen;
- an accentuated flood peak.

The Late Pleistocene Blue Nile was a seasonal river as it is today, but with a more pronounced flood peak. During winter months the river may not have reached the main Nile (a situation that now exists with the Atbara river).

The Early Holocene Blue Nile, of about 11 000 BP, differs greatly from the Late Pleistocene river. After about 12 000 BP ocean temperatures had become noticeably higher, and there was an increase in intertropical rainfall (Kendall 1969). Montane forests covered the slopes of the Ethiopian mountains and protected them from erosion. There was chemical weathering and clay formation, and red and black soils developed on the basalts and tuffs. The soil pattern may have been similar to the present soil geography in the area (see for example, Semmel 1964). The Early Holocene Blue Nile must have been a seasonal river with a high summer discharge, carrying much silt- and clay-sized suspended matter which was eroded from the sedentary soils, together with a still significant coarser-textured bed load. The deposition of this material in the Sudan basin was dependent on the extent and duration of the annual flooding, and on the trapping action of the vegetation in the plains.

These models refer to the Blue Nile as a river depositing material in the Sudan basin. The models are particularly useful in understanding the nature and geographical distribution of the successive sediments belonging to the Gezira and the El Atshan Formations.

4.4.3 The Gezira aggradational clay plain as a complex alluvial fan

The occurrence of a radiating distribution pattern of sinuous, sandy to gravelly palaeochannels over the Gezira was first described by Williams (1966). Some of these occur as linear bodies of gravel at varying depths and are now covered by Gezira clay. Buried sandy palaeochannels are presently the main aquifers of the Gezira. Gravel lenses, up to 24 km long and from less than 1 m to over 30 m thick, occur in these sandy aquifers (Abdel Salam 1966, cited by Williams and Adamson 1973). Other palaeochannels are on the surface and can be detected from aerial photographs and satellite imagery. The channels follow a SE-NW course, from between Hasaheisa and Sennar to the White Nile valley below 14° North. The distal ends of these palaeochannels are associated with sand dunes along the White Nile east bank which attain their maximum extent between Naima and El Geteina (Fig. 4.3).

The sands and gravel of the Gezira palaeochannels, and the sand dunes east of the White Nile have a strong similarity in mineral composition to present Blue Nile bed loads. Quartz is the main mineral within the sands and gravels, but there are also fragments of basalts, agate, zeolites, feldspars and iron pisolites (Abdel Salam 1966). The mineral assemblage suggests a provenance from Basement Complex rocks, Nubian sandstones and Cenozoic lava. The minerals of volcanic origin show that sedimentation was from the Blue Nile.

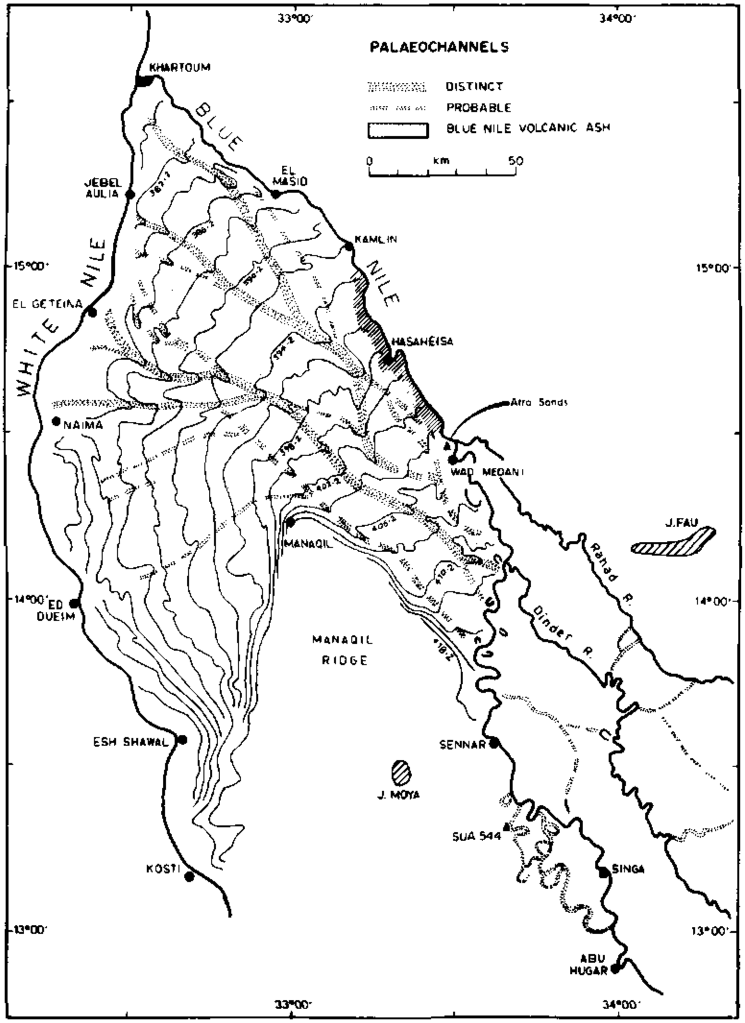

Fig. 4.3. Distribution of paleao-channels on the present surface of the Gezira plain and on part of the Rahad-Dinder-Blue Nile Gezira. Location of high-level oxbows of the Blue Nile between Wad Medani and Sennar, and of volcanic ash deposits on the Blue Nile west bank between Wad Medani and Kamlin (after Adamson et al. 1982)

Rather pure deposits of volcanic ash, in the form of microscopic glassy fragments, are exposed in the 'kerrib' of the Blue Nile between Wad Medani and Kamlin (Fig. 4.3); they have been described by Williams and Adamson (1980) and Adamson et al. (1982). The ash was laid down in 3 to 4 m deep and 20 to 30 m wide, relatively straight, channels. The occurrence of the ash deposits downstream of the Rahad/Blue Nile confluence suggests that the palaeo-Rahad supplied the ash. It is not known how far west the ash deposits or ash-derived soils occur. In some locations in the Gezira the ash is the parent material of the Laota sandy clay loam (the Laota series was defined in 1968 by a UNDP/Soil Survey Division team). Laota occurs in linear zones, several kilometres in length and sub-parallel to the Blue Nile. These zones may represent ash-filled palaeochannels of a proto-Blue Nile or a proto-Rahad. The ash deposits were dated - from carbonate nodules in or just below the deposits - at around 24 000 BP (Adamson et al. 1982).

Berry and Whiteman (1968) found that the Gezira Formation had many characteristics of an inland delta graded to the White Nile. Within the Formation there is a striking contrast between the heterogeneity of the Lower Members (Chapter 3), and the comparative uniformity of the Upper Member, the Gezira clay. The clay surface cover is only occasionally broken by sandy patches and sand dunes. The sandy sites appear to be associated with shallow discontinuous channel systems, the palaeochannels referred to above. The Gezira clay plain would have been formed as a braided river deposit by overbank-flooding, through these channels, from the Blue Nile towards the White Nile. This mode of deposition includes the Lower Sandy Member of the Formation, as shown in a study of the groundwater geology (Abdel Salam 1966, cited by Whiteman 1971; El Boushi and Abdel Salam 1982).

Blokhuis et al. (1964) suggested that the homogeneous nature of the surface clays indicated semi-lake conditions during deposition: with extended annual periods of inundation, clay-size sediments would have been carried away from the river over large distances. However, it will be shown in a later section of this Chapter, that the deep yellowish-brown clay underlying the dark grayish-brown clay of the Gezira at a depth of between 130 and 170 cm (Ochtman 1963), predates 12 000 BP and is, therefore, either deposited in a period that has been generally indicated as cold and dry in Ethiopia and dry in the east-central Sudan (20 000 to 12 000 BP), or in the relatively warm and wet period prior to 20 000 BP. Most of what we know about the formation of the Gezira plain is from the Holocene period, since around 12,500 BP: sedimentation by overbank-flooding or deltaic deposition from radiating palaeochannels of a proto-Blue Nile, building an inland alluvial delta with, on average, upward fining sediments. This knowledge is now firmly based on mineralogical and granulometric composition of the sediments; the presence of defunct and headless palaeochannels - some on the surface, some covered by a clay mantle; the present contour pattern (Fig. 2.5), and the occurrence and radiocarbon dating of sub-fossil shells of aquatic, amphibious and terrestrial mollusc species.

Before discussing the Pleistocene deposition of the deeper layers of the Gezira clay, we will first turn our attention to the study of molluscs - by Tothill (1946), taken up again by Williams and Adamson (1980) - which are most revealing for the hydrological conditions on the Gezira plain during deposition and for the terrestrial climatic conditions after this deposition had come to an end. Radiocarbon measurement has enabled more precise dating of the surface clays of the Gezira (Williams and Adamson 1980).

Tothill (1946) studied molluscan remains in the upper 180 cm of Gezira clay and in the adjacent White Nile deposits (below the 382 m lake level). Throughout the 180 cm profile of Gezira clay he found shells of the amphibious snail species *Ampullaria wernei*, Phil., now renamed *Pila wernei*, and *Lanistes carinatus*, Oliv.. Shells of the aquatic species *Cleopatra bulimoides*, Oliv., were only found in a 40 km wide belt west of the Blue Nile (Fig. 4.4), where they occurred at depths of between 150 and 180 cm. This species is found today in 'maiyas' on the inner meander bends of the Blue Nile, which are inundated by muddy river water for approximately five months of the year. Tothill concluded that a similar inundation must have occurred in the eastern Gezira. Further west flooding must have been of a shorter duration and mainly caused by rainfall considerably higher than today. The *Pila/Lanistes* stage is representative of the annual flooding over most of the Gezira. In the eastern Gezira it was preceeded by the *Cleopatra* stage.

Shells of river bottom species, common in White Nile clays, are not found in the Gezira clay. Tothill came to the conclusion that the Gezira plain had never been a lake.

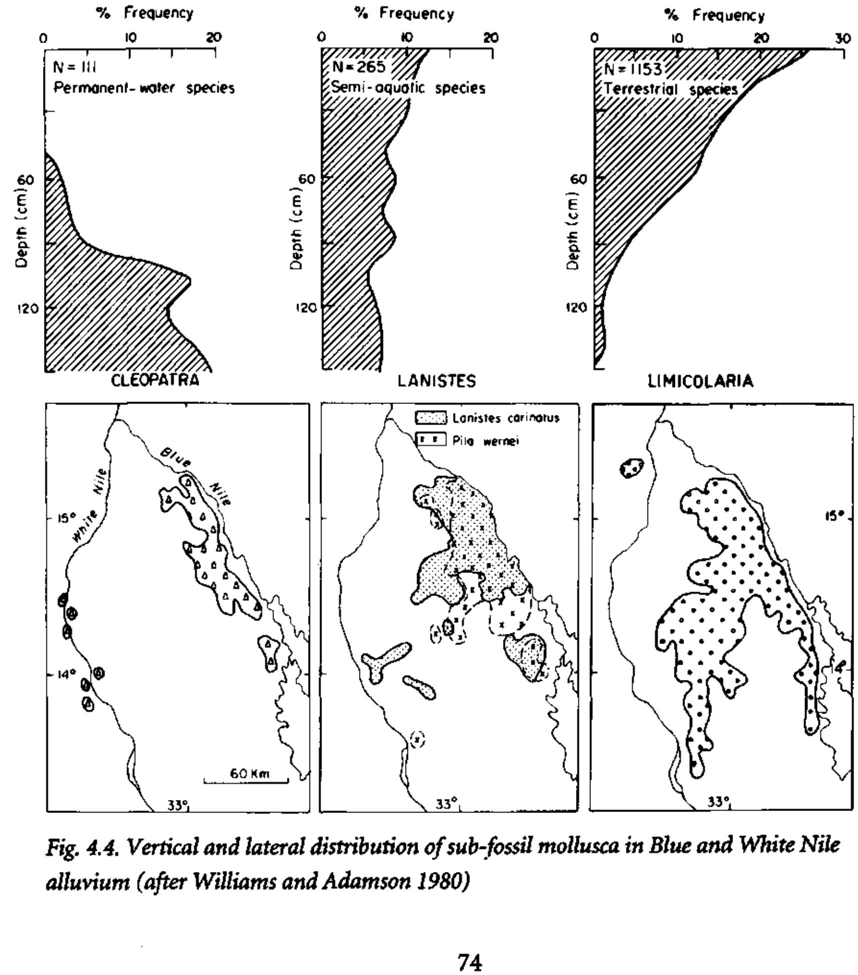

Fig. 4.4. Vertical and lateral distribution of sub-fossil mollusca in Blue and White Nile alluvium (after Williams and Adamson 1980)

Shells of the land snail *Limicolaria flammata*, Caill. are abundant in the upper 15 cm of the Gezira clay, and are still present in large quantities to a depth of 50 cm, before gradually decreasing. Below 150 cm no *Limicolaria* shells have been found. Tothill writes (1946, p. 159): 'The vertical distribution is consistent with the view that the presence of these shells in the lower layers is due to their having fallen down the cracking system, the lower point of which is at the level of the vanishing point of *Limicolaria*. In and probably throughout historical times the triangle (Gezira, WAB) has been a dura (*Sorghum vulgare*) cultivation plain, and seasonally has carried great herds of domestic animals, and this has undoubtedly provided ample opportunity for the shells of the surface to have been pushed into the cracks.' Today *Limicolaria* is found as a living species on clay plains with a rainfall of between 500 and 800 mm; it never occurs with *Ampullaria*. *Limicolaria* would thus represent the final stage of aggradation - when conditions had become too dry for the amphibious species - and a period thereafter under relatively high rainfall.

Tothill concluded that the homogeneous, fine-textured sediments in the surface 180 cm of the Gezira plain were laid down by annual inundations carrying very little suspended material.

The importance of Tothill's study is his contribution to the knowledge of the environment during deposition of the upper clays. His observations and conclusions remain unchallenged.

Williams and Adamson (1980) and Adamson et al. (1982) gave a follow-up to Tothill's work. They published frequency diagrams of sub-fossil molluscs in the upper 150 cm of Gezira clay (Fig. 4.4). These confirm the *Cleopatra*-stage with prolonged annual flooding of a strip along the Blue Nile west bank, which was followed by a *Lanistes/Pila* stage with seasonal flooding over a large part of the Gezira, whereas the final stages of deposition and the change to terrestrial conditions were characterized by *Limicolaria*. The progressive increase towards the surface soil of *Pila* and *Lanistes* at the expense of *Cleopatra*, together with the larger areal extent of *Pila* and *Lanistes* indicate an increase, with time, in the area subject to shallow seasonal flooding and, in the same time, a decrease in the area subject to long annual inundation. Blue Nile flood levels during the *Pila/Lanistes* stage were distinctly higher than they are today. Arkell (1949) mentions Blue Nile high flood levels at Khartoum dated 7 000 BP, which were 4 to 5 m higher than at present.

Radiocarbon dates from shell samples, calcitic nodules and artefacts have made it possible to date the upper 1.5 to 2 m of Gezira clay (Williams and Adamson 1980). It has been shown that deposition of these surface clays date back to at least 12 000 BP. The *Cleopatra* stage was Early Holocene, the *Pila/Lanistes* stage Early to Middle Holocene. Most samples of sub-fossil shells of the Gezira were radiocarbon dated around 11 000 to 12 000 BP (Adamson et al. 1982).

Cleopatra and *Lanistes* shells at a depth of 160 to 170 cm in 'dark grey-brown clay' at the site of the Gezira Agricultural Research Station, Wad Medani, gave a radiocarbon date of 11 975 ± 260 BP (Adamson et al. 1982). If we assume that at this depth pedoturbation[2] was weak and that cracks developed from the present surface never reached this depth, the age of the shell samples would represent the time of deposition of the clays. Hard, black calcitic nodules from the same location and depth, however, were dated at 27 370 ± 800 BP. These nodules cannot have formed 'in situ' at this depth, as comparison with the age of the shell samples shows. It should be noted that both the shell and the carbonate sample are from the dark gray-brown clay, which apparently forms a thicker layer in this Wad Medani profile than in our representative profile GARS 141 (see below; nr. 9 in Appendix 2).

We will now try to relate past climates and modes of deposition to the present profile of the Gezira Formation, and in particular to the Upper Member or Gezira Clay.

The thickness of the Gezira clay has been given as varying between 7 and 45 m (Berry and Whiteman 1968). In the Gezira Northwest Extension, the clay is 6 to 30 m thick and generally about 20 m (Hunting/MacDonald 1963-1967). Blokhuis et al. (1964) found a depth of over 20 m at Wad Medani.

The representative profile of the Gezira fan, GARS 141 (Appendix 2), shows the following horizons/layers (Photo 21):

0-60 cm: dark brown clay, Munsell colour approx. 10YR 3/3.5;
60-90 cm: transitional;
90-130 cm: dark grayish brown clay, Munsell 10YR 4/1.5;
130-250 cm+: brown to yellowish brown clay, Munsell 10YR 5/3.5.

Blokhuis et al. (1964) suggested that this profile developed in two sediments, viz. 0-130 cm, and 130-250 cm and deeper. The two sediments would have been deposited under different environmental conditions (Chapter 7). The lower sediment in six profiles from various parts of the Gezira begins at a depth of between 130 and 175 cm (Ochtman 1963). The dark brown colour of the surface clay (0-60cm), strongly contrasting with the dark grayish-brown subsurface clay (90-130 cm), was related by Finck (1961) to drier climatic conditions, probably after 5 000 BP, which acted upon the upper part of the dark grayish-brown sediment. The soil process involved is known as rubefaction (see for example, Buringh 1979).

The *Cleopatra* and *Lanistes* shells at the Wad Medani site, and dated at 11 975 ± 260 BP (Adamson et al. 1982), were from a depth, which on account of its soil colour, is comparable to the 90-130 cm depth in our profile. The shells of both species were dated at about 12 000 (Williams and Adamson 1973). As older radiocarbon datings of shells have not been reported, we can assume that the deposition of the dark grayish-brown surface clay began around 12 000 BP. The end

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[2] The process of pedoturbation is discussed in section 9.2.4. Active pedoturbation would probably have crushed the shells beyond recognition.

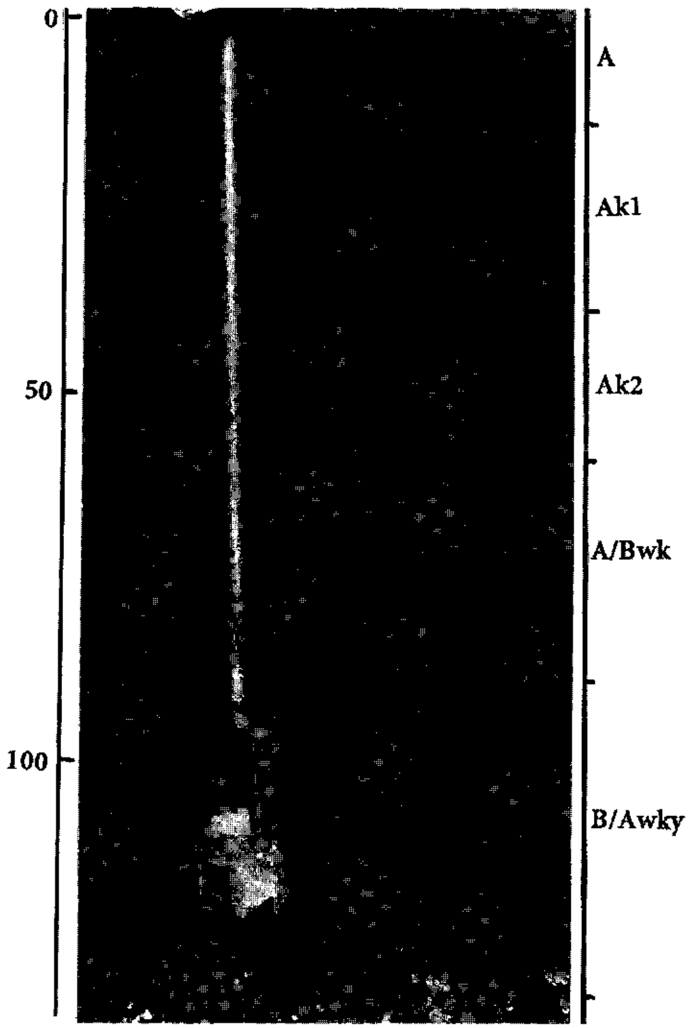

Photo 21: Profile GARS 141. The auger is 120 cm.

of the depositional period is usually set at about 5 000 BP. *Limicolaria* represents a post-sedimentary period under relatively moist, but terrestrial conditions, probably 5 000 to 3 500 BP. The rubefaction of the surface soil could then be related to the period 3 500 until the present time.

Adamson et al. (1982) considered the hard black nodules, common throughout the Gezira profile, to be allochthonous, and the soft carbonate and the gypsum crystals to be autochthonous. This is in agreement with our findings based on field observations and study of thin sections (Blokhuis et al. 1968/1969). The joint presence of clay and fine-gravel size carbonate nodules, and the lack of particles of intermediate size classes, was tentatively ascribed by Adamson and co-workers to transport of the carbonate gravel by river action from a site where the nodules had formed 'in situ', probably in clay, and where no bed load of sand was present. This suggestion, in our opinion, does not sufficiently account for the ubiquity of the nodules or of their distribution in the soil, viz. largest and most plentiful on the surface and in the surface soil, decreasing with depth in size and abundance. Relatively small black nodules are locally abundant in the yellowish-brown deeper clays.

Mermut and Dasog (1986) found an increasing age of carbonate glaebules with depth in Vertisols of the Deccan Plateau of India. Glaebular formation would be a continuous process, illustrated for example by the infilling of cavities in the glaebules by new calcite precipitation, and by the coating of manganese oxides, turning white glaebules into black ones. Black carbonate glaebules had relatively older radiocarbon dates (26 000 BP) than white glaebules (4 000 to 14 000 BP). The occurrence, in some profiles, of the larger glaebules in the surface soil, was ascribed to an upward transport due to pedoturbation.

In our view, an allochthonous occurrence of the dark-grey nodules is due to the process of pedoturbation: the nodules may have formed in deeper layers and been gradually pushed upwards by internal soil movement as the deposition of clay continued. There are two observations to support this hypothesis:

1. The present depth of pedoturbation (depth of cracking and of annual moisture changes) in the Gezira clay varies between 30 and 90 cm (Ochtman 1963; see also Chapter 7). Pedogenic features below that depth are fossil. The dark grayish-brown clay has a vertic structure (see Chapter 7) throughout and contains soft 'in situ' carbonate. The underlying yellowish-brown clay has slickensides that may reach a depth of 19 m (at Wad Medani; Blokhuis et al. 1964), and this suggests for both deposits that periods of sedimentation alternated - annually or over longer periods - with periods of soil formation.
2. Hard, grey carbonate nodules are coarsening upwards, and this is in line with pedoturbation as the main process governing their distribution.

We have related the origin of the grey carbonate nodules to the yellowish-brown deeper clays that pre-date the dark brown and dark grayish-brown surface clays. The hard, black carbonate nodules from the profile at Wad Medani sampled by Adamson et al. (1982) were dated at 27 370 ± 800 BP. This would imply that deposition of the yellowish brown substratum clays had already started at that time. The question of when it started, and when it ended remains open to debate.

The colour difference between the upper and lower part of the clay mantle of the Gezira, the inferred ages which are very different, and the occurrence of specific soil features at the boundary between the two clay layers (to be discussed below), make it likely that there have been two major periods of deposition, separated by a period of standstill.

The yellowish-brown colour of the lower sediment, strongly contrasting with the dark grayish-brown clay overlying it, suggests deposition on an arid plain. One could assume that deposition was by annual floods of short duration, spreading fine-textured sediments uniformly over large areas, and that arid conditions existed for the rest of the year over a bare, dry plain. Similar conditions were suggested by Adamson et al. (1982) for the period between 12 500 and 17 000 BP.

The period of standstill was probably characterised by marshy conditions on the clay plain and an arid climate: marshy because of accumulation of shells in ponded areas (sections 4.4.4 and 6.5.1), and arid because of high salinity, and heavy accumulation of gypsum and calcium carbonate, precisely in the boundary zone between the two sediments. Dating of shells at this boundary location in Khashm el Girba in a similar alluvial clay soil gave an age of about 12 000 BP (section 4.4.4). This would be in accordance with a beginning of the sedimentation of the dark grayish-brown clay around 12 000 BP. Prior to 12 000 BP there would have been a period of unknown duration in which sedimentation came to a standstill. A more precise dating is difficult, as there are no data available of the period between ca. 12 000 and ca. 20 000 BP (Adamson et al. 1982).

The problem that remains is how to relate a Late Pleistocene Blue Nile cf. Williams and Adamson (1980) to a homogeneous clay cover over large distances. In the Atbara clay plain (section 6.5.1.) the sediment below the dark grayish-brown clay is not homogeneous; it shows features of a meandering river landscape rather than of a braided river. In the Gezira, the sediment below the dark grayish-brown clays seems to be a more regular feature, except for sites of palaeochannels. One must, however, be aware of the fact that this supposed uniformity has not been firmly established; it would require very detailed soil surveys to do so.

If we are guided by the radiocarbon age of the carbonate nodules investigated by Adamson et al. (1982), then the yellowish-brown clay is deposited prior to 20 000 BP, i.e. during a warm and wet period (cf. section 4.2). A Blue Nile river of the Holocene model (Williams and Adamson 1980) could have spread fine-textured sediments over the Sudan plain. The non-depositional interval would have covered the entire period from ca. 20 000 to ca. 12 000 BP - when indeed the climate over the Sudan plain was dry - or part of that period. However, the contrasting colours of the two sediments and the great difference in magnitude of gypsum and carbonate accumulation, suggest that the environmental conditions on the sedimentation plain in the Sudan, were different for the yellowish-brown substratum clays and the dark grayish-brown surface clays.

Three tentative conclusions can be drawn from the above data and their interpretations:

1. The change in depositional regime represented by the boundary between the yellowish-brown and dark grayish-brown clay, represents a period of standstill in sedimentation of longer or shorter duration in the period between 20 000 and 12 000 BP. In that period there were, at least partly, marshy conditions on the Sudan plain and an arid or semi-arid climate.

2. Palaeochannel activity later than about 5 000 BP has not been recorded; one must therefore assume that deposition on the Gezira plain ended in Mid-Holocene.
3. The bulk of the Upper Clay member of the Gezira Formation must have been laid down prior to 12 000 BP and may have begun before 40 000 BP. The depositional regime was one that allowed both clay deposition over the larger part of the plain, and sedimentation of coarser sediment load over small areas. The yellowish-brown substratum clay was probably deposited in a relatively warm and wet period (prior to 20 000 BP).

4.4.4 The El Atshan Formation and the Khashm el Girba clay plain

The El Atshan formation, as mapped by Whiteman (1971), covers the Rahad-Dinder-Blue Nile Gezira and the adjoining aggradational plain west of the Blue Nile (the eastern Kenana). The physiography of this area is more irregular than that of the Gezira, and slightly elevated sandy to silty areas alternate with lower-lying clay basins. The sandy areas have been identified and provisionally mapped by Adamson et al. (1982) (Fig. 4.5) as palaeochannels of a braided river system consisting of former channels of the Rahad, the Dinder and the Blue Nile. This drainage network is Late

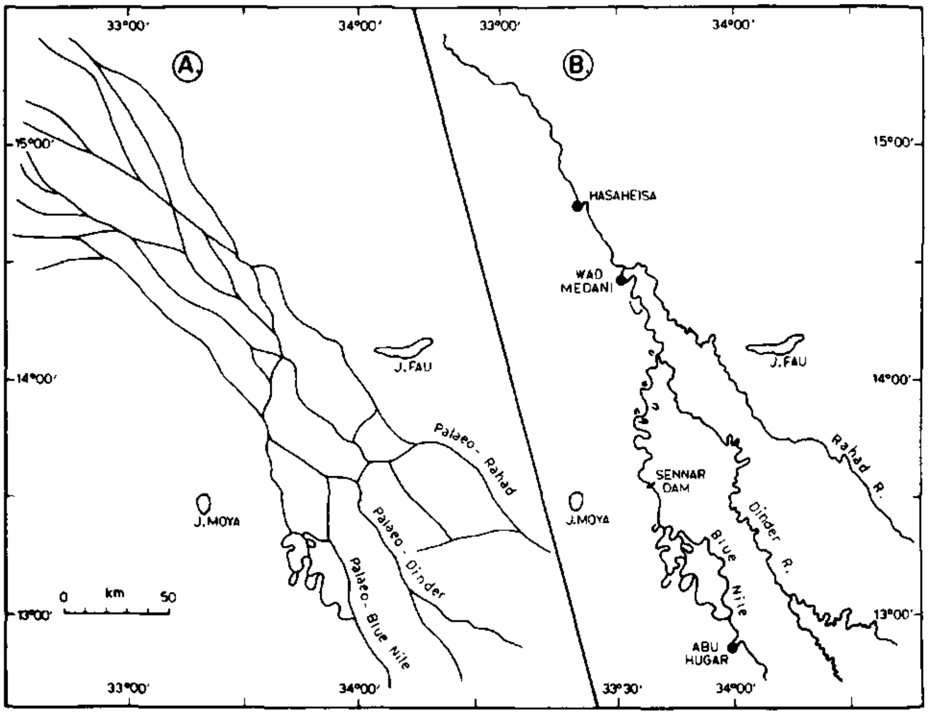

Fig. 4.5. A. The probable Late Pleistocene to Early Holocene network of palaeo-channels of the former Blue Nile, Dinder and Rahad drainage systems; B. Present drainage pattern of the Blue Nile, Dinder and Rahad rivers (after Adamson et al. 1982)

Pleistocene to Early Holocene and is continuous with the Gezira palaeochannels. It still exerts considerable influence on the present relief (Chapter 6). The channels were probably not deeply incised, and would have functioned as follows (Adamson et al. 1982, p. 177): 'With high river discharge, water would (...) spill across the intervening flat country by overbank flooding, and leave extensive pools and swamps in the less active channels well beyond the end of the flood season or even throughout the year. With lower discharge, seasonal flooding of the channels would have been followed by annual drying out of most of the channels. During periods of change in discharge or load, instability in the network would occur leading to the creation of many rapidly changing distributaries or the opposite trend towards consolidation of flow into one or a few major channels.'

Near Abu Na'ama, on the Blue Nile west bank in the northeastern Kenana, a cliff in the outer river bend shows the profile of the aggradational clay plain. The succession dark- brown clay/dark grayish-brown clay/yellowish-brown clay, is similar to the representative profile of the Gezira (GARS 141), with two main differences: first, the yellowish-brown substratum clay begins at a greater depth (between 2 and 3 m from the surface), and, second, the colour differentiation in the upper sediment is less pronounced. In the Damazeen profile (nr. 14), situated further south, colour differentiation within the upper sediment has vanished completely. The observations indicate that rubefaction diminishes with increasing rainfall.

An exposure in a bank of a newly dug irrigation canal in the Khashm el Girba clay plain showed a layer, approximately 2 cm thick, with abundant unbroken and broken shells of *Lanistes carinatus* and *Cleopatra bulimoides*[3]. The shells occur embedded in a matrix of clay with silty pockets, forming a 15 cm thick layer between a surface cover of clay (0-160 cm) and a silty to fine-sandy substratum (175-275 cm+) (Fig. 4.6). The shell accumulation layer is discontinuous and could have been a small pond. The soil belongs to the Asubri series (section 6.5.1) which represents fossil stream beds or levee sites. The shells were dated at 12 420 ± 110 BP[4]. Most of the soils in this area belong to the Khashm el Girba series, which has a similar surface cover of clay. The difference with the Asubri series is in the nature of the substratum: in the Khashm el Girba series this is a yellowish-brown clay similar to that of the Gezira clay, but thinner.

We will see in section 6.5.1 that there are many similarities between the Gezira and the Atbara aggradational clay plains: in the nature of the sediments, and in the radiocarbon dates of shells of the same species and occurring in the same profile

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[3] Sample GrN-6832C, radiocarbon date by W.G.Mook, Department of Physics, University of Groningen, Netherlands.

[4] Sample GrN-6832C, 'adiocarbon date by W.G.Mook, Department of Physics, University of Groningen, Netherlands.

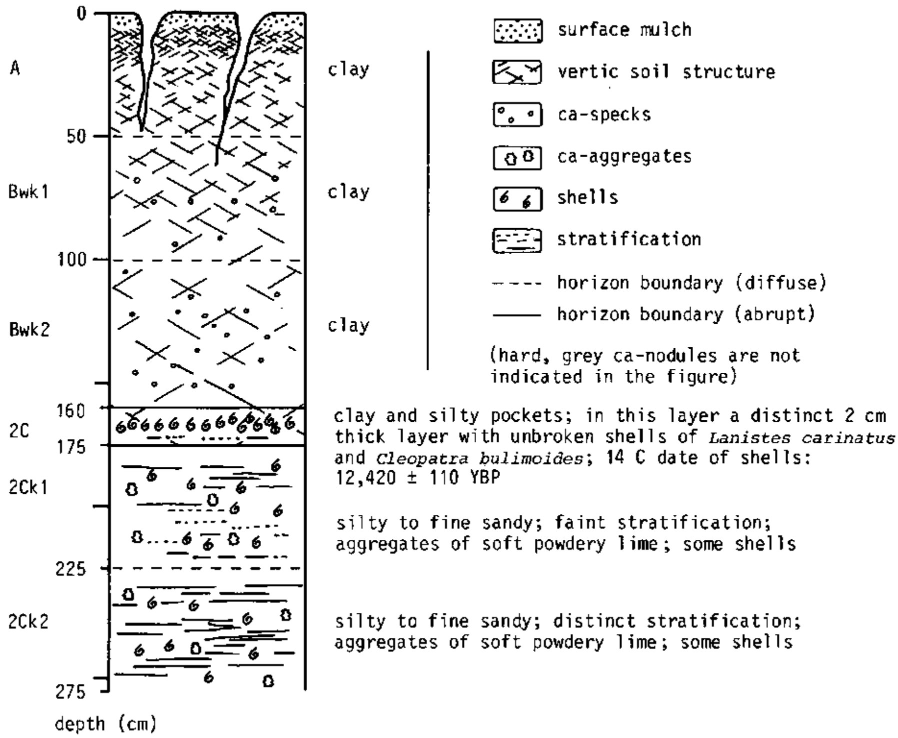

Fig. 4.6. Profile Khashm el Girba South, nr. 258, Asubri series; location: near 15°25'N, 35°30'E; flat clay plain; profile in exposed wall of recently dug irrigation canal

positions. There are, however, differences in physiography which show that the Khashm el Girba clay plain is not formed as an alluvial fan.

Coarse-textured strata probably underlie the entire Atbara alluvial clay plain at rather shallow depth (Blokhuis et al. 1964). These are covered by a sediment which is mainly a uniform yellowish-brown clay (Khashm el Girba series), but at places is silty to sandy (Asubri series). The coarser-textured areas represent a system of silted-up stream beds and small river levees. The surface relief of this sediment has been smoothed by a paludal deposition of a uniform dark grayish-brown clay, similar to that of the Gezira. The upper part of this surface mantle has acquired a higher chroma due to post-sedimentary rubefaction.

4.4.5 Late Pleistocene and Holocene deposition by the White Nile

Deposition in the Central Clay Plain area by the White Nile system is restricted to below the 387/386 m contour east of the river upstream of Malakal, but is distinct only below the 382 m level. There is an interplay of Blue Nile deposition from palaeochannels reaching the White Nile valley (or White Nile 382 m lake), periods of dune formation from the sandy distal ends of the palaeochannels crossing the Gezira fan, and periods of sedimentation by the White Nile.

The flatness of the clay plains of eastern and southern Sudan, and the recognition of the fact that a small increase in flood level would flood extensive areas, has inspired several writers to think that at some time in the Pleistocene a vast lake existed covering the entire Southern Clay Plain and parts of the Central Clay Plain. The presence of such a lake, blocked at its northern end by the Sabaloka barrier, is in agreement with the theory that the connection between a Nile system above Khartoum, and an Egyptian Proto-Nile is of Late Pleistocene date, a hypothesis revived by De Heinzelin (1967) and Butzer and Hansen (1967), but strongly rejected by Berry and Whiteman (1968) and Adamson (1982).

The idea of a Pleistocene lake was first put forward in 1865 by Lombardini (cited by Whiteman 1981, p. 109). Lawson (1927) was the first to use the name 'Lake Sudd', because of the supposed resemblance to the present 'sudd'-region of perennial marshes south of Malakal. This hypothetical lake covered the present Southern Clay Plain and almost the entire Gezira, Kenana and Rahad-Dinder-Blue Nile Gezira, extending well into the Kordofan Provinces. Ball (1939) developed the hypothesis further and came to a lake of smaller dimensions: the present 'sudd'-region and adjoining seasonally flooded areas narrowing towards the north into the White Nile valley as far as the Sabaloka barrier. This lake would have had a length of 1 050 km north to south, a maximum width of 530 km east to west, and an area of 230 000 square kilometres. Both Ball and Lawson made calculations showing that the surface area of the lake would have been sufficient to dispose of all water, brought in by river discharge and by rainfall on the lake.

Berry and Whiteman (1968) rejected the Lake Sudd hypothesis as no shore line features, terraces or fossil shells were found, except at levels of 382 and 386 m in the White Nile valley between Malakal and Khartoum (Berry 1962). Moreover, apart from the sediments in these relatively small White Nile lakes, the Umm Ruwaba sediments (including those from the El Atshan and Gezira Formations) lack the uniformity and fine grain-size of lake-bottom deposits. Tothill's (1946) studies on molluscs, discussed in section 4.4.3, showed that most of the Gezira had never been a lake.

Several suggestions have been put forward for the damming of the White Nile lakes. Berry (1962) proposed the combined effect of two mechanisms: (1) damming by an extensive Blue Nile flood at a time when the White Nile peak discharge was much less vigorous, and (2) backflooding of the Blue Nile into the White Nile valley at times when the White Nile flow would be insufficient to reach the confluence with the Blue Nile and, consequently, dropping of Blue Nile sedimentary load at the northern end of the White Nile valley. Williams and Adamson (1980) suggested that the White Nile lakes were entirely due to backflooding of the Blue Nile. These authors do not consider the building of a sediment bar in the White Nile valley just upstream of its confluence with the Blue Nile to be feasible, because of the simultaneous occurrence of White Nile and Blue Nile high flood levels. Earlier hypotheses such as damming by the Sabaloka gorge north of Khartoum are now obsolete (Berry and Whiteman, 1968).

Williams and Adamson (1973; 1974; 1980) discussed the depositional history of the White Nile valley below Malakal, and dated the deposits from radiocarbon ages of shell samples. In the dry period prior to 12 000 BP, Lake Victoria had no outlet and the regional climate was dry. Water from Uganda lakes could not reach the White Nile, and the river valley perhaps dried out for part of the year. After the overflow of Lake Victoria around 12 000 BP, the level of the White Nile rose and the dunes along the river were partly buried by alluvial clays. The White Nile was stable at a level of 386 m and later at a level of 382 m in the period 12 000 to 8 000 BP.

Tothill (1946) found sub-fossil shells of river bottom species (*Melanoides, Corbicula* and *Biomphalaria*) below 382 m along both banks of the White Nile, which indicated that conditions had been lacustrine. Further evidence for such an environment was provided by the absence of shells of the land snail *Limicolaria.* A shell-bearing sample containing unbroken freshwater and river bottom species (*Cleopatra, Corbicula* and *Biomphalaria*), collected below the 382 m level, was dated at 11 350 ± 220 BP (Williams and Adamson 1974), and another sample, at a ground elevation of 381 m, containing large shells of the amphibious *Ampullaria* (*Pila*) *wernei* was dated 8 370 ± 350 BP (Williams 1966). These samples span the entire period when the lakes would have existed.

The snail-bearing deposits of White Nile origin are covered by some 150 cm of clay, and these may represent local aggradations in swamps bordering the receding White Nile. However, the abundance of gypsum and mica suggests a possible Blue Nile origin (Williams 1966). Fine sands and silts that were laid down in the 382 m lake as littoral deposits may have the same origin: they are too coarse-textured to be authigenic White Nile sediments, and they also contain much gypsum and mica.

The sand dunes on the White Nile east bank, which are most extensive between Naima and El Geteina, are reworked sandy palaeochannel deposits and a Blue Nile origin is beyond doubt, as shown in the mineralogy (Williams et al. 1982). The dunes may have formed in the drier period after 8 000 BP.

Whether or not the White Nile lakes existed throughout the long period 12 000 to 8 000 BP is not clear, but it seems unlikely; there were high White Nile and Blue Nile flood levels from 12 000 to 11 000 BP and again in the period 8 400 to 6 800 BP (Williams and Adamson 1980), but lower levels existed in other periods.

There is no evidence that material from Blue Nile origin older than 12 000 BP - for example, the yellowish-brown substratum of the Gezira clay - reached the White Nile valley.

4.5 Summary

The Pleistocene and Recent history of the Nile system in the Sudan is summarized in Table 4.1; it has been strongly defined by climatic conditions in the catchment areas of the river (Ethiopia and East Africa) and by the climate in the Sudan basin. These three regions were subjected to comparable climatic fluctuations, roughly as follows:

- from 27 000 BP or earlier until 20 000 BP: one or more warm and wet periods;
- 20 000 to 12 000 BP: dry and cold;
- 12 000 to 8 000 BP: warm and wet;
- 8 000 to 3 000 BP: warm; gradually getting drier, with wetter and drier intervals;
- 3 000 to present: climate as it is today.

Deposition by the Blue Nile can be understood from two models (Williams and Adamason 1980) pertaining to morphodynamic and morphostatic stages in the headwaters region, respectively. The Late Pleistocene Blue Nile of around 18 000 BP was a seasonal river as it is today, but with a more pronounced flood peak; bed load was coarser-grained and more abundant than today, and suspended load much reduced. During winter months, the river may not have reached the main Nile. The Early Holocene Blue Nile, of about 11 000 BP was a seasonal river with a high summer discharge, carrying much silt- and clay-sized suspended matter which was eroded from sedentary soils in the Ethiopia catchment, together with a still significant bedload. The deposition of this material in the Sudan basin was dependent on the extent and duration of the annual flooding, and on the trapping action of the vegetation in the plains.

The Gezira aggradational clay plain has formed as a Blue Nile alluvial fan graded to the White Nile: the Gezira Formation. The Formation consists of two members: the Lower Member, which is heterogeneous, including sandy and gravelly next to silty and clayey deposits, and the Upper Clay Member (Gezira clay) consisting of a uniform clay sediment, 7 to 45 m thick, locally interrupted by a system of sandy to gravelly palaeochannels.

Two deposits can be recognized in the upper 250 cm of the Gezira clay: a surface mantle of 130 to 150 cm thick, the upper 60 cm of which have acquired a dark-brown colour due to soil-forming processes, and a yellowish-brown substratum clay till 250 cm or below (at one site to over 20 m). The colour difference between the two sediments, and the occurrence of specific soil features at their boundary, together with different radiocarbon ages, makes it likely that there have been two major periods of deposition, separated by a period of standstill:

- from 27 000 BP or earlier until 20 000/18 000 BP: deposition of yellowish brown substratum clay;
- between 20 000 and 12 000 BP: period of standstill in deposition with locally marshy conditions and an arid climate on the clay plain;
- from 12 000 until about 4 000 BP: deposition of dark grayish brown surface clay.

This depositional history of the Upper Clay Member of the Gezira Formation is at variance with deposition by a Late Pleistocene Blue Nile of the Williams and Adamson (1980) model. It would indeed be difficult to relate deposition of thick, uniform clay sediments with an arid type river system.

The Atbara clay plain must have had a history similar to the Gezira plain: a paludal dark grayish-brown clay (with a dark-brown surface soil) overlies a yellowish-brown clay which, however, is much thinner than in the Gezira and often interrupted by coarser-textured strata representing former palaeochannels or silted-up meanders.

The White Nile system has developed quite differently. The White Nile valley in the central Sudan has acquired the dimensions of a lake during at least two relatively wet periods between 12 000 and 8 000 BP. The lakes could have developed due to damming or backflooding by Blue Nile floods at the confluence of the two rivers. After 8 000 BP the lakes shrank. White Nile sedimentation was under lacustrine conditions. Blue Nile deposits have at times spread into the White Nile valley.

Chapter 5

Origin and geomorphology of the degradational clay plains

5.1 Degradational and aggradational plains

Over large areas the clays of the central plain are derived from local rocks. These are the degradational clay plains, which have not been subject to flooding and sedimentation by rivers of the Nile system, but owe their origin to the weathering of Basement Complex rocks and Tertiary lavas, and the subsequent transportation of part of the fine-textured weathering debris to local erosion levels. In total acreage they exceed the aggradational plains; they cover the major parts of the Butana, the Gedaref clay plain and the Kenana. The processes of landscape evolution include parallel slope retreat (back-wearing), pedimentation and rock weathering (Ruxton and Berry 1961). It must be assumed that water transport has been insufficient to move the debris towards perennial streams connected with the Nile drainage system, and under these circumstances debris fans and bahadas become the most extensive forms in the landscape (King 1967, p.170). The last stage of degradation is a gently undulating clay plain with few remnants of the older surface as hill groups and inselbergs with fringing pediments. Most of the degradational clay plains are now in this stage.

At first sight the aggradational and degradational plains look alike; they are both apparently flat and have similar smectite clay soils. Such variations that do occur in the morphology and characteristics of the soils reflect a climatic zonality rather than differences in parent material or landscape evolution.

Tothill (1948) was probably the first to recognize that the 'more steeply sloping plains' like the Butana, the area around Gedaref and Qala en Nahl, the clay plain between Sennar and Kosti, and the area between Renk and Guli 'and onwards through the lower parts of the Fung', were covered by cracking clays derived from the decomposition of rocks 'in situ'. These observations have been amply confirmed for the Butana (Ruxton 1956) and the Southern Gedaref clay plain (Ruxton 1958; Ruxton and Berry 1961). A cross-section from Sennar to Gedaref (Ruxton and Berry 1978) shows the aggradational Blue Nile-Dinder-Rahad clay plain at a level of approximately 430 m, whereas east of the Rahad the degradational clay plain rises towards Gedaref at an elevation of 600 m. In the reports of the Roseires Soil Survey (Hunting/MacDonald 1963-1967), reference is made to clays derived from Basement Complex rock by sheet-flooding or colluviation in the western Butana and east of the river Rahad. A local origin is also suggested for some clays in the western fringe of the Manaqil ridge.

In the Khashm el Girba South soil survey (Blokhuis 1963), the boundary between aggradational and degradational plain could be traced accurately from the contour pattern (Fig. 2.4); it appeared that clays on either side of this boundary line differed markedly in profile morphology of the subsoil.

In the report covering the Umm Simsim and Umm Seinat soil surveys in the Southern Gedaref district (Ilaco/Nedeco 1966) a local origin (Basement Complex and Tertiary basalt) was assumed for most of the soil parent materials. These areas form part of the Khor Simsim catchment, a gently concave surface regularly sloping from the Gedaref-Gallabat ridge to the river Rahad, with a gradient of 0.2% (Fig. 2.3). Ruxton and Berry (1978) consider it to be a classical pediplain surface.

There is now consensus on the degradational nature of the Butana and Gedaref clay plains, the southern Kenana and the Ethiopian foot slope plains (cf.Chapter 6). There remains, however, controversy about the origin of the clays in the northern part of the Kenana.

Gunn (1982) considered the entire Kenana north of the latitude of Er Roseires as an alluvial plain built from Blue Nile deposits, whereas Williams and Adamson (1982) suggest that at least part of the area has been formed as a result of weathering of local rocks.

Buursink (1971, p.43) describes the plain between the White Nile-Blue Nile watershed in the Kenana and the Blue Nile/Rahad-Atbara divide in the Butana as 'a landscape related to the Blue Nile and its tributaries the Dinder and Rahad'. The Nile river system should be the main building agent of this clay plain which has a maximum width of 250 km.

In a report on a semi-detailed soil survey of parts of the Central Clay Plain (FAO 1970b), it is stated that the superficial cover of this plain consists of 'fine-textured material deposited by floodwaters of the Blue Nile river'. The rocks underlying these strata belong to the Basement Complex and the Umm Ruwaba formation, but these 'have little influence on the present soil except for isolated spots near jebels, or where jebels are only partially covered with alluvial clay'.

A Blue Nile origin of most of the clays in the central Kenana was also suggested by Purnell et al.(1976).

Gunn (1982) did not rule out the possibility of a Blue Nile origin of a clay mantle over 4.3 m thick near Jebel Bozi, in the Kenana. Clays in the area around Jebel Mazmum have also been considered to be a Blue Nile deposit (FAO 1970a).

For some parts of the northern Kenana the difference of opinion can be understood, but for other parts a quick glance at contours and relative heights (Fig. 2.2) should suffice to rule out an alluvial origin.

The edge of the clay plain near Er Roseires is at an elevation of 470 m; this implies that sedimentation from the Blue Nile at this latitude could never be above this level. Figure 2.2. shows a fairly level area northwest of Er Roseires, stretching north to Abu Na'ama, and bounded at its western side by the 470 m contour. At Singa the edge of the clay plain is at 430 m, and halfway between Singa and Abu Na'ama at 435 m. The highest level in a cross-section at the latitude of Singa, is just above 435 m. This implies that at one time Blue Nile floods could have reached beyond that part of the Blue Nile-White Nile divide which is at about 435 m. Gunn (1982) considered this saddle to be a potential spillway from Blue Nile flooding into the White Nile valley. Figure 2.2 also shows clearly that the White Nile, with highest levels at 380 m in Late Pleistocene/Early Holocene (cf. Chapter 4), hardly contributed to the formation of the Kenana plain. Ruxton and Berry (1978), considering Gunn's draft cross-sections of the Kenana, suggested that tilting could have accounted for the way the thick alluvial clays west of the Blue Nile appear to drown the lower pediplains of the watershed.

We consider the alluvial Blue Nile plain in the northern Kenana to be restricted to the near-level part, reaching almost to the watershed, but not beyond (cf. Chapter 6).

Not only the elevation of the terrain surface. but also the contour pattern is very different between the more or less level eastern part, and the gently sloping plains in the central and western areas. Extensive hill groups like Jebel Terru and Jebel Abu Qurud, or large single hills such as Jebel Dali and Jebel Bozi, have a distinct relation to the contour pattern, as one would expect to find on a pediplain.

There are differences in soil morphology and in mineralogical composition of the soil materials between the degradational and the aggradational plains. These will be discussed in Chapters 6, 7 and 8. In this chapter we will briefly describe possible processes of landscape formation in the degradational plains.

5.2 Age of the degradational clay plains

The entire Central Clay Plain area was probably once covered by the Nubian sandstone formation, but most of it has been removed in subsequent periods of erosion, which, according to Andrew (1948, p.90) have been active since Late Cretaceous for a long time. The Tertiary was a period of active tectonics and the Sudan basin was formed. The infilling of depressions in this basin began in the Pliocene with the 'old alluvium' (cf. Chapter 4). The Late Quaternary was a period of relative tectonic stability. It is probably since that time, that the areas now covered by degradational clay plains have been subject to planation, while downwarping and downtilting of the Sudan basin continued. Planation resulted in grading towards local base levels. At present, drainage channels from small hill groups fade out on the plain; larger channels are poorly integrated and only a few reach the major rivers (Ruxton and Berry 1978).

Cooke and Warren (1973, p. 37) emphasized that in many arid and semi-arid areas geomorphic processes have almost certainly changed as a result of climatic fluctuations. Such changes may refer to the nature, magnitude and frequency of the processes. Their effects, on the other hand, should not be overestimated: 'Particular landforms or erosion systems may respond to climatic change merely in the rate of their development. For example, an erosion system composed of mountains, pediments and alluvial plains may develop more slowly under conditions of increased aridity and may experience no distinguishable change of form. It is true that such systems do often show evidence of adjustments to climatic change but such adjustments are by no means essential.' Ruxton and Berry (1961), on the other hand, differentiate between present arid, savannah and humid types of landform and regolith mantle on granite in the Sudan (section 5.3).

To ascertain the age of the clays of the degradational plains is a more complex problem than age assessment of the aggradational plains. Tothill (1948) and Ruxton and Berry (1978) consider the clay mantles of the degradational plains to be older than those of the aggradational plains. The authors arrive at an age of over 500 000 years, in agreement with King (1953), who found that major cyclic erosion scarps in several continents retreat at a rate of 30 cm in 150 to 300 years. However, clay sedimentation in the aggradational plains has been a finite process, whereas on the degradational plains back-wearing, down-wearing and clay movement over the plain are actual processes. The Butana grass patterns (Worrall 1959; Ruxton and Berry 1960) show that some form of soil creep is active on the degradational plains. The surface clay could therefore be considered a young deposit. The downslope clay migration shows that the landforms are not passive, although the morphology is that of a pediplain approaching the final stages of gradation.

5.3 Pediplanation and rock weathering

Ruxton and Berry (1961; see also Berry and Ruxton 1959, and Ruxton 1956) identified large areas of the Butana and Gedaref clay plains as pediplains in a late stage of degradation. Their studies were concentrated in the area near Qala en Nahl, in the Gedaref clay plain. Hills and inselbergs that rise above the plain belong to the Basement Complex which also underlies the clays of the plain. This being a granitic area, their studies can be compared with most classical studies on landscape evolution in (semi)-arid environments, which have concentrated on regions with granitic bedrock (see, for example, Davis 1933).

In order to understand landscape evolution in arid regions the concept of pediplanation was developed, but the same fundamental processes are active in semi-arid and humid tropical regions (King 1967; Holmes 1955; Ruxton and Berry 1961). The essential differentiating factor in pediplanation is the nature of the rock; climatic differences and related diversity in vegetation cover cause modifications of the rock-defined type of hillslope development.

Ruxton and Berry (1961) differentiated Sudan landforms and regolith mantles in granite into arid, savannah and humid types. Climatic fluctuations must also have affected these regions, but the authors assume that the present pattern of gradational changes has been maintained throughout. Savannah landforms would develop where rainfall is between 300 and 750 mm. The weathering profiles are generally 6 to 9 m thick. Almost the entire Central Clay Plain is within this range. The clay plains of the savannah type give way to plains mantled with silt and fine sand when rainfall is below 300 mm. In these arid landforms the pediments[1] of inselbergs are broader and steeper. In the Butana the boundary between degradational clay plain and the desert denudation plain north of it (cf. Chapter 2) corresponds roughly with the present 300 mm isohyet (Ruxton and Berry 1978). Above 750 mm rainfall (Ingessana Hills, part of the Gedaref clay plain, southern Kenana) landforms differ from the savannah type in having less steep hillslopes that merge gradually into deeply-weathered and dissected pediments. In the Ingessana Hills the regolith is up to 24 m deep.

In semi-arid and sub-humid environments back-weathering and down-weathering normally precede or accompany back-wearing and down-wearing. A weathering profile is formed and the products of weathering migrate downslope. Ruxton and Berry (1961) describe the complete regolith profile of the savannah type landform as follows (Fig. 5.1):

- Soil migratory layer: reddish or grey-brown arkosic silty sand in which a soil profile is formed.
- Zone I: reddish-brown clayey sand.
- Zone II: pale-brown arkosic sand or gravel,with some relics of the granite texture preserved in places.
- Zone III: gravel-sized chips of iron-stained granitic rock.
- Zone IV: slightly weathered bedrock.
- The basal surface separates zone IV from the fresh bedrock.

The hillslope has a thin and patchy cover, up to 3.5 m deep, of debris that conforms to zones III and IV of the regolith. The pediments are covered by a migratory layer, up to 2 m deep, overlying a complete weathering profile with a thickness of 6 to 9 m.

Berry and Ruxton (1959) devised a model for the processes of weathering, erosion, migration and aggradation, which is shown in Fig. 5.2. Weathering is most rapid on the hillslope where sub-surface water flows strongest and is most frequently replenished. Weathering is most intensive on the pediment, where sub-surface water lingers longest, especially on the upper part that receives surface and seepage water from the hillslope. Weathering is least in the truncated (see below) regolith that underlies the clay plain, as rainwater hardly penetrates through the highly

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[1] Pediments are usually defined as rock-cut surfaces over which weathering debris from hill slopes is transported towards valleys connected with a major river system or, in the absence of this, towards local base-level plains. Pediments would, according to Ruxton and Berry (1961), be only correctly defined as rock-cut surfaces when rock includes the sedentary weathering profile. These authors prefer the term 'plinth', because 'pediment' sometimes includes the piedmont (aggradational) slope (the bahada, alluvial plain, clay plain), for example by Dixey (1955). We use the term pediment for the zone beneath the hill slope, where weathering, erosion and transport exceed aggradational processes.

impermeable soil cover. Up to 70 per cent by volume of the original rock may be removed by solution and sub-surface mechanical eluviation, and it is washed out onto the pediment surface at a seepage line that separates the upper from the lower pediment.

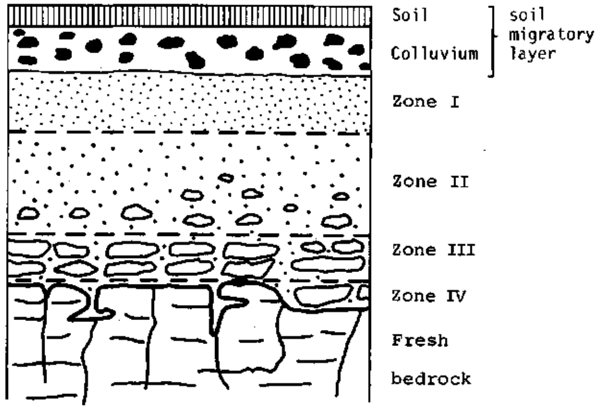


Fig. 5.1. The complete regolith profile (after Berry and Ruxton 1959; adapted)

Weathering on the hillslope is followed by denudation as a result of sheetwash and rillwash. The debris is transported across the lower pediment, and during transport mineral weathering continues: clay is formed and the quartz is disintegrated to a fine sand. The finest material is deposited below the pediment where it forms a bahada. In the Qala en Nahl area the granites contain 24% quartz, and the soils of the clay plain have a sand fraction of about 20% (Ruxton and Berry 1978). Finer-textured soils are found in areas with intermediate and basic rock (cf. Chapter 8).

Next to denudation of the (upper) pediment by sub-surface erosion and solution, there is also denudation as a result of gullying and lateral planation, and - especially on the lower pediment - of sheetwash. As a result, the weathering profiles of the

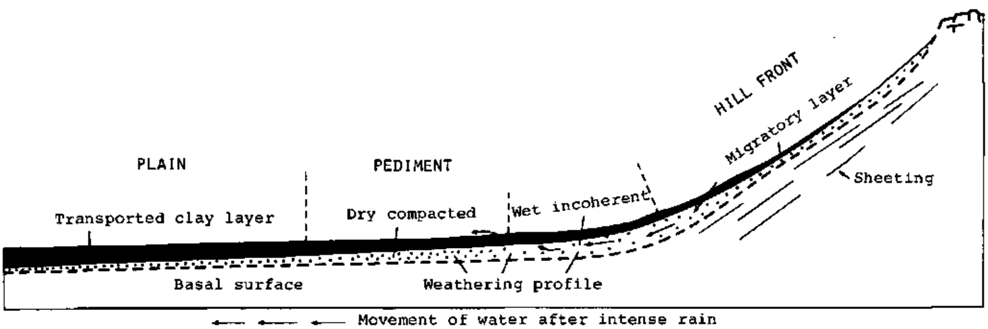


Fig. 5.2. Representative section near Qala En Nahl showing the form of the weathering profile and migrating debris on the concave slopes of hill, pediment and plain (after Berry and Ruxton 1959)

pediment are truncated, and the lower part of the pediment and the bahada receive debris from the upper part of the pediment that further weathers to a clay.

The general picture that emerges is a retreat of the hillslope and an advance, upslope, of the clay plain over the lower pediment. So it can be understood that the clays overly truncated weathering profiles. Once deposited the clay is little affected by erosion as the drainage density on the semi-arid clay plain is very low. Erosion by wind is negligible as the clay is well-aggregated into sand-size and larger aggregates. There is, however, a slow migration downslope due to sheetwash and a special type of soil creep (see below).

In order to understand the present physiography of the degradational clay plains in east-central Sudan, the scale of study must be enlarged from the single hillslope, to for example, a group of hills. Ruxton and Berry (1961) choose the scale of the 'topographic compartment', which they defined as 'the smallest area of land which is almost or completely surrounded and limited by stream courses, valleys or depressions including cols, or a combination of these'. Four phases can be distinguished in the evolution of compartments (Fig. 5.3):

1. The establishment of a profile of equilibrium: the steep hillslopes are reduced to less steep slopes of equilibrium.
2. Parallel lateral retreat. The hillslopes and pediments retain the same declivity as they recede; this imples that the well-defined piedmont angle is constant. There is a simple relation between the thickness of material removed from the hillslope and that removed from the pediment. In Qala en Nahl it was found that the thickness removed from the hillslope in a given unit of retreat was 8.5 times that removed from the pediment. This ratio is related to weathering intensities and rate.
3. Down-wearing of hills in the compartment centre. The lowering of a compartment centre (residual hill) begins when opposing parallel retreating slopes meet. At this stage down-wearing becomes of equal or greater importance than back-wearing. When the compartment centre has been completely reduced onto the pediment level, opposing pediments meet.
4. The lowering of divides. In a late stage of degradation the concave pediment slopes merge with the intervening convex slope of the divide. Smooth,gently undulating plains are formed. Relief continues to decrease as a result of weathering on the pediments and the eluviation of fine-grained debris and soluble and colloidal compounds towards the plain. The degradational clay plains in east-central Sudan are in this stage (Photos 22, 23 and 26).

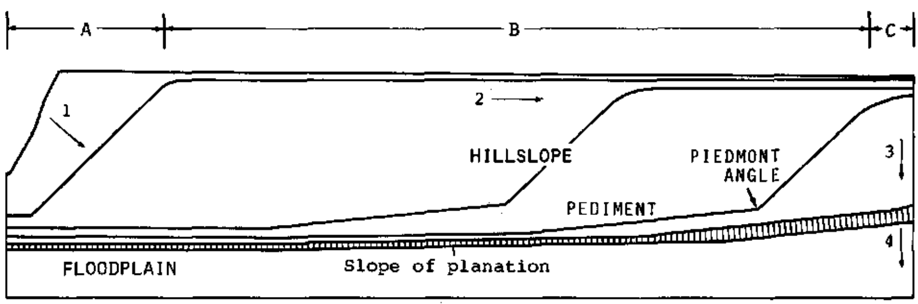


Fig. 5.3. The four stages of compartment evolution in arid regions: 1.the flattening of cliffs; 2.parallel lateral retreat of hillslopes; 3.down-wearing of hills in the compartment centre; 4.the lowering of divides. The ratio of back-wearing to down-wearing can be roughly assessed as the ratio of length B to length C (after Ruxton and Berry 1961)

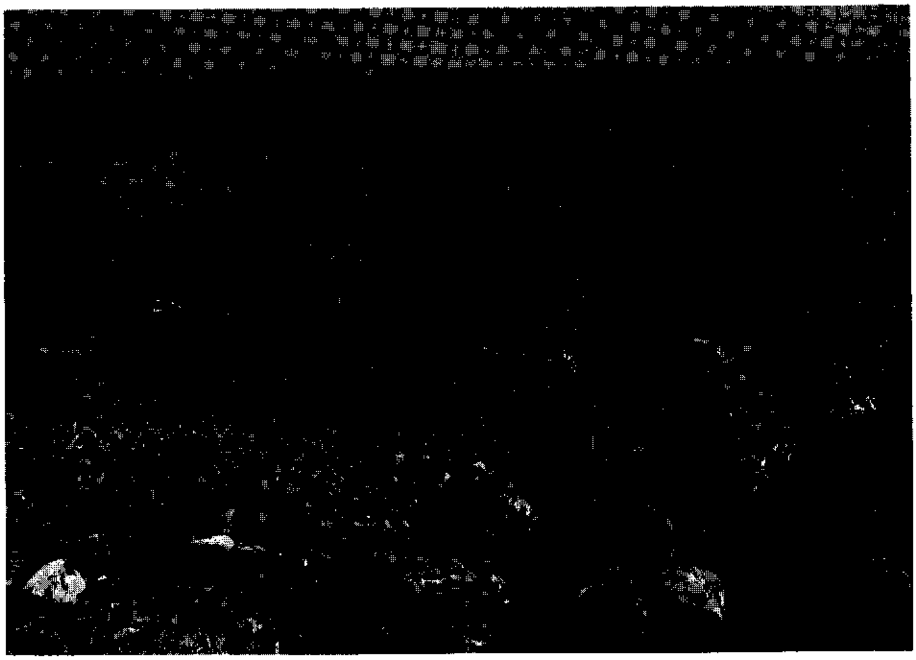


Photo 22: Hillside slope, pediment and clay plain. Rock fragments of quartzite in the foreground; broad-leaved trees on the hillslope; Acacia seyal - Balanites *savannah on the clay plain. View towards NE from Jebel Umm Seinat.*

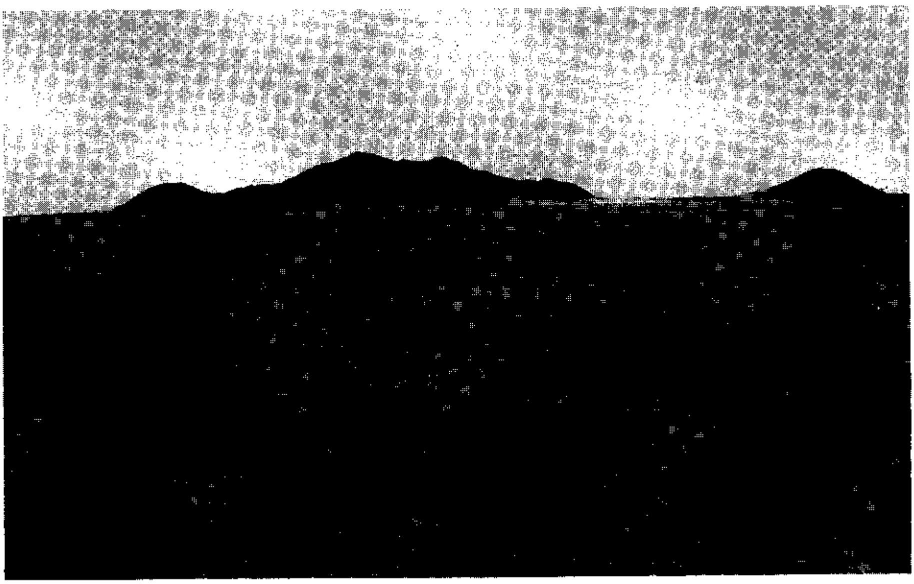


Photo 23: Butana pediplain with Jebel Tawal group, between El Husheib and Wad Medani; note the light-coloured pediment around the inselbergs. Grass plain with scattered Acacia mellifera.

Ruxton and Berry (1978) estimate that the hill groups in the area between Gedaref and El Hawata must have been 1 to 2 km larger in radius than at present to account for the quantity of clay present on the plain, assuming that surface planation is entirely due to back-wearing (parallel slope retreat). If this were true, one would expect areas of the plain distant from watersheds and hill groups to have a thinner cover of clay or even a different soil as compared with areas near hill groups. This not being the case, Ruxton and Berry conclude that in addition to back-wearing, down-wearing (vertical lowering) must have been important for the production of clay. Very slight down-wearing would be equivalent to a large amount of back-wearing in terms of clay production, because of the vastly different surface areas involved (when parallel slope retreat has created pediments of considerable surface area). The importance of local down-wearing is also shown in the mineralogy of the sand fraction: on the clay plain near Ghadambaliya, basalt minerals (olivine and zeolite) diminish downslope from their source, whereas some distance beyond the contact with the Basement Complex, quartz and green hornblende appear in the surface soil.

The geomorphic processes have resulted in the formation of three types of clay mantle on the Butana clay plain:

1. The plain proper is very gently undulating with slopes of between 0.25 and 1%. The clay mantle has an average thickness of 3 m. The average clay content is 60%, pH averages 8, CaCO3 percentage 2 to 4. The mineralogy of the fine sand fraction varies in sympathy with the local rock (Ruxton and Berry 1978, summarizing data from various sources).

2. The clay mantle on low rises, around and within hill groups and on the watershed, is thinner, sandier (25 to 50% clay), has a pH of 7 to 8 and little carbonate. The mineralogy of the sand fraction is directly related to the underlying rock.

3. In depressed locations and along floodplains the clay cover is thickest, 4 to 5 m thick; average clay percentage is 70. Salts and gypsum may be present.

A characteristic feature of the Butana plain is the occurrence of grass patterns (Worrall 1959) which are indistinct when viewed from the ground but conspicuous from the air (Photos 24 and 25). The pattern consists of strips with tall grasses, alternating with strips that have short and medium grasses in a less dense stand. The strips run parallel with the contour, and appear to occur only on slopes over 0.2%. Worrall found that the occurrence of the grass patterns was related to other site characteristics, notably water supply, slope, and nature of the soil. He suggested that the pattern may have been initiated by a type of soil slip or a rhythmic deposition of vegetation. In a reaction Ruxton and Berry (1960) proposed that the patterns are the result of some form of soil creep.

The patterns extend north of the Butana grasslands (Photo 26) into areas where there is only a vegetation of annual herbs (Blokhuis 1963). On the lower-rainfall aggradational clay plains these grass patterns are absent, and this must be due to a more level topography. In higher-rainfall degradational clay plains of sufficient slope

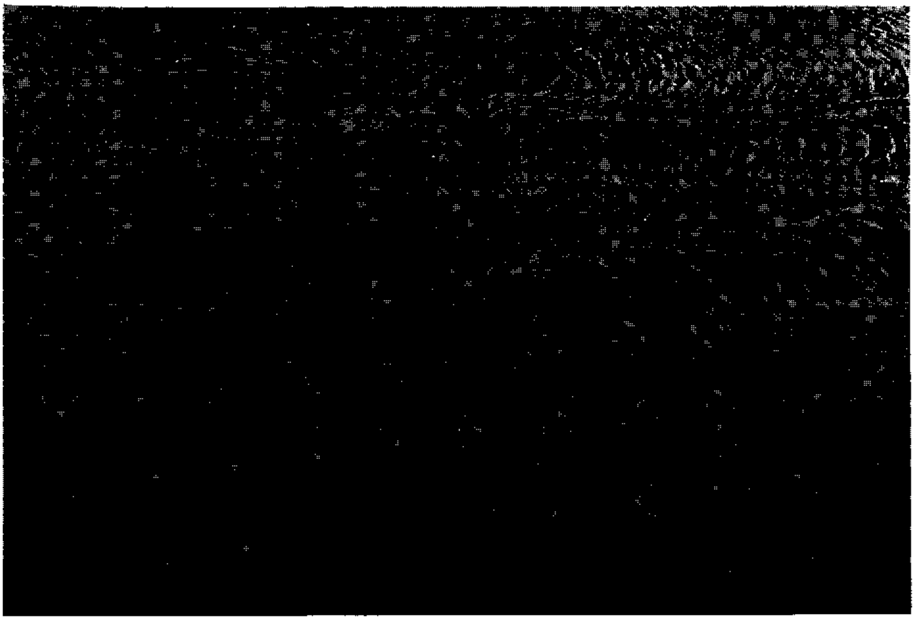


Photo 24: Aerial view of the Butana grass patterns. Between Khartoum and the Atbara river.

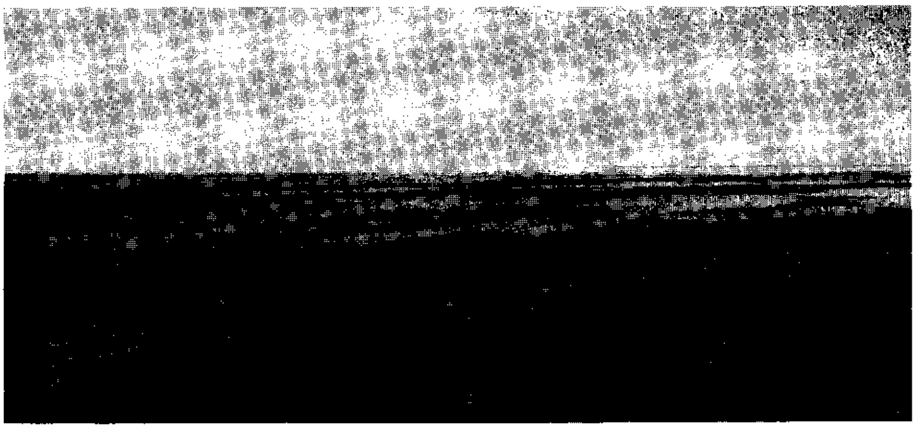


Photo 25: Grass/herb pattern in the Butana. Light-coloured strips have short grasses (mainly Setaria spp); they alternate with strips having a vegetation of annual herbs, that look bare in the dry season.

the patterns are also absent, both under tree cover and in the grassland areas which alternate with the *Acacia seyal-Balanites* savannah and the *Anogeissus-Combretum* savannah woodland, perhaps due to a more stable, intensely rooted surface soil. However, in woodland savannah areas with a rainfall over 600 mm, a different type of surface pattern is common: the gilgai microrelief that takes round forms on flat terrain, and striped forms (a pattern that runs with the slopes) on slightly sloping terrain.

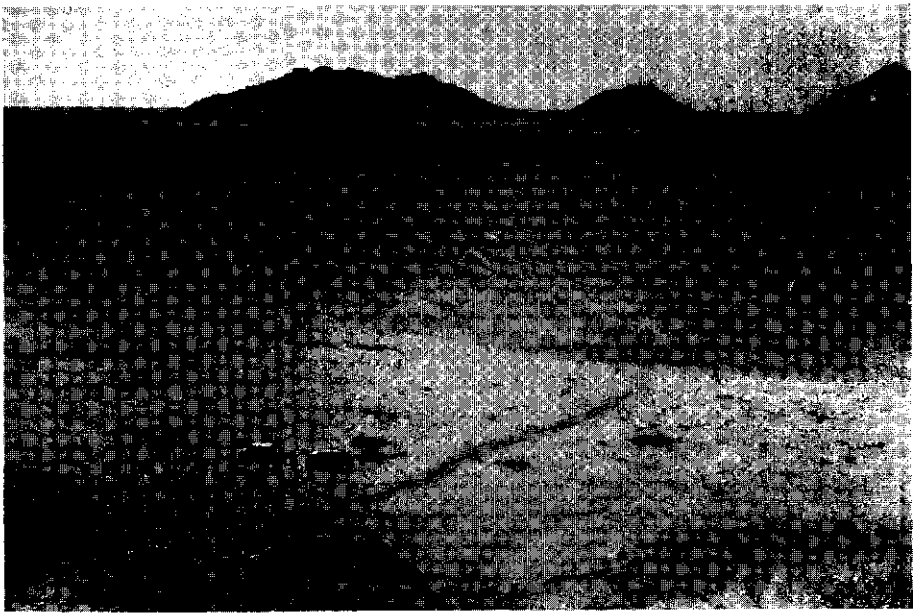


Photo 26: Herb pattern in Khashm el Girba North, seen from one of the inselbergs of the Jebel Saba'at group. The pattern consists of strips with a vegetation of annual herbs, alternating with almost bare strips. Note the pediments fringing the granitic inselbergs.

An example of slope retreat and planation in a basalt area where landscape evolution resulted in a relative increase of the clay plain area with Vertisols, is given for Queensland, Australia, by Beckmann et al. (1974). The annual rainfall is 600 to 700 mm. The landscape consists of a series of almost parallel basalt platforms separated by low scarps and pediments. Lithic soils, Alfisols and Vertisols occur in close juxtaposition, and their relative coverages change with time (Fig. 5.4) as platforms are reduced in size, scarps retreat and flatten, and pediments extend upslope. In the final stage of degradation, Vertisols cover a gently undulating landscape formed on pediments.

A marked difference with landscape evolution on granite is that Vertisols in a basalt-derived landscape not only cover the clay plain, but also the hillslopes and (upper) pediments. The basalt landscape between Gedaref and Gallabat greatly resembles the Australian example. Low-chroma Vertisols occur on the plains, as in the Basement Complex areas, but gentle hillside slopes are covered by reddish-brown Vertisols. Only the steeper slopes and the stone-covered plateau remnants have shallow non-vertic soils (Photo 27).

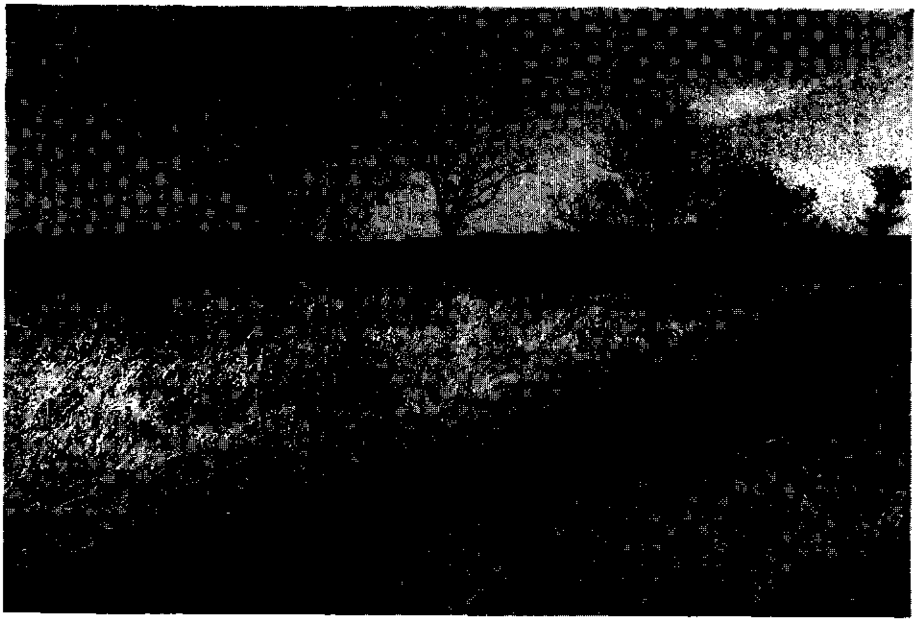


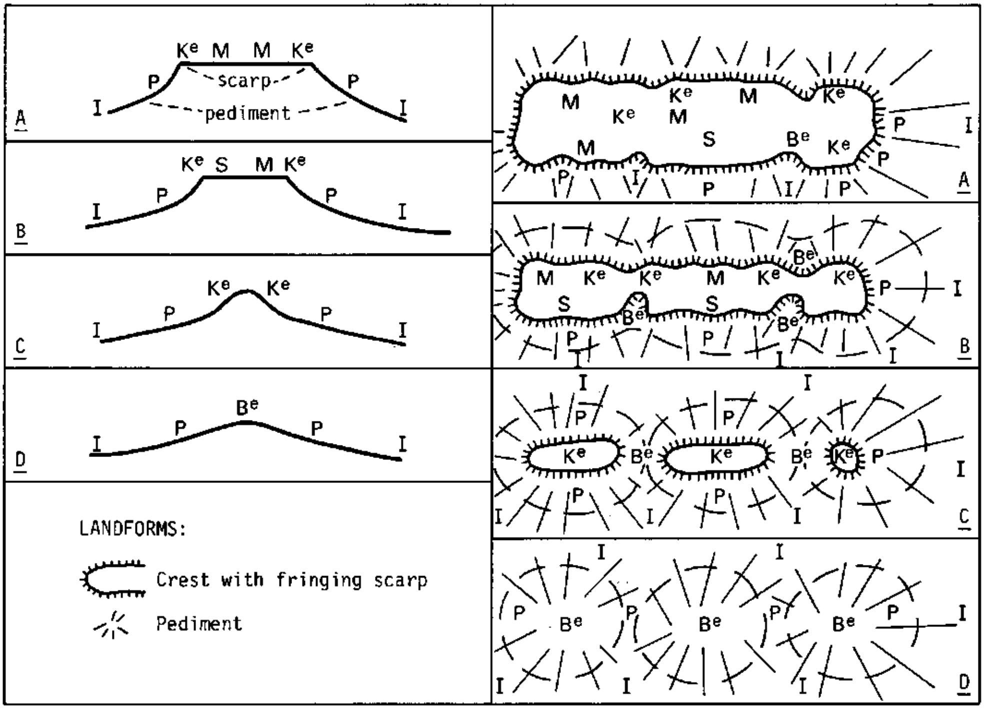
Photo 27: Basaltic ridge with red stony soils. In this landscape Vertisols cover hillside slopes, footslopes and plains. Between Abu Irwa and Gallabat.

5.4 Major differences between aggradational and degradational clay plains

Ruxton (1956) summed up the differences between aggradational and degradational clays and clay plains as follows:

characteristic	*plains of aggradation*	*plains of degradation*
thickness	3 to 50 m,average 9 m	1 to 6 m, average 3 m
nature of underlying strata	sands, gravels, calcrete	truncated weathering profiles on solid rock
stratification	often present	absent
surface gradient	about 0.02%	0.2 to 0.5%
grass patterns	absent	very common
stony surfaces	very rare	common
heavy minerals	related to source of drainage	related to local rock types
gypsum	usually present	rare
salt content	about 15 meq/100 g	ca. 2 to 6 meq/100 g
kankar[2]	abundant	moderate or minor content
semi-aquatic molluscs	common	rare
isolated hill masses and rock outcrops	very rare	not uncommon

[2] Soft and hard glaebules of calcium carbonate



SOILS:

K^e Kenmuir - soil series of a lithic subgroup

M Mallard } soil series of shallow Vertisols
S Southbrook

B^e Beauaraba } soil series of deep Vertisols
P Purrawunda

I Irving - unspecified soil series

Fig. 5.4. Series of plans and sections showing progressive landscape reduction and soil development; Queensland, Australia (after Beckmann et al. 1974)

A few comments must be made on this overview:

a. Ruxton made the remark that the clay on the floodplains of the degradational plains has many of the characteristics of the clay of the aggradational plains.

b. Ruxton's study was restricted to the lower-rainfall clay plains: Gezira, northern Kenana and Butana.

c. The differences in gypsum, salt content and 'kankar', when considered over the entire Central Clay Plain are only partly due to landscape formation and parent materials; in general, these compounds decrease with increasing rainfall, both on the aggradational and on the degradational clay plains.

In Chapters 7 and 8 the differentiating characteristics in soil morphology, soil mineralogy and physical and chemical soil characteristics between various parts of the

Central Clay Plain will be discussed at some length, whereas geographic aspects of the soil cover are dealt with in Chapter 6. Preceding the more detailed discussions in the subsequent chapters, some of the main differentiating characteristics between aggradational and degradational clay plains can be summarized now:

1. Clay soils derived from the weathering of Basement Complex rocks are usually sandier than those from basalt or from other basic rock types. This is evident in the Southern Gedaref clay plain (cf. section 6.5.2) on those sites that are near the source of basaltic rock.
2. Soils derived from Basement Complex rock differ from soils of aggradational clay plains in containing no volcanic minerals (cf. Chapter 8), whereas the mineralogy of the fine-sand fraction varies in sympathy with the local rock. Much variation can be expected in Basement Complex derived soils: although the majority of Basement Complex rocks are granites and gneisses, there are also basic rock types that produce relatively more clay upon weathering. However, in clay-plains soils widely separated from present hills or inselbergs, any attempt to find a relation between minerals of the fine sand fraction, and the nature of the rock from which this sand has derived, is futile; such differences as have occurred are likely to have faded during colluviation, alluviation and soil creep.
3. The small relief differences between aggradational and degradational plains are not important for soil formation: both types of plain are usually 'flat', with slopes below 0.5%. However, 'maiyas' and other mesorelief features like levees, backswamps and silted-up meanders are confined to the aggradational plains. Low-chroma Vertisols occur on the aggradational plains in depressions, on the degradational plains they occur 'in situ' on hillslopes and foot slopes, overlying basic rocks (cf. Chapter 6).
4. In areas of the same latitude, which receive the same amount of annual rain, relatively less salinity and sodicity are found in soils of the degradational clay plains. The latter did not receive, with the sediment, excess floodwater left to evaporate.

Chapter 6

The pedogeomorphic map of the Central Clay Plain

6.1 Field observations, soil surveys and maps

The exploratory map 1:2 000 000 of the Central Clay Plain (Appendix 4) has been given the name pedogeomorphic map. This term is used in order to indicate that it is neither a soil map nor a geomorphic map, but contains aspects of both. The legend of the map shows three categories. The highest category differentiates between geomorphic units. The second category contains geomorphic sub-units. Units of the third category are differentiated on both landscape and soil aspects; these are the pedogeomorphic units. Most mapping units are on this third level, some are geomorphic sub-units (second category) or geomorphic units (highest category).

The 1:2 000 000 scale is too small for the definition of mapping units that are mainly or entirely based on soil characteristics. Such units are in the legend of the larger-scale maps of two sample areas (Figures 6.1, 6.3 and 6.4).

The 1:2 000 000 map is based on the following sources:

A. Field observations

- From traverses over the Central Clay Plain on geology, physiography, soils, vegetation and other landscape features. The soil observations consist of profile descriptions from soil pits and soil augerings, and soil surface observations (including observations at 10 to 30 cm depth, mainly on colour).
- From an excursion in connection with the 5th International Soil Classification Workshop, Khartoum/Wad Medani, 1982.

B. Soil surveys in parts of the Central Clay Plain:

- Proposed Agricultural Research Station at Sennar, 1:40 000(1959 and 1963); representative of mapping unit 121.
- Proposed Agricultural Research Station at Abu Na'ama, 1:20 000(1960); representative of mapping unit 122.
- Soil Survey of River Atbara Diversion Scheme, Part I : Khashmel Girba South, 1:100 000 (1963); representative of mappingunits 131 and 211.
- Southern Gedaref Soil Survey, 1:100 000 (Nedeco/Ilaco,1966);representative of mapping unit 212.

C. Information from other soil surveys:

- Roseires Soil Survey (Hunting Technical Services/MacDonald & partners 1963-1967): soil surveys in areas along the White Nile, Blue Nile, Rahad and Dinder.
- Soil surveys of proposed Mechanized Crop Production Schemes (MCPS) in Gedaref District, by the Soil Survey Division, Wad Medani: Report nr. 10/KA/2,

1964, with:
- Knibbe, M.: Rawashda-Gabub extension, 1:100 000 ; and
- Beinroth, F.H. and H.Duemmler : Abu Irwa, 1:100 000.

- Soil Survey of River Atbara Diversion Scheme, Part II :Khashm el Girba South (Ochtman 1965).
- Reports to the Government of the Sudan on Strengthening of the Soil Survey Division of the Ministry of Agriculture (FAO 1970a; 1970b).
- Reports of Joint Project FAO/UNDP/Min.of Agriculture,Sudan, notably:
  - Purnell, M.F., E.F.de Pauw and Omar Khodary, 1976. Soil resource regions of the Blue Nile, White Nile, Gezira and Khartoum Provinces of the Sudan;
  - Van der Kevie, W. and Ibrahim M.Buraymah, 1976. Exploratory soil survey of Kassala Province.

D. Satellite images LANDSAT-1, scale 1:3 369 000, taken October, November, December 1972 and February, May, 1973; MSS Sensor 5 (of some frames MSS 6 and 7 were also available). Some examples are given as Photos 28, 29 and 30.

- Zeiss Ikon calendar for 1985, sheet November: false-colour satellite image of Gezira Scheme and surroundings.
- M.Sc.-dissertations by students of the Agricultural University, Wageningen, on interpretation of LANDSAT-1 satellite images: Messrs. P.Anker, R.van der Goes, R.van Grootveld, H.Sterenberg, P.Vrins and J.Wijsmuller.

E. Maps:

- Topographic maps 1:250 000 (Sudan Survey Department, Khartoum);.
- International Map of the World, 1:1 000 000, sheets Khartoumand Sobat;
- Geological Map of the Sudan, 1:2 000 000 (Ministry of Energy and Mines, Geological and Mineral Resources Department, Khartoum 198l);
- Geological Map of the Democratic Republic of the Sudan andadjoining areas, 1:2 000 000 (Vail 1978).
- Vegetation map of the Sudan, 1:4 000 000 (Harrison and Jackson 1958).

F. Publications:

- Whiteman (1971), Williams and Adamson (1980), Ruxton and Berry (1978) and several papers in Williams and Adamson (1982) and Williams and Faure (1980).

6.2 Methods of map compilation

The procedure for compiling the 1:2 000 000 map was as follows:

a. Field observations from traverses over the Central Clay Plain and adjoining areas were transferred to 1:250 000 topographic maps.

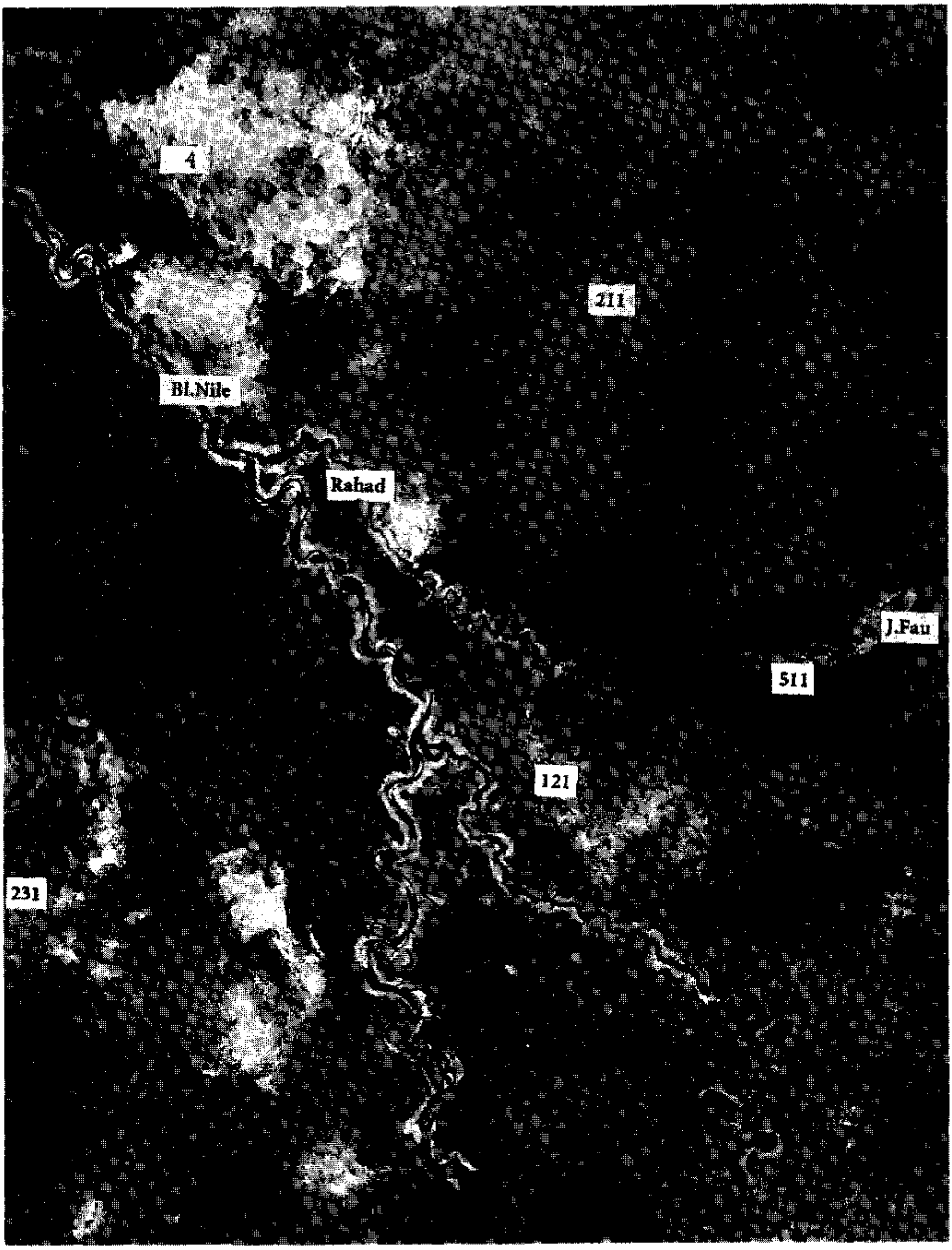


Photo 28: Satellite image Landsat-1, MSS Sensor 5, scale 1:1 000 000, winter 1972-'73. Southern part of the Gezira Scheme, Jebel Fau and other inselbergs in the Butana, rivers Blue Nile, Dinder and Rahad. Mapping units include 121, 211, 231, 4, 511.

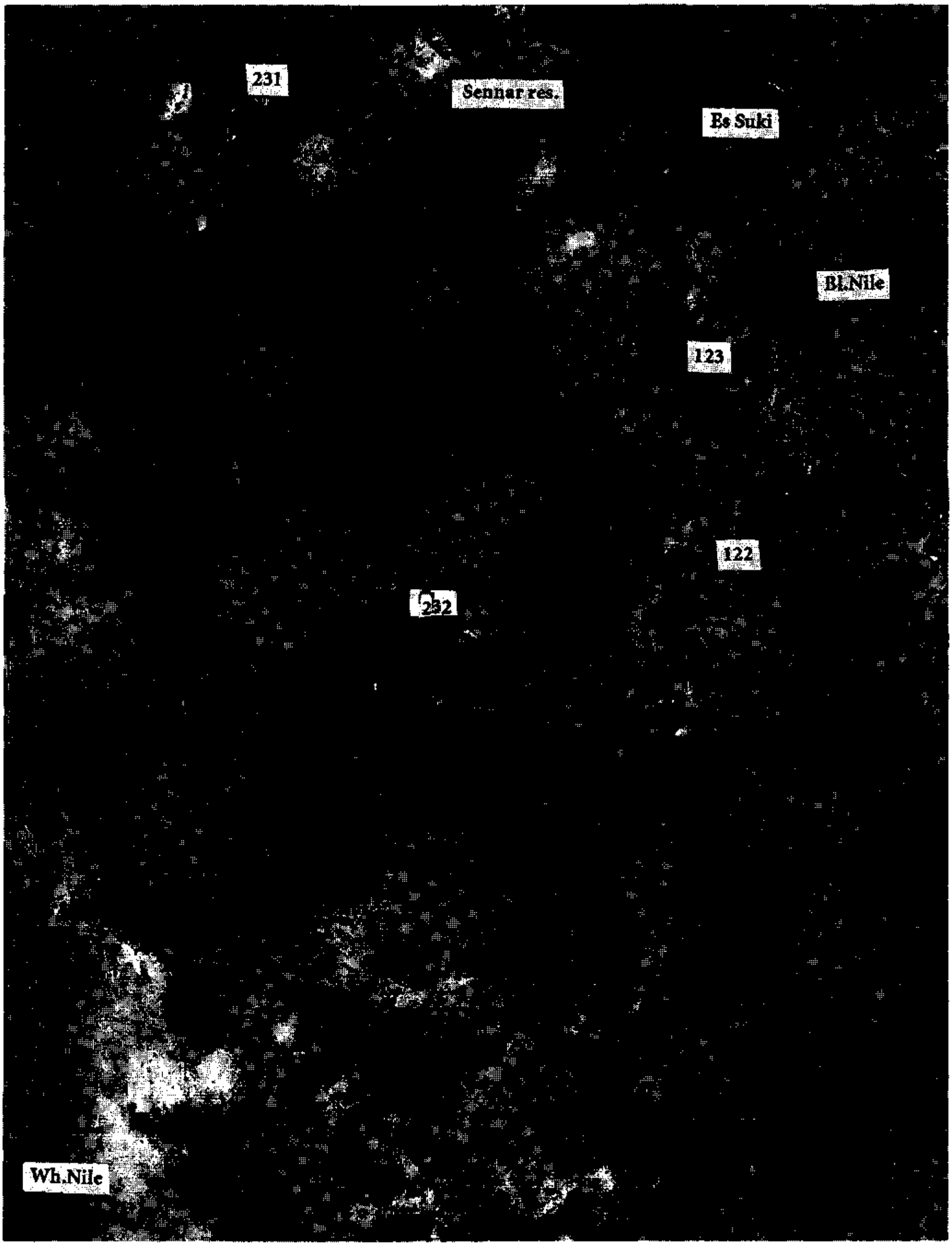


Photo 29: Satellite image Landsat-1, MSS Sensor 5, scale 1:1 000 000, winter 1972-'73. Kenana, White Nile, Blue Nile, Singa meander belt, Es Suki Scheme, Sennar reservoir. Mechanised Crop Production Schemes at lower centre and right. Mapping units include 122, 123, 231 and 232.

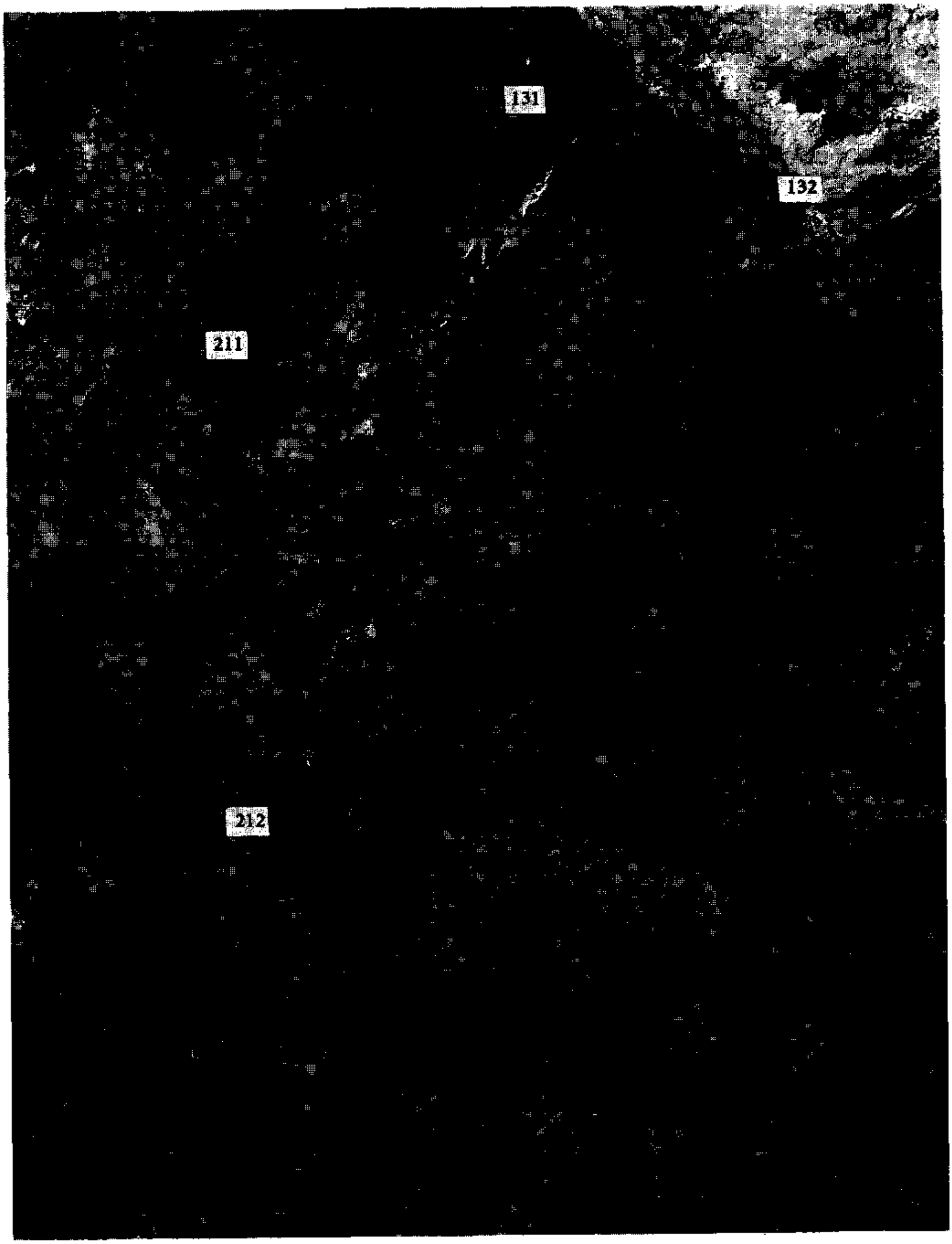


Photo 30: Satellite image Landsat-1, MSS Sensor 5, scale 1:1 000 000, winter 1972-'73. Khashm el Girba Irrigation Scheme, southern part, and Atbara river with reservoir and 'kerrib' land. Mechanised Crop Production Schemes in Gedaref clay plain and southern Butana. Mapping units include 131, 132, 211 and 212.

b. Information from soil survey reports and maps, publications, and M.Sc.-dissertations were added to the 1:250 000 topographic sheets.
c. Transparant positive prints of LANDSAT-1 satellite images (MSS 5) and diazo's (MSS 5, 6 and 7), both enlarged to a scale of 1:1 000 000, were projected onto the annotated 1:250 000 topographical map sheets. This enabled the drafting of boundaries between pedogeomorphic units that were traversed during the field trips.

The base map for this compilation study was an assembly of black-and-white photographs of the annotated 1:250 000 topographical map sheets, reduced to a scale of 1:1 000 000. The pedogeomorphic map was drafted on an overlay over this base map. As base map and enlarged satellite images were of the same scale, satellite image features could be compared to the draft map by direct superposition, using an overhead projector for the transparent satellite images. The map was then reduced to a scale of 1:2 000 000.

The accuracy of boundaries between mapping units is not the same for the entire map; it depends on how much, and the kind of information that was available. The reliability of pedogeomorphic boundaries has been assigned to three classes:
1. detailed information available from own soil surveys on a scale of 1:100 000; additional information available from other sources.
2. detailed information available along traverses; additional information available from other sources.
3. no information available from soil surveys or traverses; all information obtained from other sources.

A reliability map is given as an inset with the pedogeomorphic map.

The 1:2 000 000 scale sets some limitations: features such as inselbergs and hill groups, and the strip of 'kerrib' land along the main rivers, could only be delineated if they were of sufficient size.

6.3 Soil classification; taxonomy of representative profiles

For the terminology and classification of soils we used the system of the US Department of Agriculture, Soil Taxonomy (Soil Survey Staff 1975). This is a multi-categorical, comprehensive and natural system, devised for internal (USA) and worldwide use.

Of the ten classes of the highest category, the order, the following occur on the Central Clay Plain: Alfisols, Aridisols, Entisols, Inceptisols, Mollisols and Vertisols. Our study concentrated on Vertisols as these cover almost the entire clay plain.

We used the latest, amended version of the classification system (Soil Survey Staff 1990). The definitions of the Vertisols order and its four suborders, and also the criteria for defining soil families have remained unchanged since 1975; on the great group and subgroup levels there have been slight modifications. Vertisols are defined as follows (Soil Survey Staff 1975, p.376): 'Vertisols are mineral soils (....) that have 30 per cent or more clay in all horizons down to a depth of 50 cm or more; that at some period in most years have cracks that are open to the surface or to the base of a plow layer or surface crust and that are at least 1 cm wide at a depth of 50 cm unless the soil is irrigated; and that have one or more of the following characteristics:

1. Gilgai;
2. At some depth between 25 cm and 1 m, slickensides close enough to intersect; or
3. At some depth between 25 cm and 1 m, wedge-shaped (sphenoid) structural aggregates whose long axes are tilted 10 to 60 degrees from the horizontal.'

Of the four suborders (Xererts, Torrerts, Uderts and Usterts), only the Usterts are found on the Central Clay Plain. Usterts are defined as 'Vertisols that have cracks that remain open for 90 cumulative days or more in most years but that are closed for at least 60 consecutive days at a time when the soil temperature at a depth of 50 cm is continuously above 8 degrees Celsius (....).' (Soil Survey Staff 1975, p.379).

There are two great groups in the Usterts (Soil Survey Staff 1990): Chromusterts and Pellusterts. Chromusterts have chroma of 2 or more, Pellusterts have chroma of 1.5 or less in the upper 30 cm. Most of the Chromusterts and some of the Pellusterts of the Central Clay Plain belong to the subgroup that represents the modal soil of the great group, the Typic subgroup. These have a value of the moist colour throughout the upper 30 cm of less than 4, or a value of the dry colour less than 6. The Entic Chromusterts, which occur in the northern Butana and the Gezira fan, have higher values of the colour, that is: they are less dark. Entic Pellusterts, which occur on level or depressional sites, are defined in the same way.

On the family level most of the Vertisols belong to the very-fine particle-size class, the montmorillonitic mineralogy class, and the isohyperthermic soil temperature class. In short the meaning of these terms is, respectively : 60% or more clay in the fine-earth fraction (the fraction < 2 mm); the clay fraction (the fraction < 0.002 mm) has over 50% (by mass) of montmorillonite + nontronite, or there is more montmorillonite than any other clay mineral; mean annual soil temperature at 50 cm depth is 22°C. or higher, and the difference between the mean summer and mean winter temperatures at 50 cm depth differ by less than 5°C. (for the Sudan, summer is June to August, winter is December to February).

It is remarkable that even at the family level the majority of the Vertisols belong to one and the same class. This illustrates the rare, perhaps unique, occurrence of uniform soils over such an immense area. On the other hand, with another choice of diagnostic criteria, some of the differences that exist, would appear in the taxonomy.

Representative profiles of the main mapping units are listed in Table 6.1. Their location is indicated on the 1:2 000 000 geographic map (Appendix 3), except for those occurring in the Khashm el Girba and Southern Gedaref soil survey areas (nrs. 1 to 5, and 21 to 27, respectively). The latter profiles are to be found on the larger-scale soil maps of these areas (Figures 6.1, 6.3 and 6.4). The profile numbers are referred to in the text of section 6.4. Table 6.1 also shows the annual rainfall, the geographic region, the map unit on the 1:2 000 000 pedogeomorphic map, and the soil parent material.

6.4 The legend of the pedogeomorphic map 1:2 000 000

The Central Clay Plain consists largely of two geomorphic units, the Aggradational, and the Degradational clay plains, legend units 1 and 2, respectively. These clay plains have in common that they extend over large distances with very gradual changes in landscape, vegetation and soils. The aggradational plains consist of the Gezira fan, the adjacent Clay plain of Blue Nile, Dinder and Rahad, and the relatively small Clay plain of Atbara. The degradational clay plains are the Kenana clay plain and Manaqil ridge, and the Butana/Gedaref, the Abu Irwa and the Ethiopian foot slope clay plains.

The other geomorphic units are the much less uniform White Nile east bank plain (3); transitional areas where degradational clay plains are interrupted by Nubian sandstone outcrops and denudation surfaces (4), hilly and rocky land from igneous rocks (6), transitional areas between these and the degradational plains (5); Nubian Formation sandstone outcrops and denudation plains (7), and, finally, the Southern Clay Plain (8), an aggradational plain from the White Nile.

The geomorphic units 1, 2, 3 and 5 are sub-divided into geomorphic sub-units and most of these into pedogeomorphic units. Units 4, 6, 7 and 8 are not subdivided; these geomorphic units appear as mapping units.

In the following the numbers and names of the geomorphic units and sub-units, as they appear in the Legend, will be used as headings.

1 Aggradational clay plains

11 Gezira fan

The Gezira fan or Gezira clay plain is largely covered by the Gezira/Manaqil gravity irrigation scheme. Its origin as an alluvial fan is shown by the contour pattern (Fig. 2.5) and by a radiating system of palaeochannels (Fig. 4.3). The main irrigation canals are also aligned in a radiating pattern (see Appendix 3). The very slight and regular slope reflects the final stage of fan formation by a receding river system which deposits a uniform clay blanket over the fan. The clay mantle is thickest at the fan apex, and thins out towards the most northern and western ends of the fan. The Gezira fan slopes from 405 m at Manaqil to 380 m near Khartoum, a difference of 25 m over 170 km, or 0.15% (Williams et al. 1982). The clay plain is mapping unit 111.

Northwest of Wad Medani and west of El Hasaheisa parts of the main palaeochannels appear on the surface. These channels are conspicuous on satellite photos; they form uncultivated strips inside the irrigated area and form mapping unit 112. The largest of these palaeochannels ends in a triangular area that stretches towards the White Nile clay plain. This area, part of mapping unit 113, has a surface cover that consists of sandy to loamy Blue Nile fan deposits, with perhaps an admixture of sand blown in from the dunes along the White Nile east bank (mapping unit 312). On the 1:2 000 000 Geological Map of the Sudan (Fig. 3.1) this area is mapped as Alluvium, and is separated from the Gezira Formation.

Mapping unit 113 extends towards the northernmost part of the Gezira, north of the irrigation scheme. It is situatedbelow the 386 m contour, and partly below the 382 m contour, and was once part of the White Nile lake or of the floodplain of a gently flowing White Nile river (Berry 1962). However, it also includes clays of the Gezira fan, and has therefore been included in the Gezira fan. The sandy surface cover is probably derived from the bordering Nubian formation and/or from the White Nile dunes in the southwest. On the Geological Map this area is mapped as part of the Gezira Formation.

The soils of the Gezira Scheme have been extensively studied and described (Greene 1928; Jewitt 1955b; Ochtman 1963; Blokhuis et al. 1964; Nachtergaele 1976). Most of the soils are Entic or Typic Chromusterts, smaller areas are Pellusterts or intergrades between Chromusterts and Pellusterts. Profile GARS 141 (nr. 9) is representative of most of the Gezira soils prior to irrigation. It is a Typic Chromustert, belonging to the very-fine, montmorillonitic, isohyperthermic family, and is situated in a permanently non-irrigated and non-cultivated plot of the experimental area of the Gezira Agricultural Research Station (GARS). Nachtergaele (1976) described this soil as Suleimi series.

Soils in mapping units 112 and 113 are coarser-textured (loamy, sandy), and sometimes gravelly. Soils in the area south of Khartoum were studied during the field tour of the 5th International Soil Classification Workshop, in November 1982. They are Camborthids, Haplargids and Natrargids. Some have a clayey subsoil with a distinct vertic structure, and could be described as sand-covered Vertisols.

The Gezira fan contains three vegetation zones according to Harrison and Jackson's map (1958) (Chapter 2). Most of the area is now under cultivation, and the non-cultivated parts are strongly overgrazed and almost treeless. There are scattered trees of *Acacia nubica, Acacia seyal, Acacia mellifera* and *Balanites aegyptiaca* but most of the uncultivated parts are semi-desert plains with grasses and herbs.

The boundary of the Gezira clay plain (mapping unit 111) with the degradational plain and rocky outcrops of the Manaqil ridge (mapping unit 231) is marked by a sudden change in density and direction of the contours (Fig. 2.5.). The eastern boundary is along the 'kerrib' land of the Blue Nile (mapping unit 124). The western boundary, with the White Nile east bank plain (geomorphic unit 3), marks the transition from a gently downsloping area into a level floodplain; the soils are also quite different between these two mapping units.

12 Clay plain of Blue Nile, Dinder and Rahad

The extended and almost uninterrupted clay plain that stretches from east of the Rahad to west of the Blue Nile is a sedimentary plain of the rivers Rahad, Dinder and Blue Nile. The sediments belong to the Umm Ruwaba and Gezira Formations. Whiteman (1971) mapped this area as the El Atshan Formation. The surface sediments are similar to those of the Gezira fan, but the relief forms (Figures 2.2, 2.5 and 2.6) suggest that there have been differences in mode of deposition between the two plains.

The physiography of this clay plain is not uniform, but the differences, in most cases, are not matched by clear and consistent landscape boundaries (with the exception of the Singa meander belt (mapping unit 123) and the 'kerrib'-land of the Blue Nile (mapping unit 124)). The vastness of the clay plain is very seldom interrupted by inselbergs. A small group of isolated granite outcrops west of Abu Na'ama, and some hill groups east of the Blue Nile belong to the Basement Complex.

The clay plain proper (mapping units 121 and 122) has many of the characteristics of a river floodplain, and its gently undulating mesorelief is due to the presence of old stream channels, levees and backswamps. This topography can be clearly observed between Es Suki and El Hawata (along the Sennar-Gedaref railway line), and east of Abu Na'ama, between the Blue Nile and the Dinder. Abandoned meander courses between the Dinder and Rahad are described by Ruxton and Berry (1978). The macrotopography is apparently level, but the contour pattern (Fig. 2.6) shows that the plain is very slightly downsloping with the river, i.e. from SE to NW. We have no observations from the southern part of this clay plain, a sparsely populated area with few access roads. It is the site of the Dinder Game Reserve.

In the southeast the plain merges with a degradational clay plain below the Ethiopian hills: the Ethiopian foot slope clay plain (mapping unit 24). The boundary has been drawn along the line on the geological map which separates the Umm Ruwaba Formation from the Basement Complex and which roughly follows the 500 m contour.

Photo 31: Level site of the aggradational clay plain near Khor Simsim. The soils are Pellusterts, the trees are Acacia fistula.

On the Blue Nile east bank below Wad Medani, and east of the river Rahad, the clay plain is relatively narrow. The Blue

Nile east bank plain widens north of El Hasaheisa; this is the site of the Guneid Pump Scheme. East of the Rahad the plain includes the floodplain of Khor Simsim (section 6.5.2).

West of the Blue Nile the aggradational clay plain extends well into the Kenana area between latitudes 13° and 12° North. The boundary with the degradational Kenana clay plain (mapping units 232 and 233) is based on the contour pattern (Fig. 2.2) and on soil and vegetation differences. The soils on the level aggradational clay plain are mainly Pellusterts, with a characteristic dominance in the tree cover of *Acacia fistula* (Photo 31) (in addition to the ubiquitous *Acacia seyal*), whereas the soils on the gently undulating degradational plain are Pellusterts and Chromusterts, with *Acacia seyal* woodland. North of Sennar, the aggradational plain on the Blue Nile west bank merges with the Gezira fan.

Generally speaking, the soils of the Blue Nile-Dinder-Rahad clay plain are Typic and Entic Chromusterts and Pellusterts. Chromusterts are dominant, except for most of the area west of the Blue Nile. All representative profiles belong to the same family class: very-fine, montmorillonitic, isohyperthermic.

From north to south there are very gradual changes in soil profile morphology, that run parallel with equally gradual changes in rainfall and vegetation. The 600 mm isohyet (Fig. 2.8) separates the *Acacia mellifera* thornland from the *Acacia seyal-Balanites savannah* (Fig. 2.12). North of about latitude 13°30' surface soil colours are 10YR 3-4/3-4, south of this latitude they are 10YR-2.5Y 3/2. A similar difference exists between the soils of the Butana and Gedaref degradational clay plains. In the lower-rainfall zone, there is also a colour difference in the surface soil between aggradational and degradational clay plains, which disappears in the higher-rainfall zone; it is not found south of the Sennar-Gedaref railway line (section 7.3.4).

A separation of the Blue Nile-Dinder-Rahad clay plain in a northern part (mapping unit 121) and a southern part (mapping unit 122) is justified by the differences just mentioned. The profiles Sennar 49 (nr. 10), a Typic Chromustert and Sennar 71 (nr. 11), an Entic Chromustert are representative of mapping unit 121; Jebel Abel (nr. 12), an Entic Chromustert, Tozi (nr. 13), an Entic Pellustert and Damazeen (nr. 14), a Typic Chromustert, of mapping unit 122.

Some parts of the clay plain have been studied in detail: the sites of the proposed agricultural research stations at Sennar (in mapping unit 121) and Abu Na'ama (mapping unit 122), both on the Blue Nile westbank.

The soils at the Sennar site (13 250 hectares) are very uniform: the mapping units of the 1:40 000 soil map were three phases of one soil series, defined at the depth where gypsum crystals appeared. This depth increases west to east from 65 to 120 cm or more, following a slight upslope towards a Nubian Sandstone Formation outcrop. Sennar 49 (nr.10) is a representative profile, a Typic Chromustert, with a surface soil colour of 10YR-2.5Y 3/2. Sennar 71 (nr. 11), an Entic Chromustert, is situated in a ponded area.

The Abu Na'ama site (850 hectares) is even more uniform: the detailed soil map (1:20 000) shows no soil boundaries: all soils belong to one soil series. The surface soil colour is 10YR-2.5Y 3-4/2. There is no gypsum in the Abu Na'ama soils.

West of Singa is an area with abandoned meander courses, loamy and sandy levees and clayey backswamps, which has been separately mapped as the Singa meander belt (mapping unit 123). Nowhere else along the present Blue Nile valley is a similar extensive occurrence of abandoned meander courses.

The strip of land immediately bordering the Blue Nile is mapped as 'kerrib'-land (mapping unit 124). 'Kerrib' or 'karab', literally 'waste', is the Arabic word for the strongly eroded and dissected riverbanks. The mapping unit, however, includes other features of a recent floodplain : old meanders on the inside of bends, now the site of pools ('maiyas') where water stands for most of the year and which have a characteristic vegetation of *Acacia arabica.* Along the Dinder and Rahad rivers the 'kerrib' zone is too narrow to be mapped. The rivers are much smaller than the Blue Nile and less deeply incised into the clay plain (no more than 5 m, according to Ruxton and Berry (1978)). The 'kerrib' is not continuous; on some undercut outer bends the river channel cuts directly into the adjacent clay plain (Gunn 1982).

13 Clay plain of Atbara

On the west bank of the Atbara, between Khashm el Girba and approximately latitude 16° North, an alluvial clay plain (mapping unit 131) has formed with a width varying between 15 and 35 km. It also extends east of the Atbara river (Van der Kevie and Buraymah 1976). The western boundary, with the Butana degradational clay plain, is well-defined by a change in degree and direction of slope (Fig. 2.4), and in substratum properties of the soils.

North of latitude 16° North, sedimentation has been less, and the surface material has an admixture of sand from nearby Nubian sandstone surfaces (mapping unit 7). This northern part of the Atbara clay plain has been mapped as clay plain/Nubian Formation transitional zone (mapping unit 133).

The 'kerrib'-land of the Atbara (mapping unit 132) is a zone of strongly gully-eroded riverbanks several kilometres wide. The Atbara river has incised deeply into its older, coarser-textured strata. At Showak the incision is 50 m deep (Hurst 1952), and several terrace levels can be distinguished. A recent floodplain - a characteristic feature of what has been mapped as the Blue Nile 'kerrib' - is not present. The Atbara flow is strongly seasonal: a wild, muddy river in the rainy season, and nothing more than a series of pools in the dry season.

Between latitudes 15° and 16° North the soils of the Atbara clay plain have been mapped on a scale 1:100 000 (Blokhuis 1963; Blokhuis et al. 1964 ; Ochtman 1965). The clays are similar to those of the Gezira fan, but less deep. Representative profiles are Khashm el Girba 213 (nr.1), 215 (nr.2) and 238 (nr.4), all three Typic Chromusterts, very-fine, montmorillonitic and isohyperthermic. The soil survey of Khashm el Girba South is discussed in section 6.5.1.

2 Degradational clay plains

21 Butana/Gedaref clay plain

The Butana/Gedaref clay plain comprises a vast area east of the Blue Nile-Dinder-Rahad clay plain. Hilly regions and groups of inselbergs that interrupt the uniformity of the plain, are singled out as units 511 or 512, if they are of sufficient size. Basalt ridges with associated soils (mapping unit 52) separate the Gedaref clay plain (mapping unit 212) from the Abu Irwa clay plain (mapping unit 22).

The boundary between the Butana degradational and the Atbara aggradational clay plain is distinct in the contour pattern. In the field, this boundary can hardly be recognized, but there is a difference in the colour of the surface soil. The soils of the degradational plain have a lower chroma than those of the aggradational plain; surface soil colours are 10YR 3-4/2 and 10YR 3-4/3-4, respectively.

The boundary between the Gedaref clay plain (mapping unit 212) and the Gedaref basalt landscape (mapping unit 52) is distinct; it has been traced along the lower margins of the foot slopes of the basalt ridges.

In the south, the Gedaref clay plainstretches into Ethiopia.

The boundary with the Blue Nile-Dinder-Rahad clay plain is marked by a similar difference in contour pattern as the boundary with the Atbara clay plain. In addition, north of 13°30' latitude there is the same difference in surface soil colour between degradational and aggradational plains as described above for the Butana and Atbara clay plains. South of 13°30' North the degradational and aggradational clay plains have the same surface soil solour.

The boundaries with the Nubian sandstone landscape (mapping unit 7) and with a landscape characterized by an alternation of Nubian Sandstone outcrops and clay plains (mapping unit 4) are distinct.

A division between Butana and Gedaref plain is based on the following observations:

- the Gedaref clays have developed partly from Basement Complex rocks and partly from basalt, whereas the Butana clays have developed entirely from Basement Complex rocks.
- the Gedaref clay plain contains more hill groups and rocky outcrops and, as a result has a stronger, and more varied relief.
- the Butana plain is largely a grass plain, with annual herbs and short grasses in the north, tall grasses in the central part, and tall grasses mixed or alternating with *Acacia mellifera* thickets in the south. The Gedaref clay plain is an *Acacia*

seyal-Balanites savannah in the north, and an *Anogeissus-Combretum hartmannianum* savannah woodland inthe south.

- the surface soil colours (at approximately 10 cm depth) in the Butana clay plain are from 10YR 4/2 in the north, to 10YR 3/2 in the south. In the Gedaref clay plain 10YR 3/2 remains the dominant colour over most of the plain, but there is often a tendency towards a hue of 2.5Y. The chroma tends to be lower in ponded areas and in soils developed in basaltic parent material. In Soil Taxonomy terms: Entic Chromusterts in the north of the Butana, Typic Chromusterts in central and southern Butana and in most of the Gedaref plain, Chromustert/Pellustert intergrades and Pellusterts in some parts of the Gedaref clay plain.

In the Butana clay plain (mapping unit 211) a range of inselbergs, stretching from Sufeya past Reira in a southeasterly direction, forms the divide between the Rahad/ Blue Nile and the Atbara. Apart from inselbergs and hill groups, the Butana is a very gently undulating plain with slopes not exceeding one degree. The grass patterns and herb patterns that run parallel with the contours are characteristic (Chapter 5).

Over most of the Butana the surface mulch of the Vertisols is strongly developed, 3 to 10 cm thick, obscuring some or all of the surface cracks. Certain microrelief features - unevenness, sink holes and other signs of subsidence (Berry 1970) - are found, but there is no gilgai microrelief. Pebbles and gravel, often quartz fragments, are common on the soil surface, notably in wide areas around inselbergs.

Representative profiles are Jebel Qeili (nr.6) in the north, and Khashm el Girba 251 (nr.3) and 256 (nr.5) immediately west of the Atbara alluvial plain. Jebel Qeili is an Entic Chromustert, fine, montmorillonitic, hyperthermic, the two Khashm el Girba soils are Typic Chromusterts, very-fine, montmorillonitic, isohyperthermic.

The Gedaref clay plain (mapping unit 212) is gently sloping from northeast (the Gedaref-Gallabat ridge) to southwest (the Rahad valley) (Fig. 2.3). Superimposed are gentle undulations related to the inselbergs and hill groups.

Rocky outcrops and non-rocky elevations are common. Red-black soil catenas occur, most distinctly on basic rocks. Rocky areas are mapping unit 512, but most of them are too small to be shown on the map.

There are no grass patterns. Gilgai microrelief is often distinct on the clay plains: normal gilgai on datum sites (Photo 32), lattice - sometimes wavy - gilgai on gently sloping terrain (Photo 34).

The Umm Simsim and Umm Seinat soil survey areas (Ilaco/Nedeco 1966) are part of the Gedaref clay plain. Representative profiles of the Gedaref clay plain are taken from the soil survey areas: Simsim B27 (nr.21), and Seinat B7, B10, B47, B48, B50 and B55 (nrs. 22 through 27). The soils are discussed in detail in section 6.5.2.

22 Abu Irwa clay plain

East of the Gedaref-Gallabat ridge is a clay plain that we have named Abu Irwa clay plain after the 1:100 000 soil survey of the Abu Irwa Mechanized Crop Production

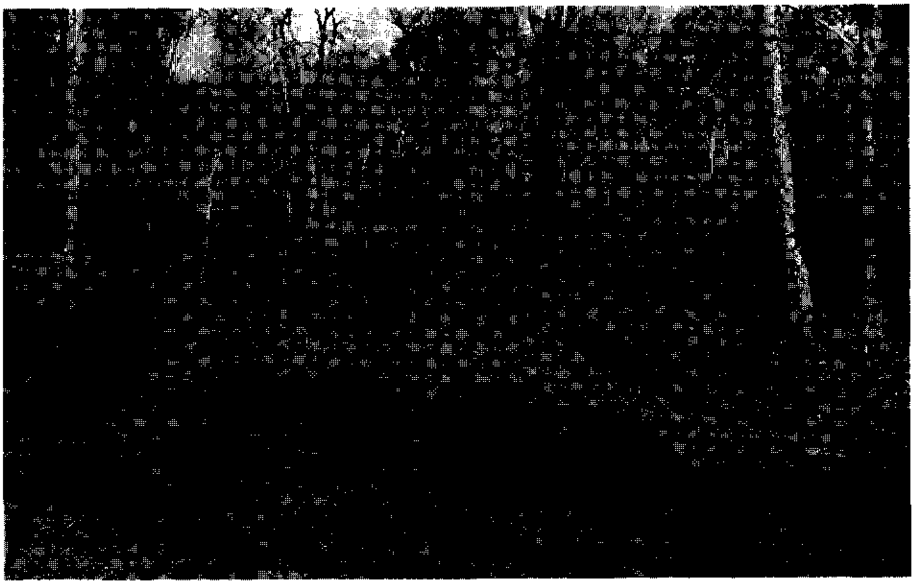


Photo 32: Normal gilgai, shown by the curved shadow line of trees. The vegetation is Acacia seyal - Balanites *savannah. Gedaref clay plain.*

Photo 34: Wavy gilgai with white carbonate nodules and quartz gravel on the microridges. The vegetation includes the white-barked Acacia fistula *and* Acacia seyal. *West of Jebel Mufwa, southern Kenana.*

Scheme (MCPS) by Beinroth and Duemmler (1964). The parent material of the soil is a black basaltic rock. On the higher-lying, more rocky parts of the area, the soils have formed 'in situ' in a clay derived from basalt weathering. In the lower and more level parts of the plain, soils have formed on colluvio/alluvial clays. The soils are Pellusterts and Chromusterts, and intergrades between these great groups.

The geological map shows that the Gedaref-Gallabat ridge rises from a Nubian Sandstone Formation surface. The latter does not outcrop: it is entirely covered by clays weathered from the basaltic rocks.

23 Kenana clay plain and Manaqil ridge

The Kenana stretches over a distance of about 600 km north to south; from east to west it varies in width from about 80 to 140 km. There are gradual changes in vegetation and soils from north to south, similar to those in the Blue Nile-Dinder-Rahad and the Butana/Gedaref clay plains. The isohyets (Fig. 2.8) run roughly NNE-SSW, and the vegetation zones follow this pattern: *Acacia mellifera* thornland alternating with grass areas in the north and west, *Acacia seyal-Balanites* savannah, alternating with grass areas in the central area, from Singa to south of Kurmuk, and *Anogeissus-Combretum hartmannianum* savannah woodland in the southeast (Fig. 2.12).

The northernmost part of the geomorphic sub-unit is the Manaqil ridge (mapping unit 231), around which the Gezira fan has formed. On the Manaqil ridge there are some outcrops of Nubian sandstone (geomorphic unit 7) surrounded by sand-covered clay soils. Most of the Vertisols of the Manaqil ridge have a relatively high value of the colour: 10YR 4/2 (Entic Chromusterts). The Manaqil ridge is distinct from the northern Kenana in geomorphology, soil parent materials and soils.

The sub-division of the Kenana in a northern and southern part (mapping units 232 and 233) is based on relief, on the relative coverage by inselbergs and hill groups, and on soil differences. The boundary between the northern and southern Kenana is an east-west line at the latitude of Jebel Mazmum. However, the entire area between the latitudes of Jebel Mazmum and Jebel Guli can be considered as a transitional zone. The southern Kenana landscape, clearly different from that of the northern Kenana, is only found south of the latitude of Jebel Guli.

The overall impression of the northern Kenana is of a flat, featureless plain with a few inselbergs and inselberg groups (Photo 33). In fact the area is very gently undulating, and the inselbergs rise from the highest positions of the plain (Fig. 2.2). The western part slopes down towards the White Nile valley. 'Khors' are few and indistinct. Gravel and stones occur scattered on the surface locally. A weakly developed gilgai microrelief is present only in the southeastern part; it is of the normal type on datum sites, and of the lattice or wavy type on gentle slopes.

The boundary with the Blue Nile-Dinder-Rahad clay plain is indistinct; it is traced on the basis of the contour pattern (Fig. 2.2): along the 470 m contour east of Jebel Mazmum, the 440 m contour east of Jebel Dali, and at the 465 to 445 m contours in between. It separates an area where slopes are related to the Blue Nile valley and are very slight, from an area where slopes are related to inselbergs and are slightly steeper.

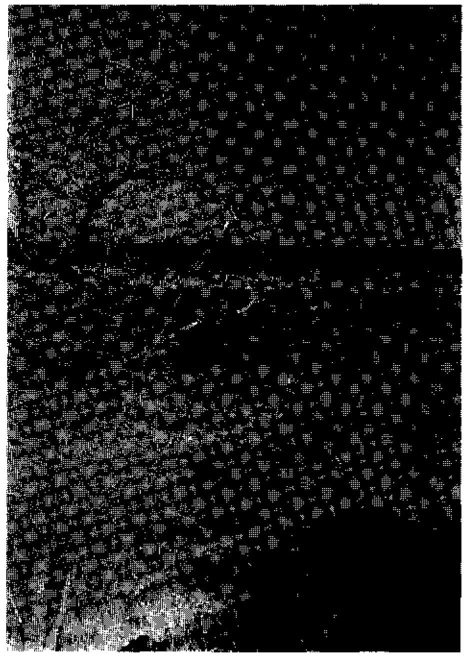


Photo 33: Northern Kenana landscape; view from small inselberg over Acacia seyal - Balanites *savannah alternating with grass areas.*

The boundary with the White Nile east bank plain (geomorphic unit 3) is also based on relief differences: the Kenana plain which slopes down towards the White Nile, and the almost perfectly level White Nile valley. Sandy ridges mark some parts of the boundary; these are probably the beach ridges of the former White Nile lake. The boundary is traced along the 386 m contour - the highestlevel of the Pleistocene lake - or, east of it, along a distinct line on the satellite image, which also occurs on the Hunting/MacDonald (1963-1967) soil maps. There is also a difference in surface colours of the Vertisols, Pellusterts being typical of the White Nile east bank clay soils and Chromusterts of the Kenana plain.

The Chromusterts of the northern Kenana have a characteristic surface colour of 10YR 3/2, sometimes with a tendency towards 2.5Y 3/2. Pellusterts are rare. A representative profile of mapping unit 232 is Bozi (nr. 15), a Typic Chromustert, very-fine, montmorillonitic, isohyperthermic.

The southern Kenana is a gently undulating plain with long slopes that are related to rock outcrops, often inselbergs or groups of inselbergs. Many of these outcrops are intrusive rocks of the Basement Complex. The largest hill group, the Ingessana hills, is mapped separately; it belongs to mapping unit 512.

In the southern Kenana clay plain, 'khors' and 'wadis' are more distinct than in the northern Kenana. On the clay plain they run in wide valleys between long and gentle slopes. Near inselbergs and in hilly areas they are often deeply incised or form wide sandy beds. Over large areas of the clay plain, gravel and pebbles are widespread on the surface, especially on the highest parts of the landscape. The gravel often consists of quartz fragments, that are probably remnants of the quartz-dykes originally present in the metamorphic rocks from which the sediments derived. Near Jebel Gerawid- a foliated basic rock - and near some other inselbergs, laterite gravel is found on the surface. There is usually a distinct gilgai microrelief. It is of the normal type,but on sloping terrain there is distinct wavy gilgai. Lattice gilgai occurs on slight slopes. The gilgai mounds have much quartz gravel and large,white carbonate nodules on the surface (Photo 34).

The area south of Khor Yabus was flooded at the time of our visit, and inaccessible. The satellite images and the 1:250 000 topographic map show no rock outcrop or hill group. This is probably a colluvio/alluvial plain related to the hills and mountains along the Sudan/Ethiopia border.

Photo 35: Southern Kenana landscape with red-black soil catenas. The hills in the background are mapping unit 512.

In the west, the southern Kenana clay plain borders on the White Nile east bank plain (geomorphic unit 3) and, more to the south, on the Southern Clay Plain (geomorphic unit 8). The boundary with the White Nile plain is similar to that between the northern Kenana clay plain and the White Nile plain. The boundary with the Southern Clay Plain is drawn between non-swampy areas (Central Clay Plain) and areas flooded over a considerable part of the year (Southern clay plain). Most of the flooded area belongs to the aggradational plain of the White Nile system, but the eastern fringes receive floodwater and sediment from smaller rivers which drain the Ethiopian border hills, traverse the southeastern part of the Kenana plain and end in swamps west of it that form part of the Southern Clay Plain.

The soils show more variation than in the northern Kenana: Chromusterts are dominant, with the characteristic colour of 10YR-2.5Y 3/2, but large areas with Pellusterts occur, mainly in depression sites. Many soils belong to Pellustert/ Chromustert intergrades. In some of the hilly areas, for example between Ulu and Jebel Mufwa, catenary successions of red and black soils occur (Photo 35). Pellusterts developed 'in situ' from basic rock are found on distinct slopes (Chapter 7). Such areas are in fact more like mapping unit 512, but their size does not allow separate delineation on the map; profile Boing (nr. 18) is representative of such a site. Profile Khadiga (nr. 17) is a Chromustert developed 'in situ' from basic rock on a foot slope site. Ulu (nr.16) and Renk (nr.19) are Typic Chromusterts on clay-plain sites.

Bordering the White Nile plain is a relatively small area, mapped as unit 234, where clay plains alternate with sandy and gravelly ridges and sand sheets. Similar sandy ridges often mark the eastern boundary of the White Nile plain (see above), but this is not the case here: the White Nile plain is more to the west, and the clays that flank the ridges have the characteristics of southern Kenana clays. The geological map gives the area as part of the Umm Ruwaba formation. Perhaps the sandy and gravelly surface deposits are reworked coarse-textured strata of that formation.

24 Ethiopian foot slope clay plain

We have no field observations of mapping unit 24, the Ethiopian foot slope clay plain. The unit is introduced because of the logic of the presence of a foot slope plain between the Ethiopian volcanic mountains and the aggradational Blue Nile-Dinder-Rahad clay plain. Its boundaries are based on the geological map - more or less following the Basement Complex/Umm Ruwaba boundary - and on the 1:250 000 topographic map - following the 500 m contour, which more or less separates areas with and without inselbergs. Williams et al.(1975) mention clay plains adjacent to the Ethiopian border that have the characteristics of piedmont alluvial plains.

3 White Nile east bank plain

North of Kosti the White Nile is a reservoir lake that has drowned the original floodplain. The dam site is at Jebel Auliya. The level of the reservoir lake changes little during the year. The White Nile eastbank alluvial sediments have an admixture of surface wash from the Kenana, the Manaqil ridge and the Gezira fan. The maximum extent of former White Nile flooding is shown by beach ridges at 382 and 386 m (Berry 1962). The 386 m terrace is not distinct (Berry 1962), but the 382 m terrace is locally present, and the boundary between the White Nile plain and Manaqil ridge/ Gezira fan is traced along this contour. The boundary is faint where coarse-textured Blue Nile deposits (mapping unit 113) border onto sand dunes alternating with clay flats in the White Nile east bank plain (mapping unit 312). South of this area mapping unit 311 contains few sand dunes; typical White Nile clays are dominant here. Adamson et al. (1982) suggested that the sand dunes were formed from sandy Blue Nile sediments. Previously it was thought that the sand had come from 'qoz' areas or Nubian sandstone outcrops west of the White Nile valley.

South of Kosti the 386 m level is a continuous feature as far as Melut. The 386 m contour is taken as the boundary with the Kenana plain. It shows up very clearly on satellite images. The road connecting the towns and villages on the White Nile east bank south of Kosti is on a sandy, sometimes gravelly ridge. East of the ridge is the higher-lying terrace, west and at a lower level the present floodplain. Gunn (1982) describes this ridge as an old levee, with sand or gravel layers at depths of 120 cm or deeper. Further to the south the floodplain merges with the permanent swamps known as 'sudd'.

There are gradual but distinct differences between the soils north and south of Kosti. North of Kosti (mapping unit 311) the clays are mixed with or covered by sand; Vertisols are of limited occurrence, and most soils are vertic intergrades towards Aridisols and Inceptisols (Purnell et al. 1976). The Vertisols are more strongly saline and sodic when compared with the soils of the adjacent Gezira fan (Williams 1968), and are often very calcareous. In mapping unit 312 sandy clay flats alternate with stabilized sand dunes.

South of Kosti Pellusterts dominate (mapping unit 32). These soils are described by Purnell et al. (1967). The hues of the colour change from 10YR via 2.5Y to 5Y when going south, and a gilgai microrelief is common. Vertisols with much sand - flanking the ridges on the eastern boundary - often have a surface crust and a gilgai microrelief with a low vertical interval and a great wave length. We found similar surface and microrelief features in the sandy Vertisols in the southern Gedaref area (section 6.5.2.).

4 Degradational clay plain and Nubian formation transitionalzone

In the western Butana outcrops of Nubian sandstone - generally low rises with red, sometimes gravelly, sandy soils - alternate with clay plains. There are wide transitional zones with sandy or sand-covered clay soils.

Most of the Nubian outcrops are distinct in the field, from the air, and on satellite imagery. Some, however, are indistinct, and others too small to be shown on the 1:2 000 000 map. It was therefore necessary to create a mapping unit that is an association of 211 and 7.

The Vertisols in this association are no different from those in the bordering mapping unit 211: in the north Entic Chromusterts, in the south Typic Chromusterts. There is often a distinct change in chroma of the surface soil colour between the degradational Butana clays (chroma 2) and the adjoining Blue Nile clays (chroma 3 or 4), and this difference has been used - together with landform and slope - for defining the western boundary of geomorphic unit 4.

The Nubian sandstone outcrops have a characteristic grass vegetation with *Aristida ssp.*, *Schoenefeldia gracilis* and others, which is different from the grass cover of the clay plains, where *Setaria ssp.* dominates in the north, and *Sorghum ssp.*, and *Cymbopogon nervatus* in the south.

5 Clay plains and igneous rock outcrops and hills

51 Basement Complex landscape

In the Butana/Gedaref clay plain and the southeastern Kenana outcrops of Basement Complex rocks cover considerable areas.

In the Butana many of the hill sides are bare, especially those of the steep-sided inselbergs, that often consist of intrusive rocks. Sandy Entisols and Aridisols occur on the foot slope, and Chromusterts on the plains.

In the higher-rainfall regions stronger weathering and denser vegetation have produced and maintained a thicker soil cover with well-developed Alfisols and Tropepts on hillslopes, and Vertisols on foot slopes, on flats, and in depressions. In landscapes developed from acid or intermediate rock, Vertisols are limited to plains and depressions, whereas in landscapes developed from basic rocks Vertisols also cover foot slopes, and sometimes hillslopes and summits. Examples are profiles Khadiga (nr. 17) and Boing (nr. 18).

Because of the great differences in landscape formation between lower-rainfall and higher-rainfall regions, two map units (511 and 512) have been distinguished.

The largest occurrence of the lower-rainfall mapping unit (511) is the area between the Butana clay plain and the Nubian sandstone landscape (mapping unit 7) north of it. It is characterized by low, gently sloping hills or merely rocky and stony rises with long, very gently sloping pediments that merge with clay plains. Vertisols are limited in extent and are often sandy. The soil surface is covered with stones and gravel, often quartz fragments. The grass cover is distinctly different between sandy and clayey soils, and characterized by the same species as described for mapping unit 4. There are wide, shallow wadis with well-defined incised khors. The soils are Entisols, Inceptisols and Aridisols, with few Entic Chromusterts.

A similar landscape stretches from Reira to beyond Husheib (in the Butana plain) and forms the Blue Nile-Atbara divide. Smaller areas are the Jebel el Fau group and a group of hills east of it.

The higher-rainfall variant (mapping unit 512) forms a transitional zone in the southwest between hills and rock land on the Sudan/Ethiopia border (mapping unit 6)and the degradational clay plains of southern Kenana (mapping unit233) and Ethiopian foothills (mapping unit 24).

Another occurrence is that of the Ingessana Hills (Photo 36) which consist mainly of ultrabasic rocks and serpentinites (Geological Map of the Sudan, 1:2 000 000). These form a ring of low hills alternating with undulating plains, and clay plains inside and outside the hill range; the latter merge with the Southern Kenana clay plain. The soils are members of a catena which consists of:

Photo 36: Ingessana Hills, a Basement Complex landscape of ultrabasic rock (mapping unit 512) in the southern Kenana.

a. Hillside slope: shallow, generally sandy soils;
b. Upper foot slope: reddish/yellow, gravelly, sandy/loamy soils; the soil surface is covered with iron-coated quartz fragments;
c. Lower foot slope: reddish/brown clays or clay loams;
d. Undulating clay plain.

Vertisols on the clay plains in mapping unit 512 have a surface soil colour of 10YR 3.5/1 or 2.5-5Y 3/2. The soil surface is strewn with stones and boulders, carbonate-coated rock fragments and calcareous glaebules. Locally there is a weakly developed gilgai microrelief. The catena is similar to what has been described by Greene (1948) as the 'alkaline catena'. On the hillslopes and foot slopes there is savannah woodland with as the main trees: *Anogeissis schimperi*, *Boswellia papyrifera*, *Combretum hartmannianum*, *Adansonia digitata*, *Hyphaene thebaica*. *Anogeissus*, *Boswellia* and *Combretum* also occur on the alluvial clay plains, together with *Balanites aegyptiaca* and *Acacia seyal*.

52 Tertiary basalt landscape

The basalt landscape consists of the Gedaref-Gallabat ridge, and of a relatively high-lyingplain with basaltic outcrops from Gedaref to Showak. Between Gedaref and Gallabat are several sub-parallel ridges and some isolated hills of basalt. Nubian sandstone outcrops occur in the extreme southeast of this ridge, between Tamra and Basunda (not on the 1:2 000 000 map).

The smooth-shaped basaltic ridges are often entirely covered by Chromusterts with a surface soil colour of 5YR 3/2 and 7.5YR 3/2. The soil surface is mantled with stones (Photo 27). Locally, Pellustert/Chromustert intergrades occur on elevations, and Pellusterts with chroma 0.5 or neutral are found on the plains between the elevations and near 'khors', in depressions. The vegetation has a similar tree cover as in map unit 512.

A soil survey on a scale 1:100 000 was made by Knibbe (1964) of an area around Er Rawashda, about 20 km east of Gedaref. The clays overly basaltic rock, locally at a depth between 100 and 200 cm, but generally deeper than 200 cm. Some soils have developed 'in situ', others are colluvio-alluvial, developed in weathering debris of the basaltic rock. The relief of the landscape is strongly related to the surface configuration of the underlying rock. Basaltic fragments are scattered on the surface. The soils on the clay plains are mainly Pellusterts, whereas both Chromusterts and Pellusterts are found on the stone-covered pediments of the low basaltic hills, for example profile Er Rawashda (nr. 7), a Typic Pellustert, very-fine, montmorillonitic, isohyperthermic.

6 Hills and rock land associated with igneous rock

Geomorphic unit 6 comprises the hills and rock land bordering the southeastern part of the Central Clay Plain. Most of this unit is in Ethiopia. The area has not been traversed, and information is entirely drawn from the 1:250 000 topographical maps, from satellite imagery and from Vail's (1978) geological map, which includes the areas bordering the Sudan. On Vail's map, most of the area of unit 6 is indicated as undifferentiated Basement Complex, and a small part as volcanic rock, mainly basalt.

7 Nubian Formation sandstone outcrops and denudational plains

At about latitude 16° North, the Butana clay plain changes abruptly into a Nubian sandstone desert denudation surface. The Nubian Formation consists of siltstones, mudstones, gravels, sands and conglomerates, and most of it weathers into a gravelly sand or loamy sand, with quartz gravel. There is insufficient weatherable material that can produce a clay. Landscape evolution in this area has created an undulating terrain with low ridges and rises, covered with gravel and stones (conglomerates, quartz, often red-coated) and yellow-red to pink-red sandy soils. Khors and wadis are more distinct than on the clay plains. Main tree species are *Acacia raddiana, Acacia tortilis* and *Acacia nubica.* Grasses include *Aristida ssp.* and *Schoenefeldia gracilis.*

Some isolated Nubian formation outcrops occur on the Manaqil ridge.

The extensive plains associated with the White Nile and tributaries in the southern Sudan, and stretching towards the plateau and hill region of Equatoria province, are generally referred to as the Southern Clay Plain. According to Jewitt (1955a) the main differences between the Central and Southern Clay Plains are: the former has more uniformly fine-textured soils, and flooding is limited, whereas the latter has many areas with coarser-textured soils, and is largely subject to flooding.

The border area between the southern Kenana clay plain and the Southern Clay Plain is a zone of very gradual changes. Away from this zone the differences between the two clay plains become apparent. We traversed the area from El Gelhak on the White Nile to Boing and Khadiga on Khor Yabus, in the southern Kenana clay plain. Along this traverse are clay plains alternating with loamy to sandy areas. The clay flats are either grass plains (Photo 37) or have an *Acacia seyal-Balanites* savannah vegetation, the coarser-textured soils have *Anogeissis schimperi, Combretum hartmannianum* and other broad-leaved trees (Photo 38). The clay flats are subject to flooding, the grass plains for longer, the *Acacia*-savannahs for shorter periods. Flooding apparently also spreads over the sandy flats too, as the trees are often confined to termite mounds, a typical feature of the 'toich' lands (grasslands subject to seasonal flooding), which border the 'sudd' areas of permanent swamps. The Southern Clay Plain is probably entirely a plain of fluvial aggradation.

The representative profile El Gelhak (nr.20), a Udic Pellustert is situated about 90 km southeast of the small White Nile east bank town El Gelhak.

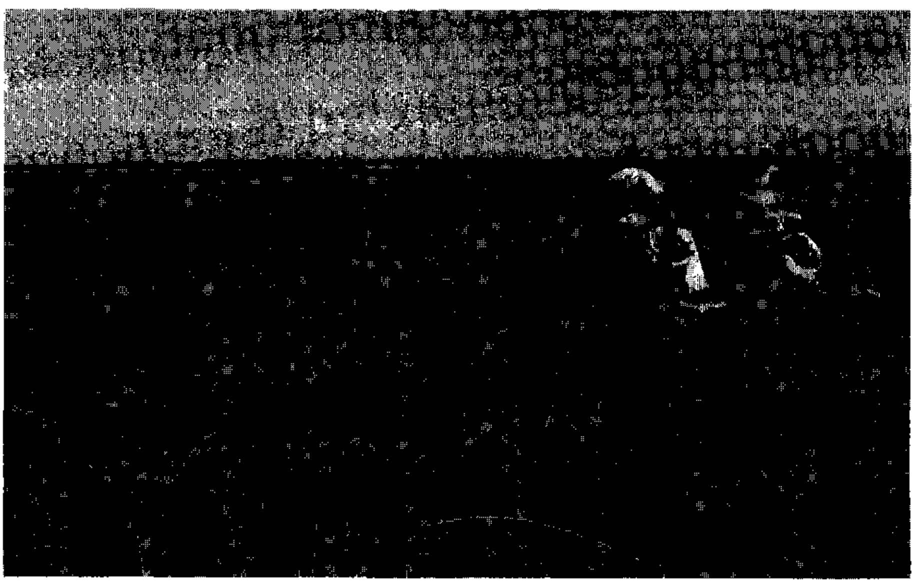


Photo 37: Clay flat of the Southern Clay Plain. This is the location of profile El Gelhak (nr.20). In the background Acacia seyal *woodland.*

Photo 38: Sandy/loamy area in the Southern Clay Plain between the site of profile El Gelhak and Khor Yabus. Trees include Anogeissus schimperi *(the large trees on termite mounds) and* Balanites aegyptiaca.

6.5 Soil surveys of key areas

6.5.1 Khashm el Girba South

Two semi-detailed soil surveys, scale 1:100 000, were conducted on the clay plain of the Atbara (geomorphic sub-unit 13):Khashm el Girba North, between latitudes 15°30' and 16°00' North (Ochtman 1965), and Khashm el Girba South, between latitudes 15° 00' and 15°30' North (Blokhuis 1963). The eastern boundary of the area to be surveyed was the 'kerrib' land of the Atbara (Photo 39), whereas the western boundary was based on commandability of the area by gravity irrigation from a reservoir above a dam in the Atbara, near the town of Khashm el Girba. In the following we will discuss landscape and soils of the Khashm el Girba South area, and compare these - where relevant - with similar features in Khashm el Girba North.

The soil survey was based on the interpretation of aerial photographs 1:22 500 and field work, including detailed studies of two sample areas.

Average annual rainfall decreases from South to North, and shows a great variationfrom year to year. This is well-illustrated by the data of four consecutive years at Khashm el Girba (latitude 15°N) and Qoz Regeb (latitude 16°N) (Table 6.2).

Table 6.2: Monthly and annual rainfall 1960-1963 of Khashm el Girba (lat. 15° North) and Qoz Regeb (lat. 16° North) in millimeters (after Ochtman 1965)

Month	Khashm el Girba				Qoz Regeb			
	1960	1961	1962	1963	1960	1961	1962	1963
May[1]	11.0	0.0	0.0	0.0	0.0	0.0	0.0	5.0
June	12.0	0.0	1.0	0.0	tr	25.0	0.0	7.0
July	96.0	179.0	106.0	33.4	7.0	196.0	107.0	52.0
August	84.0	163.0	113.0	125.5	37.0	135.0	128.0	53.0
September	97.0	18.0	69.0	38.0	66.0	?[2]	35.0	tr
October	0.0	0.0	0.0	1.5	0.0	0.0	5.0	0.0
November	0.0	0.0	0.0	3.5	0.0	0.0	0.0	0.0
Year	300.0	360.0	289.0	201.9	110.0	(356.0)	275.0	117.0

[1] no rainfall in December to April

[2] no readings available

Khashm el Girba South is an apparently level and uniform clay plain, gently and regularly downsloping from southeast towards northwest, with a gradient of 0.05%, and situated at elevations between 470 and 440 m. There are a few inselbergs of Basement Complex rock. Some of these are dome-shaped granitic intrusive rocks with spheroidal weathering, others are hill ridges with gentle slopes covered withangular quartz stones and gravel. Immediately west of the Atbara clay plain the landscape rises towards the southwest and the gradient is stronger, 0.14%.

There are two vegetation units according to the classification of Harrison and Jackson (1958). The northern part is semi-desert grassland on clay, the southern part is *Acacia mellifera* thornland alternating with grass areas (Fig. 2.12). *Acacia mellifera* is also found in the semi-desert grassland area on moisture receiving sites, such as slight depressions and 'khors'. In the semi-desert grassland there is an alternation of areas with short grass (*Setaria ssp.* as dominant species (Photo 40)) and adjoining sites where the vegetation consists dominantly of annual herbs (Photo 41). The boundaries between grass and herb areas vary from abrupt to diffuse. Abrupt boundaries were at the same location during four consecutive years of observation, whereas diffuse boundaries changed from year to year. In areas with diffuse grass/herb boundaries, *Setaria* forms a dense stand locally in a particular year, and occurs sparsely the following year, its place being taken by annual herbs. Other aspects of the vegetation also change over the years. In years of high rainfall the tall grasses *Cymbopogon nervatus* and *Sorghum ssp.* - that occur locally in the *Acacia mellifera* belt - penetrate well into the *Setaria* short grass/annual herbs area.

Photo 39: Dry bed of the Atbara river and adjoining 'kerrib' land. Trees are Balanites aegyptiaca *and flat-topped* Acacia raddiana *or* Acacia tortilis.

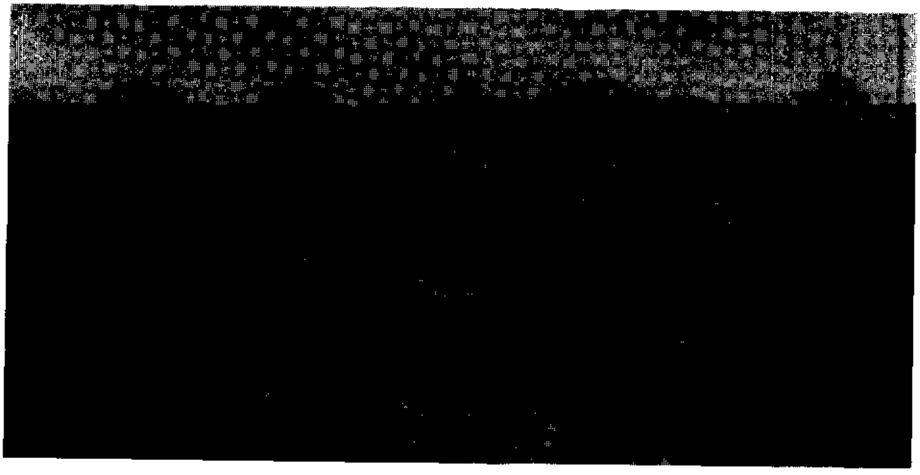


Photo 41: Annual herbs area in the dry season, Khashm el Girba North. The inselbergs of the Jebel Saba'at group appear as mirages.

The changing patterns are probably related to the considerable variation in annual rainfall, whereas the abrupt and permanent short-grass/herbs patterns are apparentlyunrelated to soil, rainfall or relief differences, whereas human influence has to be ruled out (there are, in this area, no grass fires and there is no cultivation; there is, however, rough grazing).

In the southern part, *Cymbopogon/Sorghum* grassland alternates with *Acacia mellifera* thickets, the latter varying from young and open, through mature and dense, to dying-off and open. There is, apparently, a cyclic movement of *Acacia* versus grasses, referred to earlier (Chapter 2) as *Acacia* - grassland cycle.

All soils on the clay plain are Typic Chromusterts, belonging to the very-fine, montmorillonitic, isohyperthermic family. Three soil series were distinguished (Blokhuis et al. 1964). The surface soil (A1 horizon) of the Khashm el Girba and Asubri series is a 70 to 90 cm thick dark yellowish-brown(10YR 3/4) clay, overlying a 50 to 80 cm thick dark grayish-brown (10YR 3/2) clay, which has an accumulation of soft, powdery carbonate (Bwk horizon) alone, or in combination with fine gypsum crystals (Bwky horizon). The solum of the Dimiat series has colours of lower chroma. The main differences between the three soil series are in the nature of the substratum. The soils have the following morphology:

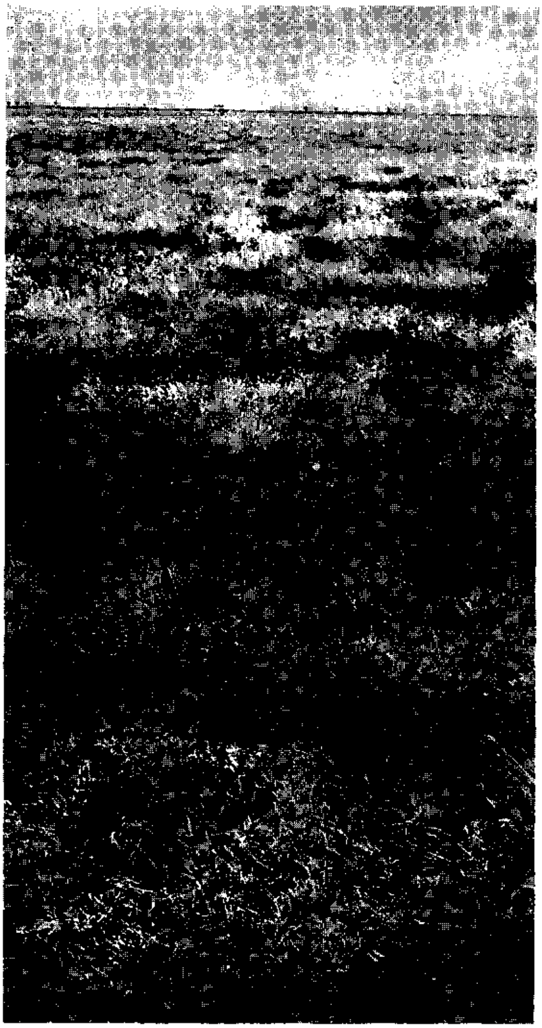


Photo 40: Short grass Setaria spp *in the Khashm el Girba soil survey area. Patchiness in the grass cover reflects uneven surface due to swelling and shrinking of the surface soil.*

Khashm el Girba series: the solum (A and B horizons) overlies a substratum of dark reddish brown clay (hue 7.5YR) with carbonates and gypsum (Cky horizon), at greater depths with carbonates alone (Ck horizon). Fine, bluish-black specks of manganese oxides occur in the substratum. Below 3 to 4 m depth coarser-textured strata with fine alluvial bedding may appear. A representative profile is Khashm el Girba 213 (nr. 1).

Asubri series: the solum is not much different from that of the Khashm el Girba series, but the substratum is different: it consists of a finely layered alluvium with alternating coarser- and finer-textured strata. The substratum is free of gypsum; the solum is free of gypsum in the deep and moderately deep phases (see below). A representative profile is Khashm el Girba 215 (nr.2). It should be realized that at the soil surface there is no difference between the Khashm el Girba and Asubri series, nor is there any visible difference in relief.

Dimiat series: the solum is comparable to that of the Khashm el Girba series, but chromas tend to be lower (2 in the A horizon, 1 in the B horizon). The substratum is a clay with hues 10YR or 2.5Y, with fine ferric iron mottles. Bluish specks of manganese

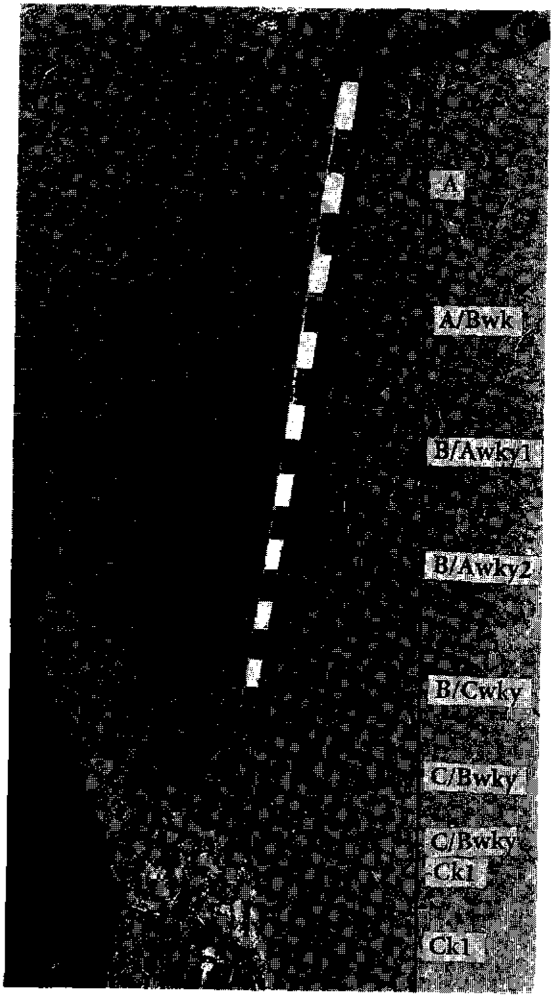


Photo 42: Profile Khashm el Girba 251 (nr.3), belonging to the Dimiat series (the wooden bar is divided into 10-cm steps). The wavy boundary between the C/Bwky and Ck1 horizons (in the photograph at about 210 to 250 cm) follows a slickenside. About 50% of the soil mass in the Ck2 horizon consists of soft powdery lime and ca-granules.

oxide are more plentiful and more conspicuous than in the Khashm el Girba substratum, and there is more pedogenic carbonate and gypsum. The substratum overlies directly, or through a horizon of calcium carbonate accumulation, weathering gneissose igneous rock. Representative profiles are Khashm el Girba 251 (nr.3; Photo 42) and 256 (nr.5).

Soil depth phases have been differentiated in the Asubri and the Dimiat series (thickness of solum to underlying coarser-textured substratum and to underlying igneous rock, respectively).

Wadi variants occur in all three series. The wadi variants have thicker surface and sub-surface soils compared with the corresponding soil series, and they are darker-coloured (lower value of the soil colour). They occur in and along 'khors'. A representative profile of the wadi variant of the Asubri series is profile Khashm el Girba 238 (nr. 4).

The three series also differ in salinity and sodicity: the Khashm el Girba and Dimiat series are often slightly saline and slightly sodic, whereas the Asubri series is non-saline, but strongly sodic at depth (cf. Chapter 8). The Asubri soils, free of gypsum, excess sodium and soluble salts, and overlying coarse-textured substrata, have probably been subjected to some leaching, in contrast to the deep clay soils of the Khashm el Girba and Dimiat series. Northwards both salinity and sodicity increase (Ochtman 1965).

The distribution of the soils and the location of the representative profiles are shown on the simplified soil map on a scale 1:500 000 (Fig. 6.1), and on a schematic ENE-WSW cross-section (Fig. 6.2), at right angles to the Atbara river (AB in Figure 6.1). Bordering the Atbara 'kerrib' land is a faint ridge with soils belonging to the Asubri series. West of this ridge the Khashm el Girba series dominates the clay plain, whereas the Asubri series covers very slight ridges and/or valleys, often found side by side. The relief differences are so small that they cannot be seen in the terrain; the contour map shows some of this relief, and in the field some of the lower-lying areas are shown by the presence of 'khors'. West of the line where the contour pattern of the plain changes - it shows a very gentle, but distinct rise towards the Butana pediplain - the Dimiat series occurs.

The parent material of the Khashm el Girba and Asubri series is alluvium of the Atbara, with some admixture of material weathered from Basement Complex rock that underlies the Butana pediplain. The parent material of the Dimiat series is a locally redistributed clay originating from weathering of Basement Complex rock, with some admixture of alluvial clays in the solum. Changing high flood levels of the Atbara may have caused an inset of alluvial clays in the older Butana pediplain clays.

The depositional history of the Atbara aggradational clay plain may have been as follows (Blokhuis et al. 1964). The first stage is hypothetical as we have no data on deeper strata, but we assume that coarser-textured material, similar in nature to the lower members of the Gezira Formation (or the El Atshan Formation) underlie the entire plain. After this sedimentation by, perhaps, a braided river system, a river

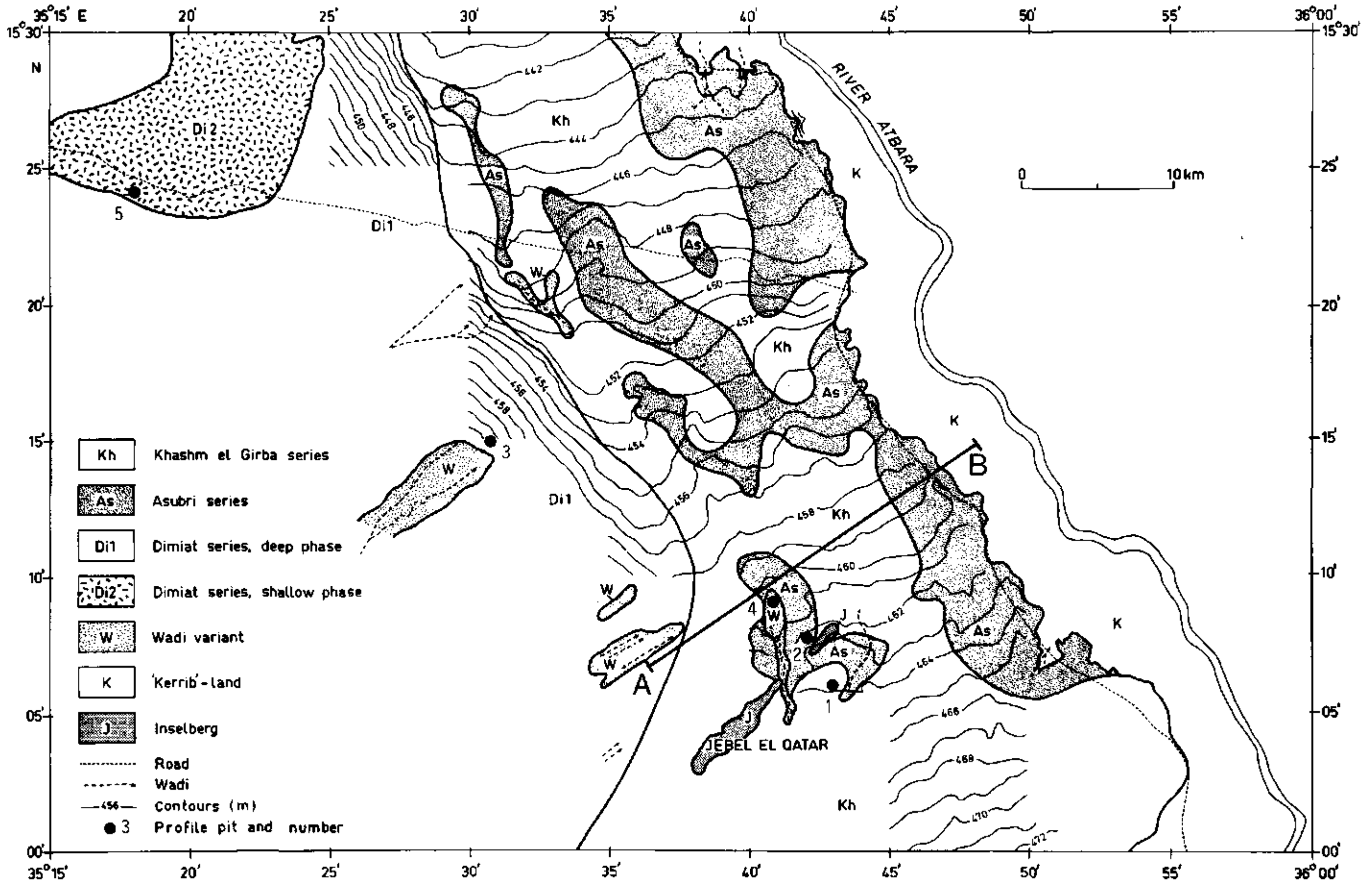


Fig. 6.1. Schematic soil map 1:500 000 of Khashm el Girba South, with location of representative profiles; for cross-section AB, see Fig. 6.2

floodplain was built by a meandering river: dark-brown clays in basin sites, sands and loams on river levees and in silted-up stream beds. These deposits now form the substratum of the Khashm el Girba and Asubri series, respectively. The last stage of deposition brought fine-textured sediments which were spread uniformly over the entire plain. In this surface cover the A and Bwk/Bwky horizons of the present soils have developed. The successive sediments, and the differences in substratum between the two series were clearly shown in the wall of a newly-dug irrigation canal (Photo 43). It should be noted that in this exposure the Asubri series only forms a narrow strip; it represents a minor, silted-up stream course. This occurrence of the Asubri series is much smaller in extent than any of the occurrences of this unit on the soil map. One wonders whether the picture of large, uniform areas of the same soil - especially of the Asubri series - is correct. The wide spacing of soil observation points -at an average distance of 2 km - would not reveal whether the Asubri series is present as a succession of narrow, sub-parallel or winding bodies, instead of one, broad, SE-NW running band in the centre of the plain. Even so, the soil map shows a main SE-NW alignment of the Asubri series and the apparently associated wadi variants of this series. This pattern continues in the northern part of the Atbara clay plain (Ochtman 1965).

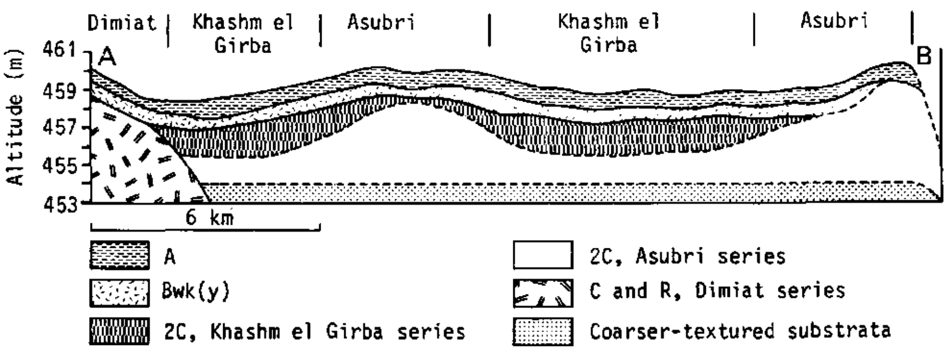


Fig. 6.2. Cross-section through the Khashm el Girba clay plain showing lateral extension of soil horizons (for location of the line AB, see Fig. 6.1)

The pattern of the presumed old levees and silted-up stream channels is different from that of the Blue Nile palaeochannels in the Gezira clay plain (Fig. 4.3), which follow the radiating pattern of an alluvial fan. There is, however, a similarity between both areas in the uniformity and continuity of the upper clay cover. For such a homogeneous clay blanket to form requires either a very constant sedimentation regime in combination with a very slight slope, or a swamp vegetation in which the fine-textured suspended matter is trapped.

Another similarity between both clay plains is that two soil horizons can be distinguished in the uniform surface clay:a 10YR 3/4 surface clay (A horizon), and a 10YR 3/2-2/1 subsurface clay (Bwk(y) horizon). We assume - following Finck (1961) -

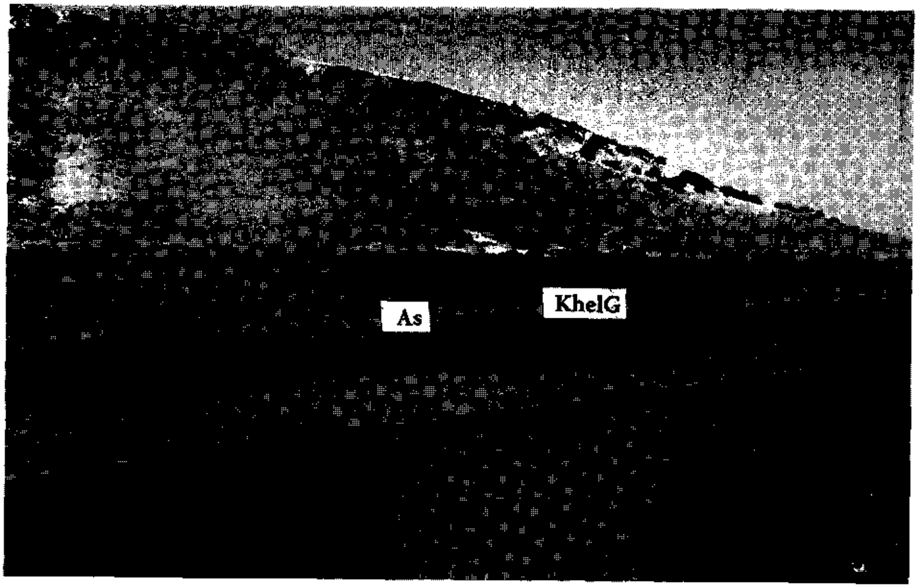


Photo 43: Cross-section along a freshly-dug irrigation canal in Khashm el Girba South. The dark-coloured solum overlies a lighter-coloured substratum. On the right this is a clayey sediment (Khashm el Girba series), on the left a sandy/loamy substratum (Asubri series).

that this differentiation is due to soil-forming processes in a continuous and uniform sediment (section 4.4.3). The fact that the 10YR 3/4 surface clay has the same thickness all over the clay plain, is further evidence that it differs from the underlying 10YR 3/2-2/1 clay due to soil-forming processes, and not to a difference in the nature of the sediment.

There are some data to support the hypothesis that the three-horizon/layer-profile is built from two sediments. The clay percentages are remarkably uniform in the A and Bwk(y) horizons of the Khashm el Girba series, at about 60, whereas in the substratum they are about 10% lower. Further evidence is provided by the abrupt appearance of abundant coarse gypsum crystals in the upper centimetres of the substratum, decreasing rapidly with depth. In the Asubri series gypsum is absent, but one finds, in some of the profiles, a large quantity of shells at the boundary between Bwk and C horizons (Fig. 4.6). These shells have the same radiocarbon age as shells in a similar position at Wad Medani (Adamson et al. 1982; cf. Chapter 4). In Khashm el Girba North shell accumulations and thin sandy strata - interpreted as fossil stream beds - occur along the upper boundary of the clay substratum (Ochtman 1965).

At about latitude 16° North the clay substratum fades out, and the solum rests directly on coarser-textured sediments (Asubri series). The upper clay mantle continues beyond 16° North, but the clay contents of the soil decrease (Ochtman 1965).

In conclusion we may say that solum and substratum of the soils represent two distinct periods of sedimentation, with an interlude under marshy conditions (accumulation of shells in ponded areas and of evaporites in level floodplain sites).

Differences in profile morphology between the Khashm el Girba and the Dimiat series are mainly confined to the substratum. The reddish-brown substratum of the Khashm el Girba series, overlying coarser-textured sediments, is in strong contrast to the dark grayish-brown substratum with ferric and manganese oxide mottles, overlying weathering rock. The Dimiat substratum consists of colluvio/alluvial clay weathered from Basement Complex rock (cf. Chapter 5), whereas the solum may have formed in a mixture of alluvial Atbara clays and colluvio/alluvial Butana clays. The physiography (Figures 6.1 and 6.2) clearly points to a pediplain rather than to an alluvial origin of the Dimiat series. And there are mineralogical differences between the Khashm el Girba and the Dimiat substrata (cf. Chapter 8).

6.5.2 Southern Gedaref

The Southern Gedaref Soil Survey (Nedeco/Ilaco,1966) covers the sites of two proposed Mechanized Crop Production Schemes (MCPS), Umm Simsim and Umm Seinat. They form part of the Gedaref clay plain (mapping unit 212) and of the southern part of the Blue Nile-Dinder-Rahad clay plain (mapping unit 121). Their location is shown in Figure 2.3 and Appendix 3.

In the soil survey, use was made of aerial photographs on a scale of 1:25 000. During the field work, traverses in a 2 x 2 km grid were followed. Most of the soil observations were made at or between grid points. Contour maps on a scale of 1:50 000 with contour intervals of 1 m, were used as field maps. The reporting scale was 1:100 000.

The overall relief of the Gedaref clay plain is gently downsloping from the Gedaref-Gallabat ridge to the river Rahad. Inselbergs, rocky hills, non-rocky elevations, and long, gentle ridges modify this contour pattern locally. This is clearly shown in the Simsim and Seinat areas (Fig. 2.3).

Umm Seinat reaches its highest level of 560 m in the northeast, and a lowest level of 475 m in the southwest. The gradient of the slope decreases from northeast to southwest from 1% to 0.1%. The general direction of slope continues in southern Umm Simsim, then turns west, following the course of Khor Simsim.The relief of the northwestern part of Umm Simsim is strongly influenced by the extensive hill groups of Jebel El Utash and Jebel Salmin. From a level of 520 m in the northwest, there is a southeasterly downslope - deviating from the southwesterly trend of the pediplain - which turns southwest, then west to reach a lowest level at 465 m. Slope gradients decrease from about 0.5% in the northwest to about 0.05% in the south.

Umm Simsim and Umm Seinat are drained by several seasonal waterways ('khors') (Figures 6.3 and 6.4). The main ones are: Khor Kafai - which rises on the Gedaref-Gallabat ridge and fades out onto the clay plain south of Qulei'at Ed Darot -, Khor Esh Shuheit - into which many small 'khors' of the Seinat area debouch -, Khor Abu Ghabita - from the northern part of the Simsim area - and Khor Simsim - into which all the above khors ultimately join. Khor Simsim is a tributary of the Rahad.

Some of the 'khors' - mainly the small ones, but also Khor Kafai - split into innumerable small, anastomizing courses on level parts of the clay plain, and become untraceable. It is not uncommon that further downslope well-defined 'khors' develop once more.

Along Khor Esh Shuheit and south of Khor Simsim are many forsaken streams, silted-up 'khor' beds and cut-off meanders. These are difficult to locate in the terrain, but they show up well on aerial photographs.

The underlying geological formations are Basement Complex and Nubian Sandstone. In this area, the Basement Complex consists of foliated metamorphic rock, mainly schists and phyllites, with intrusive rocks. The metamorphic rocks outcrop in the Qulei'at Ed Darot hills, the intrusive rocks form inselbergs and groups of steep-sided hills. There are several non-rocky, smooth hills that represent a more advanced stage of weathering; they probably have the same geology as Qulei'at Ed Darot.

The geology of some of the inselbergs and hills is as follows :

- Jebel El Utash (western border of northern Simsim) was mapped by Ruxton (1956) as part of the Umm Saqata ultrabasic group: foliated rocks with serpentinite and talc-magnesite. We collected samples that were identified as: schist rich in quartz; intrusive rock rich in quartz and feldspars; micaceous quartzite with sulfides including pyrite.
- Jebel Simsim and small inselbergs southeast of Jebel Simsim were mapped by Ruxton (1956) as solvsbergite: a hypabyssal rock composed chiefly of sodic feldspar, with some potassium feldspar, sodic pyroxene or amphibolite, and little or no quartz.(Gary et al. 1973). Rock samples collected from these inselbergs were identified as: sandstone; greenschist rich in quartz'; arkose; gneiss.
- Jebel Umm Seinat, Qal'at Wad Babun and Qulei'at Ed Darot were mapped by Ruxton (1956) as psammopeletic and foliated metamorphic rocks. The samples we collected at Jebel Umm Seinat were identified as micaceous quartzite and iron-rich quartzite. Samples from Qal'at Wad Babun were mainly quartzite. Exposed rock at Qulei'at Ed Darot was identified as micaceous schist.
- Rock samples collected from a small inselberg in southern Seinatwere identified as iron-rich quartzite; arkose; basalt.

A few outcrops of Nubian Sandstone occur in Umm Simsim,and they form slight ridges or non-rocky elevations. All samples collected from these outcrops were identified as sandstone, varying from coarse-grained to fine-grained; some of the sandstones approached quartzite, others were very rich in iron. Around Jebel Simsim, in an area mapped as solvsbergite (Ruxton 1956) sandstone and arkose were found in the field.

Pea-iron gravel, originating from a former laterization stage, occurs in the

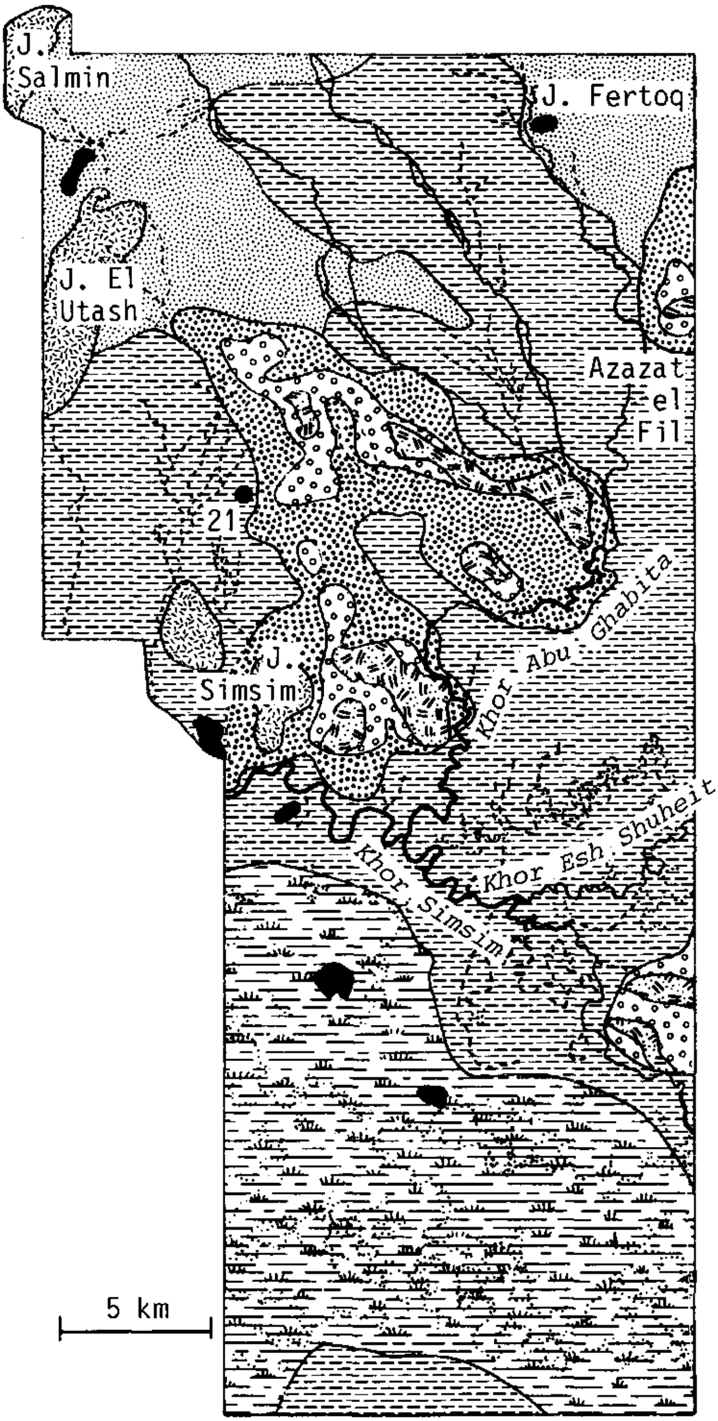


Fig. 6.3. Reconnaissance soil map of Umm Simsim, 1:250 000 (after a soil map 1:100 000 by Nedeco/Ilaco 1966), with location of profile Simsim B 27 (nr. 21) (map and legend adapted and simplified from the original)

Inselbergs
Inselbergs and fringing gravel covered clay plains
Azazat el Fil - Simsim association
Seinat series
Ghabita series
Ghabita - Shuheit association
Shuheit series
Shuheit - Kafai - Utash association

● 21 profile pit and number
seasonal water course
seasonal tributary
dead water course

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substratum of soils on the non-rocky elevations, and is exposed as cemented pea-iron gravel locally on the banks of Khor Simsim, for exampleat the eastern boundary of Umm Simsim. It should be noted that the southern part of Umm Simsim belongs to the Rahad-Dinder-Blue Nile clay plain, which is underlain by the Umm Ruwaba formation. Grove and Warren (1968) mention some zones of ironstone gravels in this formation.

The original soil maps 1:100 000 have been reduced to a scale of 1:250 000 for the present study and simplified; they are shown in Figures 6.3 (Umm Simsim) and 6.4 (Umm Seinat). Schematic cross-sections showing catenary relationships between soil series, and the vegetation cover, are shown in Figure 6.5. The mapping units are soil series, associations of two or three series, associations including rock land, and miscellaneous land types.

Table 6.3 shows the most important soil series, their classification according to the latest amendment of the USDA system (Soil Survey Staff 1990) and the names in the Ilaco/Nedeco Report (1966) that were based on the first published version of this system, the '7th Approximation' (Soil Survey Staff 1960) and on a partial revision in 1964. The nature of the soil surface was an important differentiating characteristic between Vertisols in that version.

The soil series and some of their most important differentiating characteristics are described below; the Soil Taxonomy subgroup and reference profiles are also given. Soil family names are in Appendix 2.

Darot - Lithic Ustorthent - Seinat B 10 (nr.23) (Photo 44)

Shallow soils overlying weathered micaceous schist. Surface covered with quartz stones.

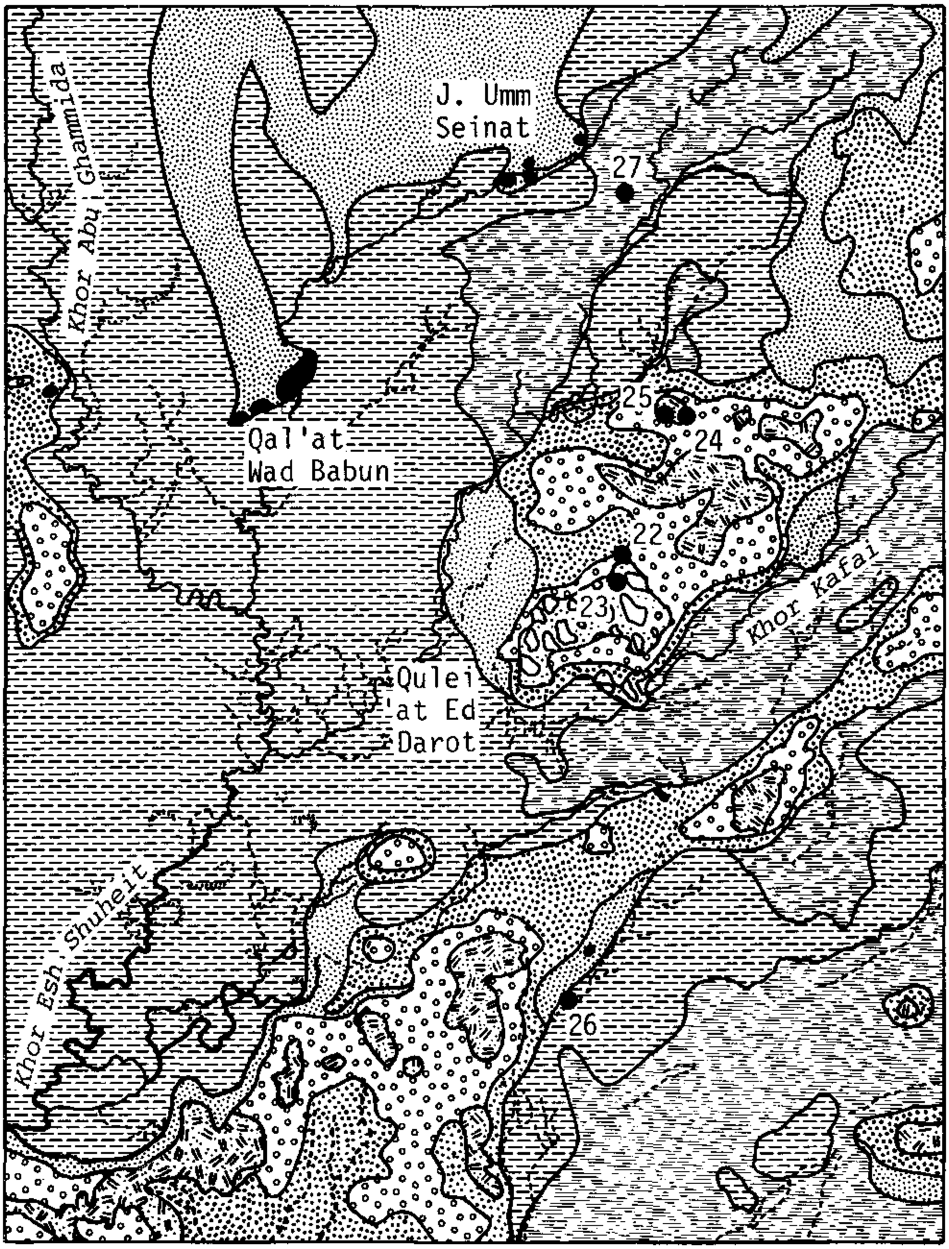

Fig. 6.4. Reconnaissance soil map of Umm Seinat, 1:250 000 (after a soil map 1:100 000 by Nedeco/Ilaco 1966), with location of representative profiles (map and legend adapted and simplified from the original)

Inselbergs

Rockland - Darot - Azazat el Fil - Simsim association

Azazat el Fil - Simsim association

Seinat series

Ghabita series

Ghabita - Shuheit association

Shuheit series

Shuheit - Kafai association

● 23 profile pit and number

seasonal water course

seasonal tributary

dead water course

Azazat el Fil - Ultic Paleustalf - Seinat B 48 (nr.25) (Photo 45)

Smooth, hard surface, reddish-coloured by a thin film of iron-coated sand and fine gravel. Characteristic are 2 to 3 m high, irregular pillar- or cone-shaped termite mounds with a ground surface of 5 to 10 m diameter. The surface soil is loamy sand to sandy loam and sandy clay loam, merging with depth to sandy clay and clay. The solum is 1 to 2 m thick and overlies a layer of pea-iron gravel.

Simsim - Typic Ustropept - Seinat B47 (nr. 24)

In fact - but not according to its formal name - the Simsim series is an intergrade between Alfisol and Vertisol. The surface is smooth and hard, with reddish-coated sand, fine gravel and pea-iron. Next to large cracks, 1 to 3 cm across, there are fine surface cracks. There is a wide, shallow gilgai microrelief (round type) with wavelength 10 to 15 m and amplitudo 10 to 60 cm, often with sink holes in the centre of the depressions. Termite mounds are large, reddish-brown cones, about 2 m high. They differ from those related to the Azazat el Fil series in having a relatively larger ground surface and less height, and in having a brown rather than a red colour. The surface soil is a heterogeneous mixture of coarse sand and clay; this overlies a clay loam, with depth merging to clay. The subsurface soil has a weak vertic structure and contains calcitic nodules. The solum overlies abruptly a thin (5 cm) calcic horizon, which for at least half of its volume consists of calcitic granules and nodules, and which is underlain by a layer of pea-iron gravel and some quartz fragments.

Seinat - Typic Chromustert - Seinat B7 (nr. 22)

Characteristic of the Seinat series is a hard, smooth surface crust, and the absence of a mulch. Sand and fine quartz gravel, and locally also pea-iron gravel and calcitic nodules cover the soil surface. Wide, shallow gilgai (wavelength 10 to 15 m, amplitudo 30 to 40 cm), often with sinkholes in the centre of the depressions, is common. Termite mounds are large, 2 to 3 m high, cone-shaped, and consist of light-brown soil; they have a ground surface with a diameter of some 10 to 15 m. There are also small, rounded, 30 to-80 cm high termite mounds, and the two types may occur together. The cracking pattern on the surface is similar to that of the Seinat series. A surface soil of gravelly and sandy clay overlies a deep, clayey subsurface soil with a distinct vertic structure. Calcitic nodules and soft, powdery lime are found below about 150 cm depth. Cracks extend to a depth of 80 to 100 cm.

Ghabita - Typic Chromustert

The Ghabita series is an intergrade between the Seinat and Shuheit series, and this refers specifically to surface and surface soil characteristics. The surface is a smooth, rather soft, crust with much, slightly reddish-coated, sand, some fine gravel and calcitic nodules, and it is either attached to the underlying soil or overlies a thin mulch. There are wide cracks in a polygonal pattern, and many fine surface cracks. Locally there are small, rounded termite mounds, 30 to 80 cm high. Normal or round gilgai is common, often with sink holes in the centre of the depressions; it is more weakly developed than in the Shuheit series. Soil texture is clay throughout, but the surface soil has more sand. There is a distinct vertic soil structure. The colour of the surface soil is 10YR 3/2 or 2.5Y 3/2.

Shuheit - Typic Chromustert - Seinat B 50 (nr. 26) and Simsim B 27 (nr. 21) (Photo 46)

The Shuheit series covers level parts of the clay plain; it is the most typical soil of both Umm Simsim and Umm Seinat, and covers the largest area.

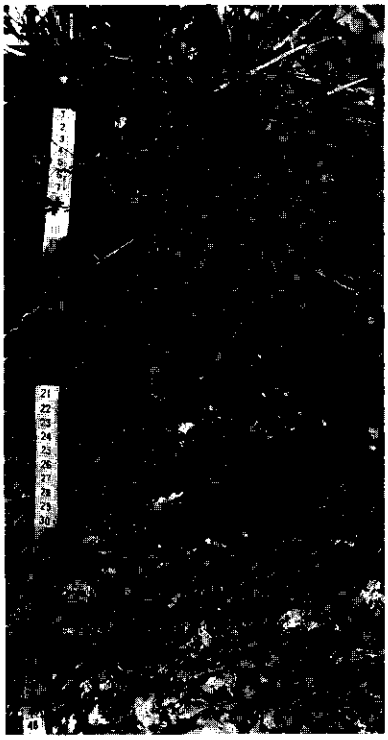

Photo 44: Profile Seinat B10 (nr.23), a Lithic Ustorthent.

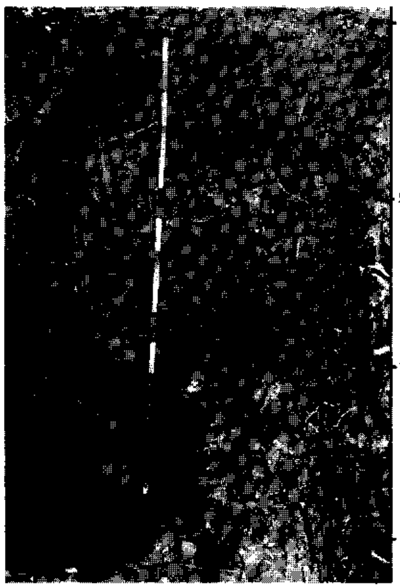

Photo 45: Profile Seinat B48 (nr.25), an Ultic Paleustalf.

The surface is a soft, brittle flake, breaking into a mulch of 2 to 6 cm thick. The surface flake contains coarse sand and calcitic nodules, and sometimes gravel. Gilgai is distinct and of the normal type, with wavelength 5 to 7 m, amplitudo 15 to 25 cm, often with sink holes in the depressions. The gilgai mounds show an accumulation of calcitic nodules and, sometimes, gravel and stones. Cracks are 2 to 5 cm wide at the surface, and 20 to 50 cm apart. They are distinct in gilgai depressions, whereas they are obscured by a thick mulch on the gilgai mounds. The texture of the soil is clayey throughout. The solum has a distinct vertic structure and is very uniform in morphology. Soft powdery lime occurs in the substratum. The surface soil colour is 10YR 3/2 or 2.5YR 3/2.

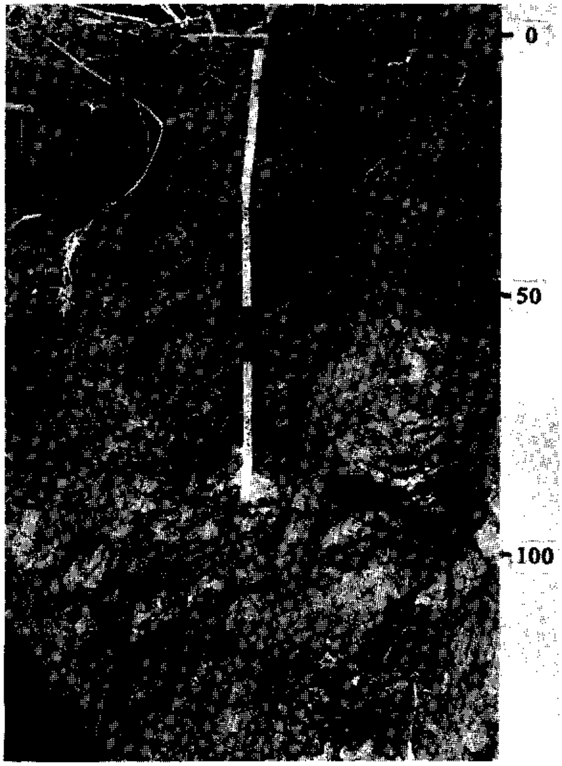

Photo 46: Profile Simsim B27 (nr.21), a Typic Chromustert.

Kafai - Entic Pellustert - Selnat B 55 (nr. 27)

The Kafai series differs from the Shuheit series mainly in the colour value and chroma of the surface soil: 10YR 3-4/1.5: the soil is an Entic Pellustert. The surface is similar to that of the Shuheit series, but there are some differences. The cracking pattern is more distinct as thesurface mulch, 2 to 4 cm thick, becomes less prominent. The surface of polygons between cracks is uneven, a feature often observed in Vertisols subject to flooding. Cracks are 5 to 15 cm wide on the surface, and about 30 cm apart. Gilgai is more weaklydeveloped than in the Shuheit series, with wavelength 4 to 8 m and amplitudo 15 to 25 cm; there are no sink holes. The solum is more than 180 cm deep; it consists of a heavy clay with a distinct vertic structure, and contains some fine carbonate nodules.

Utash - Typic Pellustert

The Utash series differs from the Kafai series mainly in the colour value of the surface soil: 10YR 3/1-1.5. Other surface features are not different from those of the Kafai series. The solum is deep, often more than 200 cm; it consists of a heavy clay with a distinct vertic structure. Calcitic nodules are few; in the lower part of the solum a few, soft calcitic segregations may occur.

Table 6.3: Southern Gedaref soil survey: main soil series, taxonomic subgroups cf. Nedeco/Ilaco (1966) (based on Soil Survey Staff 1960; 1964), and cf. Soil Taxonomy (Soil Survey Staff 1990), and representative profiles

Soil series (Nedeco/ Ilaco 1966)	Taxonomic subgroups cf. Nedeco/Ilaco 1966	Taxonomic subgroups cf. Soil Taxonomy (Soil Survey Staff 1990)	Representative profiles		
			Name	Nr. acc. to Table 6.1	Nr. in Nedeco/ Ilaco 1966
Darot	Lithic Haplorthent	Lithic Ustorthent	Seinat B10	23	155
Azazat el Fil	Oxisol	Ultic Paleustalf	Seinat B48	25	116
Simsim	'Mazustertic Haplorthent'	Typic Ustropept	Seinat B47	24	117
Seinat	Typic Mazustert	Typic Chromustert	Seinat B7	22	152
Ghabita	'Mazic Grumustert'	Typic Chromustert	Simsim B27	21	81
Shuheit	Typic Grumustert	Typic Chromustert	Seinat B50	26	253
Kafai	'Aquic Grumustert'	Entic Pellustert	Seinat B55	27	55
Utash	Typic Grumaquert	Typic Pellustert	-	-	-

The soil mapping units are the following (Figures 6.3 and 6.4; the mapping unit codes refer to the catenas in Figure 6.5):

Inselbergs (I)

This mapping unit covers inselbergs that are apparently alien to the clay plain, and which consist of rock types that are highly resistent to weathering. They have practically no fringing pediments or foot slopes. Examples are Jebel Umm Seinat and Qal'at Wad Babun, both consisting of quartzite.

Inselbergs and fringing gravel-covered clay plains (IC)

Larger inselbergs, especially those that contain much weatherable minerals like Jebel El Utash and the Jebel Simsim group, have distinct clay-covered pediments or colluvial foot slopes. They are generally fringed by a clay plain with low-chroma Vertisols (Pellusterts), that often contain gypsum in the substratum, and have relatively higher exchangeable sodium and soluble salts than the surrounding Shuheit series clay plain soils. Except for northwestern Umm Simsim, soils with gypsum in the solum or substratum are rare. As for the source of the gypsum, it may be recalled that a rock specimen of Jebel El Utash was identified as quartzite with mica and sulfides.

The low chroma of the Vertisols fringing these inselbergs has been ascribed (Nedeco/Ilaco 1966) to a relatively long period of flooding, rainfall on the site being supplemented by surface runoff from the hillslopes. However, the basic nature of the local rock may also have had some impact: many Vertisols developed 'in situ' in well-drained positions on basic rocks are Pellusterts (see the descriptions of mapping units 22 and 52of the 1:2 000 000 pedogeomorphic map). Figure 6.5, catena 3, shows a steep-sided inselberg surrounded by a slight depression, set in a clay plain with Shuheit series. Such depressions may have (gravelly) Pellusterts (not indicated in the figure).

Mapping unit IC occurs only in Umm Simsim.

A soil profile in the fringing clay plain (profile Umm Simsim 101, Ilaco/Nedeco 1966) shows the following features (Photos 47 and 48). The soil surface is strewn with flattened rock fragments, up to 30 cm diameter; otherwise it has the normal Vertisol surface characteristics. Soil texture is clay (clay percentages are 63 to 73, silt percentages 23 to 29, sand percentages are very low, less than 5% below 80 cm depth).

Soil structure is vertic to 125 cm, angular blocky with few slickensides from 125 to 200 cm+; cracks are distinct to 50 cm, and traceable to 100 cm. Soil colour is 10YR 2-3/0.5-1 to a depth of 240 cm, 10YR 3.5/2 from 240 to 275 cm+; some 2.5Y 5/4 mottles and fine rusty mottles occur in 275 to 320 cm+.

Hard, white and black carbonate nodules are found in 0 to 150 cm; vertically arranged aggregates of soft lime, sometimes enclosing hard nodules, occur in 80 to 320 cm+. Gypsum occurs as few, fine lense-shaped crystals in 60 to 80 cm, and forms nests of crystals (often 'desert roses') and pseudomycelium in 165 to 275 cm. Gypsum accumulation increases with depth, is abundant in 240 to 275 cm, and few to 320 cm+.

Remark: the colour change at 240 cm indicates a break in either soil parent material or hydrology.

Rock land-Darot-Azazat el Fil-Simsim association (R-D-A-S)

There is but one occurrence of this unit: the Qulei'at Ed Darot hills and colluvial foot slopes in the Umm Seinat area. The hillslopes are rocky and covered with gravel and stones, mainly of quartz. The quartz stones on the surface may have accumulated as rock weathering proceeded; they are probably derived from quartz veins in the original rock. Shallow soils have developed on the rock outcrops and these belong to the Darot series (Lithic Ustorthents). The mapping unit includes colluvial foot slopes and other non-rocky areas where Azazat el Fil and Simsim series occur. The vegetation is a woodland with various broad-leafed species such as *Terminalia brownii*, *Lannea fruticosa* and *Combretum hartmannianum*.

The Rock land-Darot-Azazat el Fil-Simsim association forms the upper member of a catena which includes, in a downslope direction, the Azazat el Fil-Simsim association, Seinat series, Ghabita series and Shuheit series (Fig. 6.5, catena 1). On the 1:250 000 scale of the simplified soil maps (Figures 6.3 and 6.4) the members of the catena are used as mapping units.

Azazat el Fil-Simsim association (A-S)

The non-rocky ridges and rounded elevations with red and brown soils belonging to the Azazat el Fil and Simsim series, are mapped as Azazat el Fil-Simsim association. The highest sites are covered by Ultic Paleustalfs belonging to the Azazat el Fil series.

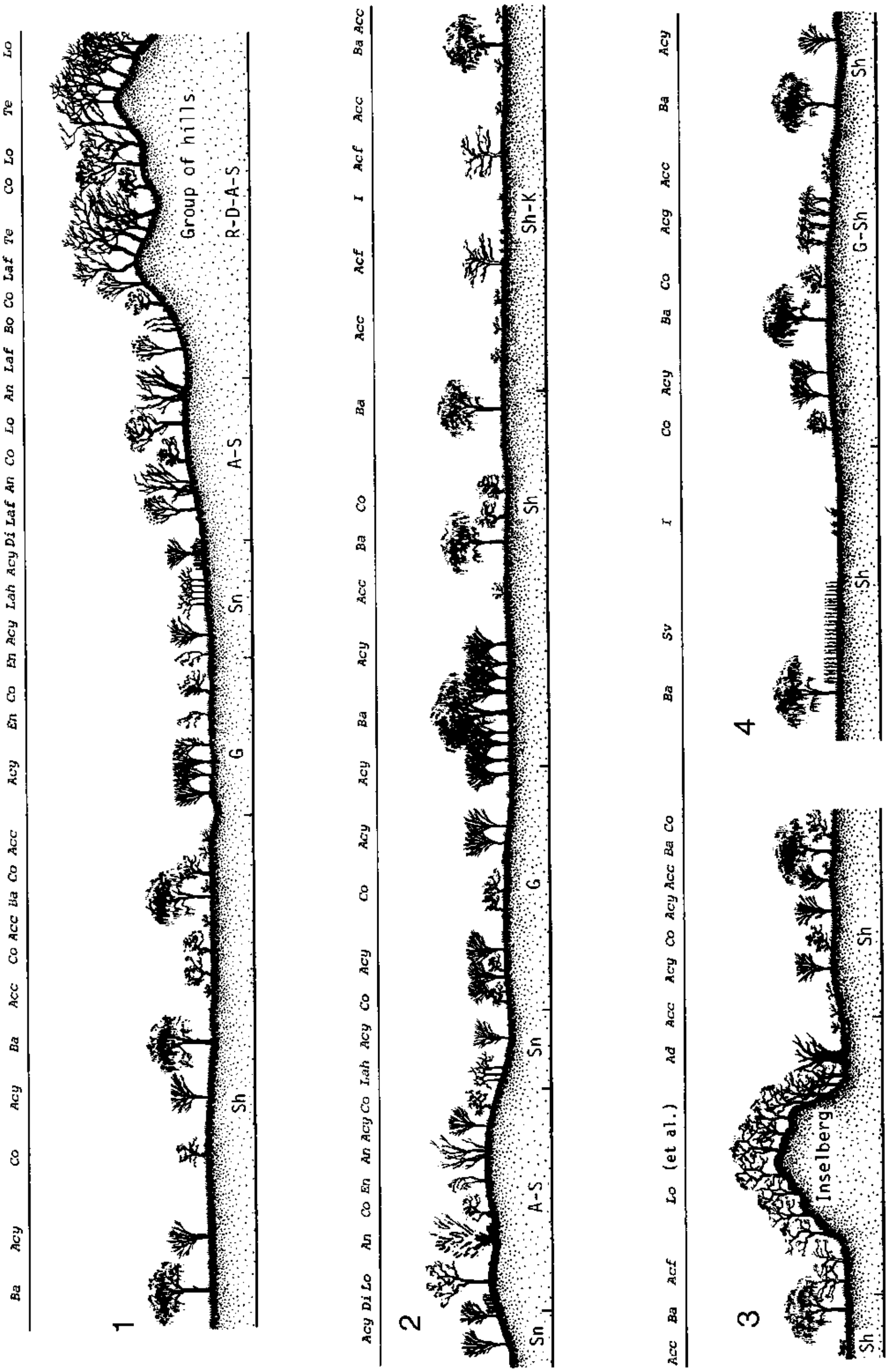
1
Ba Acy Co Acy Ba Acc Co Acc Ba Co Acc Acy En Co En Acy Lah Acy Di Laf An Co Lo An Laf Bo Co Laf Te Co Lo Te Lo
Sh
G
Sn
A-S
Group of hills
R-D-A-S
2
Acy Di Lo An Co En An Acy Co Lah Acy Co Acy Co Acy Acy Ba Acy Acc Ba Co Ba Acc Acf I Acf Acc Ba Acc
Sn
A-S
Sn
G
Sh
Sh-K
3
Acc Ba Acf Lo (et al.) Ad Acc Acy Co Acy Acc Ba Co
Sh
Inselberg
Sh
4
Ba Sv I Co Acy Ba Co Acg Acc Ba Acy
Sh
G-Sh
Sh

Fig. 6.5. Catenas in Umm Simsim and Umm Seinat (after Nedeco/Ilaco 1966, adapted), showing soil mapping units and main trees and shrubs

Soil mapping units:

R-D-A-S	*Rock land-Darot-Azazat el Fil-Simsim association*
A-S	*Azazat el Fil-Simsim association*
Sn	*Seinat series*
G	*Ghabita series*
G-Sh	*Ghabita-Shuheit association*
Sh	*Shuheit series*
Sh-K	*Shuheit-Kafai association*

Tree and shrub species:

Acc	Acacia seyal	Co	Combretum hartmannianum
Acf	Acacia fistula	Di	Dichrostachys glomerata
Acg	Acacia senegal	En	Entada sudanica
Acy	Acacia seyal	Laf	Lannea fruticosa
Ad	Adansonia digitata	Lah	Lannea humilis
An	Anogeissus schimperi	Lo	Lonchocarpus laxiflorus
Ba	Balanites aegyptiaca	Te	Terminalia brownii
Bo	Boswellia papyrifera		
I	Ischaemum brachyatherum *(perennial grass)*	Sv	Sorghum vulgare *(annual crop)*

The Typic Ustropepts of the Simsim series often mark the transition between the convex elevations or straight hillslopes, and the foot slopes where the Seinat series occurs. In some locations, the Simsim series covers relatively large areas, but in others the transition from Alfisol to Vertisol is quite abrupt. The occurrence of pea-iron gravel both on the surface and in the substratum (not in the solum) in the Simsim series, but in the substratum only in the Azazat el Fil series, is interesting. An explanation could be the vertic nature of the subsurface soil in the Simsim series, allowing an upward churning of coarse fragments.

The Azazat series covers about 45% and the Simsim series about 55% of the association. The vegetation is a woodland with broad-leafed species *Combretum hartmannianum, Lannea fruticosa, Lonchocarpus laxiflorus, Anogeissus schimperi* and some *Acacia seyal* and *Balanites aegyptiaca. Acacia seyal* is relatively most frequent on the Simsim series soils.

Catena 2 in Figure 6.5 shows the catenary succession Azazat el Fil/Simsim - Seinat - Ghabita - Shuheit - Shuheit/Kafai, from the top of the non-rocky elevation to the lowest part of the clay plain, subject to flooding.

Seinat series (Sn)

Soils of the Seinat series cover the lowest parts of the ridges and elevations; they surround the Azazat el Fil-Simsim association. The Seinat series belongs to the Typic Chromusterts with a hard surface crust, and in this respect is different from most Chromusterts in the Sudan, which have a surface mulch. The crusty-surface Vertisols in Umm Simsim and Umm Seinat are always sandy. The vegetation is an open woodland with *Acacia seyal, Balanites aegyptiaca, Combretum hartmannianum* and some *Entada sudanica.* Dense, small groves of *Lannea humilis,* and very dense patches of *Dicrostachys glomerata* occur on the lower slopes, marking the transition to the Ghabita series.

Photo 47: Inselberg and fringing clayplain with rock fragments on the surface. Umm Simsim area.

Ghabita series (G)

The soils of the Ghabita series surround those of the Seinat series; they extend downslope to the clay plain proper with Shuheit series. The Ghabita series is a Typic Chromustert, with a slightly sandy surface soil; the surface itself is intermediate between a crust and a mulch. The vegetation is an open woodland with *Acacia seyal, Balanites aegyptiaca* and *Combretum hartmannianum.*

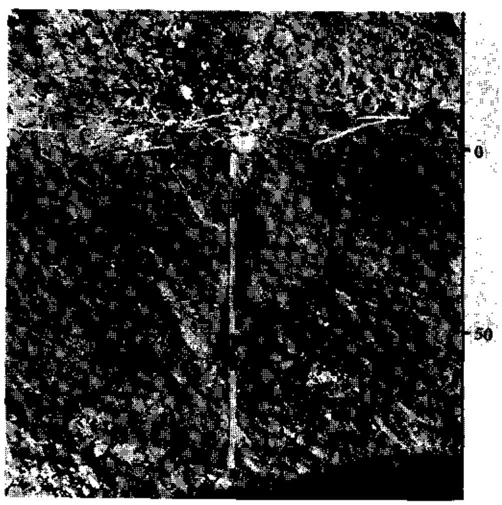

Photo 48: Pellustert profile at the location of photograph 47; the exposed part is to a depth of 100 cm.

Ghabita-Shuheit association (G-Sh)

When hillslopes are irregular, some of the successive members of catena 2 may occur together as an 'association within the catena', for example Ghabita and Shuheit. More important, however, arewide shallow ridges in the clay plain, entirely covered by sandy and gravelly surface phases of these two series, which occur in northern Umm Simsim and northern Umm Seinat. Figure 6.5, catena

4, shows such a ridge, bordered on both sides by soils of the Shuheit series. The gravel consists of quartz pebbles, whereas the solum is free of gravel. Some of these ridges are geographically related to inselberg-type rock outcrops, for example Jebel Umm Seinat and Qal'at Wad Babun, which makes it feasible that the gravel is derived from the truncated weathering profile (Ruxton and Berry 1961) of the underlying Basement Complex rock. Its concentration on the surface may be due to pedoturbation of the smectitic clay soil, or to overwash from higher-lying areas, north of the two survey areas.

Shuheit series (Sh)

The Shuheit series as a mapping unit covers the greater part of the clay plain. It also occurs in association with the Ghabita series, the Kafai series, and with both the Kafai and the Utash series. The Shuheit series covers datum sites of the clay plain. Receiving sites typically have either Kafai or Utash series, whereas areas shedding rainwater have typically the soils of the higher-lying catenary members like Darot, Azazat el Fil, Simsim, Seinat and Ghabita. The vegetation of the Shuheit series mapping unit is an open woodland with *Acacia seyal, Balanites aegyptiaca, Acacia campylacantha* and *Acacia senegal.*

Shuheit-Kafai association (Sh-K)

Parts of eastern Umm Seinat subject to overwash and flooding by 'khors' draining the Gedaref-Gallabat basaltic ridge are mapped as Shuheit-Kafai association. The Kafai series, an Entic Pellustert, occurs on sites subject to prolonged flooding, the Shuheit series on relatively higher ground. The low chroma of the Kafai series may be due to hydromorphic conditions, or to an admixture of material weathered from basaltic rock (compare the Pellusterts associated with inselbergs in the Umm Simsim area) or to both. The heavy minerals present in profile Seinat B 55 confirm an at least partly basaltic origin of the soils (cf. Chapter 8). The vegetation is similar to that of the Shuheit series, but *Acacia fistula* appears in addition to the species mentioned earlier, and is dominant in sites subject to a long period of flooding. Catena 2 in Figure 6.5 includes the Shuheit-Kafai association.

Shuheit-Kafai-Utash association (Sh-K-U)

There is only one occurrence of an association with Chromusterts, Pellusterts and intergrades: southern Umm Simsim, forming part of the Khor Simsim floodplain. Soils of the Shuheit series cover relatively well-drained sites, those of the Kafai series imperfectly drained sites, and soils of the Utash series poorly drained sites such as forsaken 'khors' and silted-up former stream beds. The low chroma of the Pellusterts must be related entirely to poor drainage conditions. The vegetation is a grass savannah with few scattered trees of *Balanites aegyptiaca, Acacia fistula* and *Acacia campylacantha.* Dominant grasses are *Ischaemum afrum* and *Sorghum purpureo-sericeum.*

The main aspects of soil formation in Umm Simsim and Umm Seinat are summarized as follows:

1. Most of the area is a clay plain with Typic Chromusterts, locally in association with Pellusterts. The Pellusterts occur at sites that are subject to prolonged flooding. In some locations weathering from basic rocks have produced low-chroma clay soils.
2. Rocky outcrops and non-rocky elevations of Basement Complex have locally given some relief to the otherwise flat clay plain. Red-black soil catenas have developed from Alfisol through Inceptisol to Chromustert and sometimes Pellustert (Figure 6.5, catenas 1 and 2). Such red-black soil catenas occur in many areas of the semi-arid tropics; they have been reviewed elsewhere (Blokhuis 1982). It is probably drainage conditions that govern the direction of weathering of the schists and phyllites of the Basement Complex: on the relatively better drained sites a red soil (Alfisol) is formed with a kaolinitic clay mineralogy, on sites with impeded drainage a black soil (Vertisol) with a smectite clay mineralogy.
3. An important feature is the occurrence of sandy and gravelly overwash spreading over the clay plains that surround the above rocky outcrops and non-rocky elevations. The sandy Chromusterts of these sites have a hard surface crust and wide, shallow gilgai, whereas the Typic Chromusterts of the clay plain have a well-developed surface mulch, and a gilgai with shorter wavelength and relatively greater amplitudo. The former differentiation on great group level between Vertisols with a surface crust (Mazusterts, Mazaquerts) and those with a surface mulch (Grumusterts, Grumaquerts) as defined in the '7th Approximation' (Soil Survey Staff 1960), was found to be very practical during the soil survey. In Soil Taxonomy (Soil Survey Staff 1975; 1990) there is only provision for such a differentiation on family level (but only implicitly so: Mazusterts, for example Seinat B7, will generally belong to the fine, Grumusterts to the very-fine particle-size class) or on series level.
4. The parent material of the clays of the plain is probably derived from basalts of the Gedaref-Gallabat ridge, with an admixture of clays formed from Basement Complex weathering, the latter particularly around the rocky and non-rocky elevations. Intrusive rocks that outcrop as inselbergs may, in some locations, have affected the surrounding clays (lower chroma; presence of gypsum).
5. Pedoturbation in smectite clays is shown by the presence of pea-iron gravel on the surface of vertic soils, and the lack of it on the surface of adjacent non-vertic soils (in both cases the pea-iron being present in the substratum). Pedoturbation is also shown in the Ghabita-Shuheit association in the occurrence of stones and gravel on the surface of the soil, but not in the profile - if we assume that these areas have not been subject to overwash.

Gilgai is a common feature of the Vertisols in Umm Simsim and Umm Seinat. Normal or round gilgai is the usual type, with sometimes lattice gilgai on slightly sloping positions. Sandy Vertisols (sand 25-35%; silt 10-20%; clay 40-60%) have a different gilgai form when compared with average Vertisols of the clay plain (sand below 15%; silt 15-25%; clay 70-80%). Gilgai may be the result of soil movement without soil mixing, rather than of pedoturbation (Chapter 9).

6. Termite mounds are characteristically different in shape, height, ground-surface and colour between the sites of the Azazat el Fil, Simsim, Seinat and Shuheit series. We have not investigated whether or not the mounds were built by the same termite species, but this may well be the case. Variation in the shape of mounds of *Macrotermes subhyalinus* was found to be related to the sand:clay ratio of the soil used for construction (Hesse 1955), whereas variation in mound-building behaviour was exhibited by *Macrotermes bellicosus* (Harris 1956; Grassé and Noirot 1961). Harris (1956) found that a termite mound represents an equilibrium of three forces: behaviour, material and climate. The physical properties of the soil, in relation to climate, have a strong impact on the shape of the mound.

In the Simsim/Seinat area the shape of large termite mounds varies with soil properties. Steep, pinnacle-like mounds occur on the non-rocky elevations (Azazat el

Photo 49: Steep-sided termite mound near the site of profile Seinat B48 (Azazat el Fil - Simsim association).

Photo 50: Dome-shaped termite mounds on footslope with vertic soil. Basaltic ridge near Tamra.

Fil) with red, kaolinitic soils having considerable resistance against erosion (Photo 49), whereas rounded, dome-shaped mounds occur on sites with brown, more easily erodable soils which have a mixed kaolinitic/smectitic clay mineralogy (Photo 50).

The small, rounded termite mounds found on the Seinat and Ghabita sites in addition to the large mounds, are probably built by a different termite species. No termite mounds are found on the clay plain proper, but subterranean nests do occur.

6.6 Remarks on verticols of clay plain mapping units

The first part of Table 6.1 lists the profiles that are representative of mapping units of the clay plain proper. Most of the profiles are from level clay plain sites (datum sites); some are from closed depressions (Tozi) or wadi areas (Khashm el Girba 238, Sennar 71, Seinat B55). Such clay plains usually have uniform soil conditions over large areas - as shown, for example in the more detailed soil surveys of Sennar, Abu Na'ama, Umm Simsim and Umm Seinat. They have minor inclusions of other pedogeomorphic units, and this refers particularly to the degradational clay plains, where inselbergs and hill groups break the monotony of the clay plain. We have no profiles that represent the Abu Irwa and Ethiopian foot slope clay plains, the Manaqil ridge and the White Nile east bank plain. The remarks that follow refer to the Gezira, the Blue Nile-Dinder-Rahad and the Atbara aggradational clay plains, and tothe Kenana, Butana and Gedaref degradational clay plains.

The second part of Table 6.1 lists the profiles that are representative of other sites in the Central Clay Plain; these include Vertisols and soils from other orders.

It is immediately evident from Table 6.1 that the clay plains have a very uniform soil cover: nearly all soils belong to a very-fine, montmorillonitic, isohyperthermic family of Typic Chromusterts, whereas Pellusterts occur in level or slightly depressed locations. The difference in colour chroma between the two great groups reflect differences in drainage conditions. On non-clay plain sites, however, Pellusterts developed 'in situ' from basic rock occur on hillslopes and foot slopes. Entic subgroups are more common in the northern, arid parts of the clay plain, and when the soil is a Pellustert. The difference Entic/Typic is, however, less easily related to soil or site characteristics than the difference Chrom/Pell.

The uniformity suggested by the soil family names, is to some extent due to the choice of differentiating characteristics in the U.S.D.A. soil classification system. Another choice would reveal differences between Vertisols of higher- and lower-rainfall regions, and - but less distinctly so - between Vertisols of aggradational and of degradational plains. The following characteristics differ between clay plain Vertisols - in addition to those already mentioned:

- salinity/sodicity;
- presence and depth of occurrence of gypsum;
- presence, size class and depth of occurrence of soft powderyconcentrations of calcium carbonate (the presence of rounded,hard nodules is not differentiating, as they are generally not formed 'in situ');
- surface characteristics, notably the presence and degree ofdevelopment of a mulch, or the presence of a hard crust;
- presence or absence of gilgai microrelief, and type of gilgai;
- colour chroma differences between Chromusterts.

These and other characteristics will be discussed in Chapter 7, which deals with the morphology of the soils.

Chapter 7

Morphology of the Vertisols in the Central Clay Plain

7.1 The morphology of Vertisols and the formation of soil structure

The subject of this chapter is the morphology of Vertisols in the Central Clay Plain of the Sudan. The morphology of Vertisols in general, and the mode of formation of the characteristic Vertisol structure profile will be discussed only in relation to this subject. The general aspects of Vertisol morphology, and especially the most important aspect of it, soil structure, have been described by several investigators: Krishna and Perumal (1948), Kaloga (1966), De Vos and Virgo (1969), Blokhuis (1982), Ahmad (1983), Hubble (1984), Wilding (1985), MacGarity (1985), Dudal and Eswaran (1988). The short outline of the morphology of Vertisols in general as given in the first section of this chapter, merely serves as a framework for the description of local variations within the Central Clay Plain of the Sudan.

The most striking aspect of Vertisol morphology is soil structure (Photo 51). Vertisols have a specific soil structure, which is of the same type throughout most of the profile, and shows differences in grade of development, and in class of the structural aggregates, whereas the structure may be compound to varying degrees.

This 'vertic structure' can be correctly described as angular blocky, following the terminology in the Soil Survey Manual (Soil Survey Staff 1951; 1962) or the FAO Guidelines (FAO 1977). However, the characteristic shape of the peds merits a specific name. It is, therefore, not surprising that non-standard terms have been used for the structural aggregates of Vertisols, for example wedge-shaped or sphenoid peds (Soil Survey Staff 1975), parallelepipeds (Soil Survey Staff 1960) and, in French publications, 'plaquettes' (Kaloga 1966), 'lentilles' and 'lentilles-polyèdres' (Wilbert 1965). The earliest description of vertic structure was by Krishna and Perumal (1948) who studied the Vertisols at Hyderabad, India. They used the terms 'lentil' for the structural aggregate, and 'lenticular' for the type of structure. The term 'lenticular' is now in common use in Australia (Hubble 1984; MacDonald et al. 1984; Stace et al. 1968).

De Vos and Virgo (1969) used the terms 'bicuneate' or 'double wedge-shaped' for the Vertisols of the Sudan. They gave the following description: 'In the freshly excavated pit these wedge-like elements protrude obliquely from the profile as sharp wedges, oriented laterally in the horizontal plane. The wedge faces are defined by polished, smooth slickensides and form an angle of 20 to 30 degrees with the longitudinal axes of the units. The ped faces vary from 2 to 5 cm in length and together the units form a firmly packed compound structure. On removal from the face a block of soil may be broken down easily into its wedge-like components. Although difficult to remove complete, the individual peds have triangular or trapezoidal faces tapering to points at each end in the form of a 'double wedge', but forming an obtuse-angled dome at the upper and lower sides.(...) The peds are double-wedge shaped and resemble lentils without rounded surfaces. Admittedly, within the profile face only one section of the double wedge is visible. Therefore the term 'wedge' seems to be unsatisfactory for the description of this structure, which appears to be a characteristic of Vertisols throughout the world.'

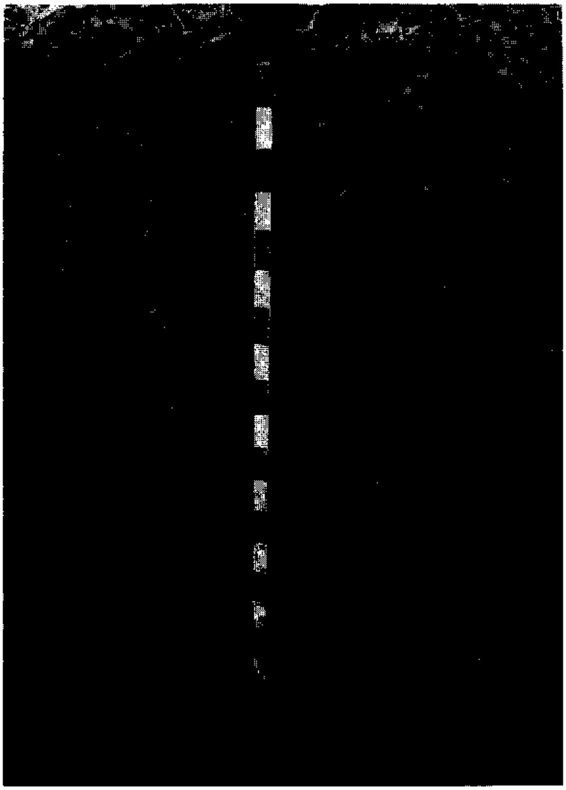

Photo 51: Vertisol profile in Khashm el Girba South, showing uniform soil structure with medium wedge-shaped peds (the wooden bar is in 10-cm steps).

The vertic structure is often compound: largest wedges can be broken into increasingly finer ones . The finest wedge-shaped peds have dimensions of about 2 to 3 mm high, 5 mm wide and 10 mm long. In most Vertisols the size of the finest peds increases with depth; the structure is no longer compound, but consists of wedge-shaped peds of more or less one size class, often 1 to 5 cm as average dimensions. In other Vertisols the compound nature of the structure may be retained throughout the solum, but in such instances the finest sub-structure is weakly developed in the lower part of the solum.

The vertic structure usually begins at some depth below the soil surface. The surface soil - below a mulch of a few centimetres, or a crust of a few millimetres thick - is generally subangular blocky, with depth merging with angular blocky. With increasing depth the faces of the angular blocky peds are tending towards a sub-horizontal direction, and, consequently, the peds acquire a flattened appearance (Photo 52). A parallelepiped substructure may also be present; if it occurs, it begins at shallow depth, often immediately below the mulch.

In the subsoil this parallelepiped substructure is often merely present as a 'visual structure': a sub-horizontal lamination of the profile wall, apparently a predisposition for a fine bicuneate structure. Although the grade is weak, this finest substructure is conspicuous in a profile wall. Probably the parallelepipeds would fully develop only when the soil dries out more completely, or when the overburden is released. It is a common observation that repeated wetting and drying of a soil fragment taken from any depth, results in its parting into the finest possible (wedge-shaped) aggregates, an observation also made by Templin et al. (1956) and Bryssine (1966). Coughlan (1984) found that the breakdown of dry aggregates with wetting and drying was favoured by slow imposed wetting rates, rapid drying, and high shrink-swell capacity of the aggregates.

The ped surfaces are flat to curved, lustrous and striated. This is most clearly shown when they are large, and such surfaces are known as slickensides or shear planes (Photo 53). The term slickenside is usually restricted to surfaces of large peds (about 2 to 10 cm), or - and perhaps preferably - to a continuous plane built from several adjoining ped surfaces. Smaller aggregate surfaces, however, show the same features; these have been described as pressure faces or stress surfaces. And even the finest peds, with dimensions of a few millimetres show the same glossiness when viewed with the aid of a hand lens or microscope (De Vos and Virgo 1969), and in many cases also the striations, said to be typical of slickensides (section 7.3). We have used the terms 'shiny ped faces' or 'shiny ped surfaces', 'slickensided ped surfaces' and 'slickensides'. These are defined in Appendix 2.

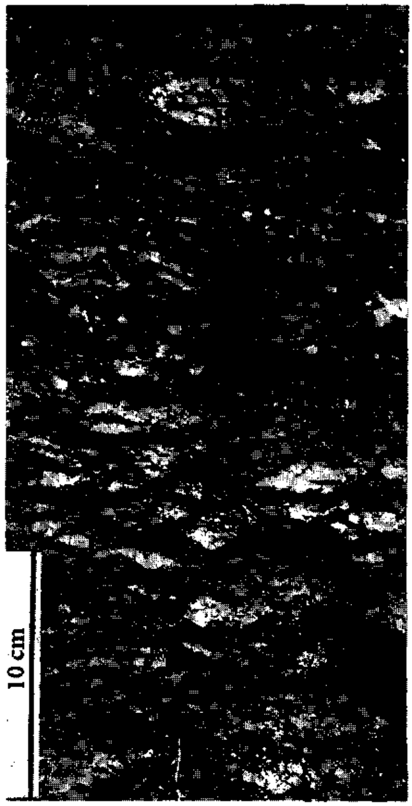

Photo 52: Wedge-shaped peds at about 100 cm depth in the Bw horizon of a Vertisol near Sennar. Structure changes with depth from subangular blocky via angular blocky to vertic with wedge-shaped peds built of finer peds of the same shape.

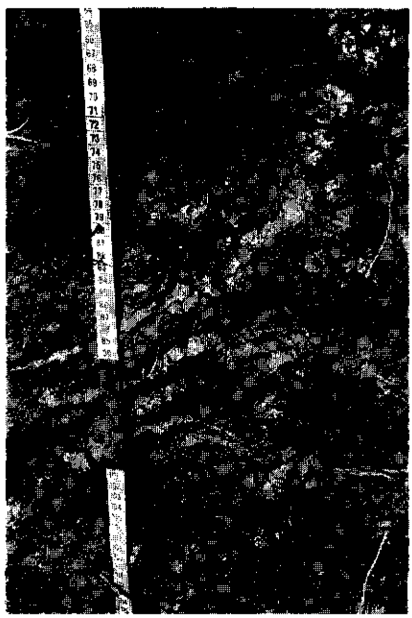

Photo 53: Part of the Bw horizon (between 65 and 115 cm depth) of a Vertisol in Umm Simsim area, showing slickensides built of adjoining ped surfaces. The surfaces are curved and lustrous.

The formation of the typical vertic structure has been discussed in an earlier publication (Blokhuis 1982). For the present study a brief and simplified account is given. The structure develops as a result of swelling and shrinking of soil material, following alternate wetting and drying. Stress is generated when wetting is unequal between adjacent soil bodies, or when swelling is obstructed by a (partial) infilling by surface mulch material of desiccation cracks. Stress in a confined volume is resolved by shear failure between adjacent soil bodies. This shear failure is in an oblique upward direction and creates wedge-shaped peds with their long axis tilted from the horizontal; the peds have slickensided surfaces. Ultimately the oblique upward movement of subsoil, combined with an infilling of cracks with surface soil, would result in a rotation of all soil material between the surface and the depth of cracking. This process is known as churning or - more adequately - as pedoturbation; it has a strong homogenizing effect on most soil properties.

Other morphological features are related to the presence or absence of internal soil movements. If pedoturbation affects the entire soil between the surface and the depth where cracks end, the soil should be homogeneous in all aspects that are not influenced by moisture content and overburden. Horizon differentiation within the zone of pedoturbation would be faint, and mainly restricted to soil structure. Within the zone of pedoturbation, soil colour, and type and amount of pedological features like carbonate and ferri-manganiferous nodules should show little or no change with depth. These features are likely to be different, however, in the underlying substratum.

Not all Vertisols are subject to a complete turnover of the solum, some show a vertical zonation in colour, soil texture and other features. One must assume, in these cases, a structure development due to shear failure without substantial displacement (Wilding 1985). Stronger horizonation is found in Vertisols which for one reason or another can be called immature or weakly developed, or Vertisols in which clay translocation processes have become active, and that are developing towards Alfisols (Blokhuis 1982; Dudal and Eswaran 1988).

In the Central Clay Plain, most Vertisols have the uniformity that complies with a complete turnover of the zone subject to alternate wetting and drying; however, in some cases the uniformity may have been inherited from the parent material.

Various approaches to horizon differentiation and coding in Vertisols will be reviewed in section 7.2. The morphological characteristics of the 27 representative profiles will be discussed in sections 7.3, 7.4 and 7.5 , with special emphasis on the Vertisols of the clay plain. Soil morphology was described at three levels:

- macromorphology: field studies of soil profiles and sites (section 7.3);
- micromorphology: the study of thin sections (section 7.5).
- stereomicroscopic study of soil fragments or peds at low magnification provides a link between macromorphology and micromorphology (section 7.4);

7.2. Horizon differentiation in Vertisols

7.2.1. General

Vertisols have been described either as AC, or as ABC profiles[1], and this more often reflects a difference in concept than in profile morphology and horizon sequence.

In the concept of a Vertisol consisting of a solum that is subject to slow but complete pedoturbation, and that overlies a substratum not subject to such internal movements, the AC code would be appropriate. Descriptions of Vertisols as AC profiles are found for example in CPCS (1967), FAO/UNESCO (1977) and Soil Survey Staff (1975).

In the concept of a Vertisol in which the development of structure is not matched by a complete turnover, and which, in addition to soil structure, has other morphological differentiation in the solum, the code ABC would be correct: swelling and shrinking would form a solum with the typical vertic structure, whereas other soil characteristics like colour, presence or absence of carbonates or oxidation/reduction mottles, would change with depth and allow differentiation between an A and a B horizon.

However, Vertisols have also been described as ABC profiles on differences in soil structure alone - and presuming complete pedoturbation - for example by French pedologists (Kaloga 1966). The A horizon, in this concept, is the surface soil with a blocky structure and only weakly expressed vertic characteristics, whereas the B horizon underlying it would have a distinct vertic structure throughout. Dudal and Eswaran (1988) recognize five zones in an idealized Vertisol structure profile: zone 1, the surface soil to 25 or 30 cm depth, consists of large prisms separated by wide cracks; zone 2 has an angular blocky structure; zone 3 has wedge-shaped aggregates with smooth and striated ped faces; zone 4 has slickensides; zone 5 is structureless, massive.

In most of the soils that we studied a differentiation could be made between an A horizon with a blocky structure and a bicuneate sub-structure, and a B horizon with a bicuneate structure throughout. The latter horizon qualifies as a Bw horizon on the ground of structure development. It would also qualify as a cambic horizon (Soil Survey Staff 1975).

There is a growing tendency to recognize B horizons in Vertisols, even if the concept of pedoturbation is adhered to. Suggestions have also been made to coin special codes and special names for the typical Vertisol subsurface horizon (Van Baren and Sombroek 1985 ; MacGarity 1985).

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[1] We have used the ABC nomenclature as proposed in a 1981 draft chapter of the new edition of the Soil Survey Manual (Soil Survey Staff 1951; 1981). Details are given in Appendix 2.

7.2.2. Vertisols of the Central Clay Plain

We have described the Vertisols of the Central Clay Plain as A-Bw-C profiles. The C horizon has features showing that it is below the zone of pedoturbation. We will also use the terms surface soil, subsoil and substratum for A, B and C, respectively. Additional differentiating characteristics refine this basic sequence. We mention the following:

a. The occurrence of soft powdery lime is characteristic of the substratum of most Vertisols: Ck horizon (Photo 54). In a number of soils fine carbonate specks occur in the Bw horizon. Such a Bwk horizon may reflect absence of pedoturbation or incomplete pedoturbation in a section of the profile that has the soil structure characteristics of a Bw horizon. In this case the B horizon could be fossil and should be regarded as a C horizon of the present solum. Bwk horizons are common in the northern, lower-rainfall regions of the Central Clay Plain; they may contain fine gypsum crystals and are then labelled Bwky (Photo 55). Although these horizons are probably C horizons as far as actual pedogenesis is concerned, we have adhered to the code Bwk, not only because this is in accordance with the common usage in soil survey reports of the term 'substratum' or C for the horizon underlying the Bwk, but also because of the much stronger appearance of features indicating an absence of pedoturbation in the underlying horizon. These features include the presence of abundant large aggregates of soft powdery lime, accumulation of coarse gypsum crystals, and of ferri-manganiferous mottles and coatings.

Photo 54: Detail of the Ck horizon in a Vertisol in Umm Simsim area, with abundant large concentrations of soft powdery lime. Note slickensides and glossy ped surfaces in the upper part of this profile section, and structureless soil below. The ruler is 10 cm.

b. Transitional horizons between A and B, and between B and C, are often mixed horizons with identifiable tongues or intrusions belonging to either one or other of the adjoining master horizons. B/C horizons are common in all Vertisols, A/B horizons are typical of the more arid northern part of the clay plain, and usually consist of a dark yellowish brown A horizon tonguing into a very dark grayish brown Bwk (Fig. 7.1 and Photo 56). If transitional horizons are not tongued, but continuous, they should be indicated as AB or BC. We have usually omitted these designations, because the boundaries between A and B, and between B and C in such soils are often diffuse. The diffuse nature of soil boundaries has been acknowledged by giving most depth measures in whole decimetres.

c. It is quite common for the horizon coded C, and labelled substratum, to show a vertic structure, albeit it less pronounced than the horizon coded B. We have given such a horizon the code C when we assumed, on morphological grounds, that it is at present below the zone of pedoturbation (exceptions to this rule-of-thumb are given under a. above). This may, however, not always have been so. Both in the aggradational and in the degradational plains sedimentation may have alternated with periods of landscape stability in which soil-forming processes could act upon the sediments. And structure formation in Vertisols is a relatively rapid process (Blokhuis 1982).

d. In some soils morphological differences with depth are so gradual that horizon boundaries cannot be defined. In extreme cases the only vertical zonation is one of grade and class of (vertic) structure, all other properties such as colour, type and abundance of carbonate concentrations, and the like, being equal. In such profiles we have omitted any horizon code. The substratum could generally be identified, but it was not always reached in the profile pit. For the sake of description and sampling such profiles were divided into sections, usually 0 to 15, 15 to 30, 30 to 60, 60 to 90 cm, etc.

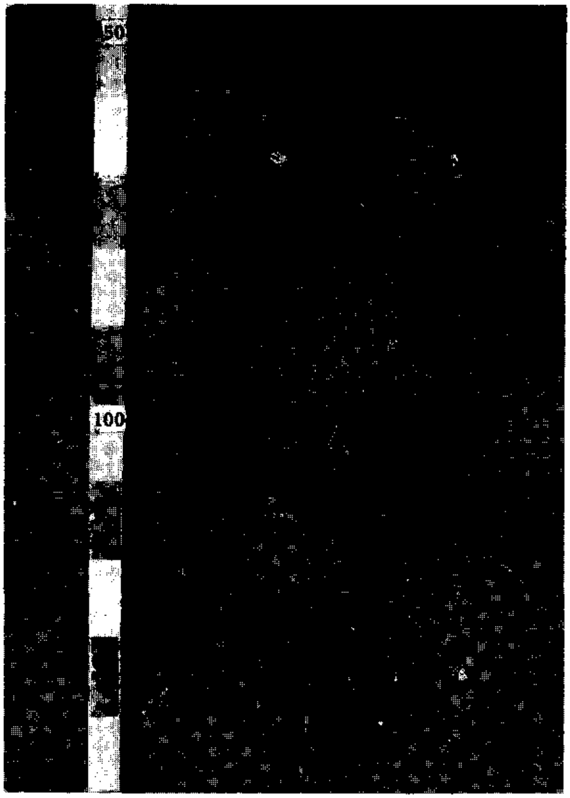


Photo 55: Vertisol profile at the Gezira Research Station. The fine ca-specks in the AB and B horizons are hardly visible; the white streaks below 120 cm are clusters of gypsum crystals.

Photo 56: Profile GARS 141 (nr.9): detail of A/Bwk horizon. The small ca-specks in vertical streaks are in intrusions belonging to the B horizon (10YR 4/1.5); the tongues belonging to the A horizon (7.5YR 3.5/2) have no ca-specks. The pen is 10 cm long.

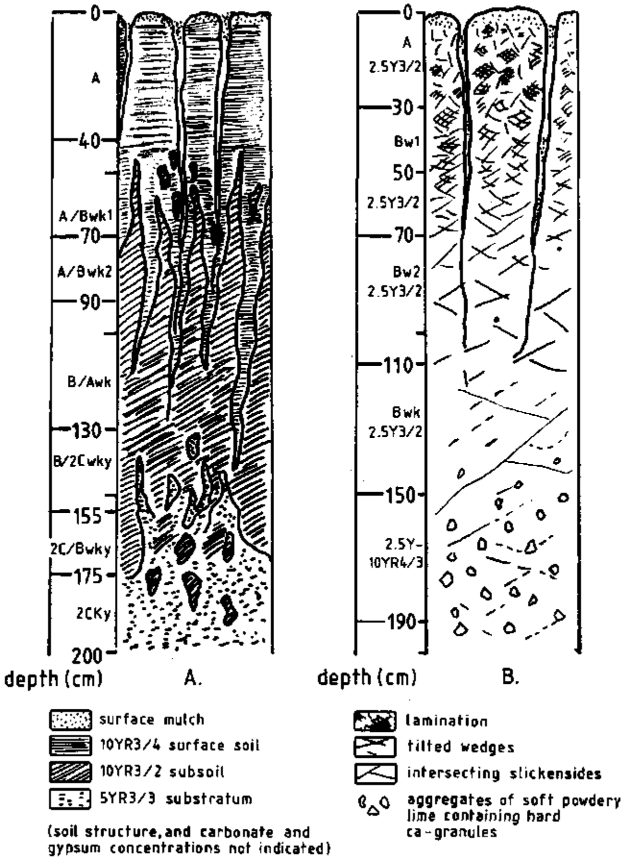


Fig. 7.1. Schematic representation of lower- and higher-rainfall clay plain Vertisol profiles: horizon sequence, soil colour and other features. A. Vertisol of the northern part of the clay plain; rainfall 400 mm (Khashm el Girba 213); B. Vertisol of the southern part of the clay plain; rainfall 800 mm (Ulu)

7.3. Field studies of soil profiles and sites

7.3.1. Material and methods

The profiles studied are listed in Table 6.1. Full site and soil descriptions are given in Appendix 2, which also contains an introductory section on items described and terms used.

7.3.2. Observations

Some of the observations on soil morphology were sufficiently reproducable to allow a comparison between soil profiles. These data have been summarized, and are presented in Tables 7.1 and 7.2. The tables have a first section on Vertisols from clay plain sites, and a second section on Vertisols and non-vertic soils from non-clay plain sites. The discussion below will, for each characteristic, concentrate on the clay plain Vertisols. This is followed by some remarks on soils from other sites, mainly as a comparison with clay plain Vertisols.

Not all morphological data are fit for such presentation and comparison, and some, for various reasons, are of lesser importance. We have left out the following:

- soil texture, moisture condition, soil consistence, the presence of hard carbonate granules and nodules, biological features, and nature of the boundary between soil horizons: all these have little differentiating value for Vertisols.
- colour of the surface crust or mulch, and width and depth of cracks, as these have been incompletely recorded. Besides, the width of cracks varies with the season, whereas the depth of cracking is not easily defined - cracks may merge with large interpedal voids bounded by slickensides. The depth of cracking is perhaps better recorded indirectly, for example by the depth at which large aggregates of soft powdery lime appear;
- some features that rarely occur have also been omitted: ferruginous mottles, and reddish streaks in the substratum.

Macromorphological features have been given in Tables 7.1 (horizon sequence and soil colour), and 7.2 (microrelief, surface characteristics, soil structure, carbonate and ferri-manganiferous concentrations 'in situ). In comparing soils one should compare similar horizons, but in case these are not discrete - as in Vertisols - soil properties at standard depths are to be preferred. The depths we have chosen are at 20, 40, 70, 100, 130, 160 and 190 cm. These depths are more often within a described soil horizon than at the boundary between soil horizons, especially in soils that have weak horizon differentiation. In the latter soils the sections for description and sampling are generally 0-15, 15-30, 30-60, 60-90 cm, etc.

Horizon sequence

Two types of horizon sequence can be distinguished in the Vertisols of the clay plain (Fig. 7.1):

a. The sequence A-A/Bwk-B/Awk-B/Cwky-C/Bwky-Cky-Ck (Khashm el Girba 213) is characteristic of the clay plains with rainfall up to about 500 mm: Atbara, Gezira, Butana, Northern Kenana clay plains, and northern part of the Blue Nile-Dinder-Rahad clay plain. The occurrence of gypsum (suffix y) in parts of the B and C horizons is the rule to which there are some exceptions (see below). The colour differences between A, B and C horizons made it possible to identify intermittent transitional horizons of the type A/B.

b. The sequence A-Bw-(Bwk)-BCwk-Ck is common of the clay plains with rainfall above 500 mm. Gypsum is rare; it occurs in the C horizon of Bozi and Simsim B27, where it may be related to a locally different mineralogy of the parent material.

When a Bwk horizon is not present, and the solum has a uniform colour, no differentiation between A and B is feasible, except for soil structure. Differences in soil structure between the A horizon and the lower part of the B horizon may be distinct, but the depth trend is so gradual that the boundary between A and B cannot be traced. The beginning of the C horizon, however, is usually clear. On the grounds of

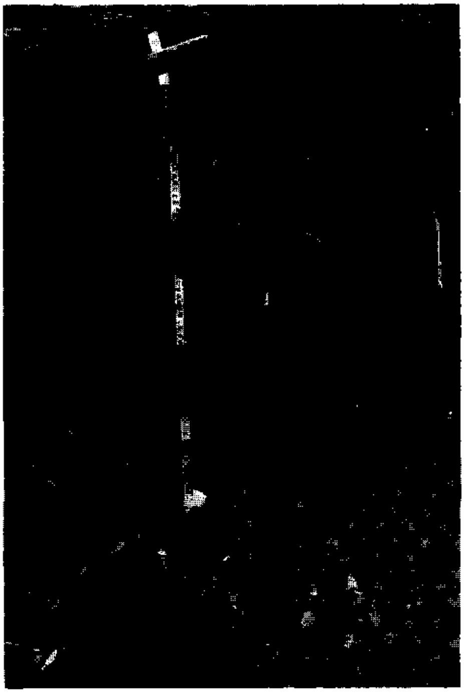


Photo 57: Profile Khadiga (nr.17), a 70-cm deep Chromustert on saprolite overlying basic metamorphic rock.

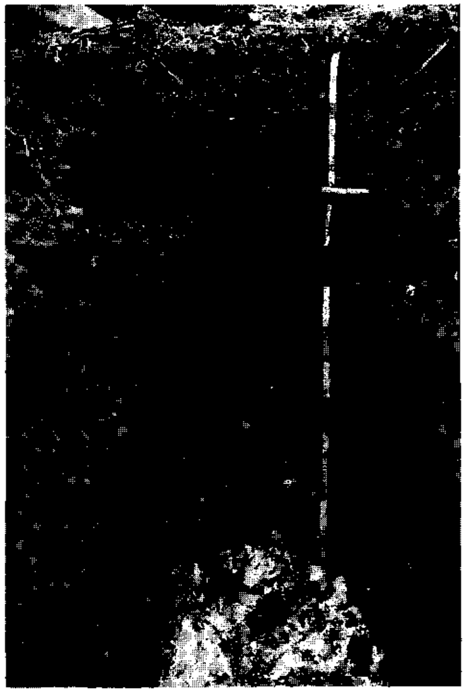


Photo 58: Profile Boing (nr.18), a 150-cm deep Pellustert on saprolite with abundant soft calcium carbonate, a secondary mineral formed 'in situ' from rock weathering.

the undefined boundary between A and B, no horizon codes have been given to the profiles Tozi, Damazeen and Renk.

Vertisols that have developed 'in situ' (Khadiga (Photo 57), Boing (Photo 58), Er Rawashda) or that are flooded for a considerable part of the year (El Gelhak) have different horizon sequences, and this also applies to the non-vertic soils.

Colour sequence

In section 6.4. surface soil colours were considered in relation to soil mapping units. There appeared to be a very gradual change with latitude: north of 13° N. colours were 10YR 3-4/3-4, south of this latitude they were 2.5Y-10YR 3/2. North of the Sennar-Gedaref railway line a difference in chroma of the surface soil was found between the degradational plain of the Butana (chroma 2) and the aggradational plain of the Blue Nile-Dinder-Rahad-Gezira (chroma 3 or 4). Substratum colours are also different: 10YR in degradational plains, 7.5YR or 5YR in aggradational plains.

The surface colours of representative Chromusterts of the clay plains (Table 7.1) show the north-south trend mentioned above. These can now be compared with subsoil colours, which allows the following generalizations to be made:

- Lower-rainfall areas have subsoil colours 10YR 2-3/2-1 (see for example the colours at 100 and 130 cm depth).
- Higher-rainfall areas have subsoil colours that are no different from the surface soil colours (2.5Y-10YR 3/2).
- Colours of the substratum are usually different from those of the subsoil; this feature is most clearly expressed in Chromusterts of the lower-rainfall areas.

Pellusterts, both within and outside the clay plain proper, have low chroma surface soils by definition. Usually, the low chroma continues throughout the solum (Tozi, Seinat B55, Er Rawashda, Boing, El Gelhak).

Microrelief

Gilgai occurs in the higher-rainfall clay plains. It is usually of the normal or round type, with wavelength from 5 to 12 m, and an amplitudo (vertical interval) between 10 and 30 cm. Sink holes in the centre of the depressions are a normal feature. In gently undulating areas, for example the Southern Kenana clay plain, wavy gilgai is widespread.

The border between gilgaied and non-gilgaied Vertisols is at approximately the 600 mm isohyet. Clay plain sites situated on the 600 mm isohyet - Jebel Abel, Tozi, Bozi - either have gilgai of shorter wavelength (2 to 3 m), or there is merely an unevenness of the surface, which does not qualify as gilgai because of its scale (see introductory section of Appendix 2).

An irregular surface is also found at some of the sites that are subject to prolonged flooding and this is probably due to a combination of more pronounced shrink/swell cycles and of gullying by 'khors'. Examples are: Tozi and Khashm el Girba 238. This unevenness also occurs in Seinat B55, on the scale of the cracking pattern, whereas the gilgai at this site is a superimposed microrelief of larger dimensions.

The patchiness described for Khashm el Girba 251 is of a different nature: the surface shows an alternation of strongly cracked and merely superficially cracked patches on a scale of one to two metres. This irregularity is matched with a certain patchiness in the *Setaria* short grass vegetation (Photo 40).

Surface

A mulch of fine to medium granular or crumb aggregates, with loose consistence when dry, is a common surface feature of the Vertisols of the Central Clay Plain. It is generally well-developed, some centimetres thick, sloughing into the cracks and partly obscuring the cracking pattern (Photos 59 and 60).

Vertisols with a hard surface crust that persists through the dry season, occur on border sites between clay plain and non-rocky elevation in the Seinat and Simsim areas (e.g. at the site of Seinat B7 (Photo 61)), on pediment slopes (e.g. Khadiga), and at some of the sites subject to more intensive flooding than the surroundings (e.g. Khashm el Girba 238). A crusty surface is also present at the site of the Vertisol/ Inceptisol intergrade (Seinat B47) and the Alfisol (Seinat B 48).

Photo 59: Cracks, developing after the rainy season (in October) at the site of profile GARS 141. The finely cracked surface between the (future) large cracks will eventually develop into a surface mulch. The pocket knife is 10 cm.

Photo 60: Fully developed cracking pattern (in March) at the Gezira Research Station. The surface mulch is sloughing into the cracks, partly covering them. The pocket knife is 10 cm (the stones are not natural).

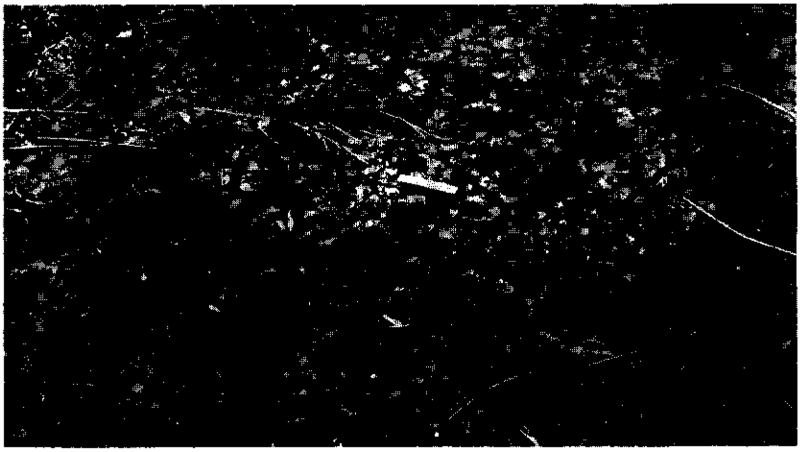


Photo 61: Hard surface crust at the site of profile Seinat B7 (nr.22), a slightly sandy and gravelly Vertisol. There is no surface mulch; cracks remain open in the dry season and have sharp edges. The ruler is 10 cm.

Soil structure

Most aspects of the soil structure of Vertisols cannot be measured or described in a way that is sufficiently reproducable to permit comparison between profiles. However, two features can be quantified: the presence of vertic structural aggregates, and the occurrence of shiny or slickensided ped faces and/or slickensides. For both features depths of both beginning and end are given in Table 7.2.

The following observations were made on clay plain Vertisols:

a. The vertic structure usually begins immediately below the surface mulch or at shallow depth (15 to 40 cm). The exception is Tozi, a slightly sodic soil (section 8.6).
b. Shiny ped surfaces begin between 5 and 160 cm depth; usually deeper in the lower-rainfall than in the higher-rainfall soils.
c. The vertic structure and the slickensided ped faces often continue below the zone of present pedoturbation, that is: well into the C horizon.

Carbonate concentrations 'in situ'

Three forms of carbonate concentrations have formed 'in situ' (see the introductory section of Appendix 1 for their definition):

a. ca-specks: fine, white, 1 to 3 mm diameter soft carbonate nodules;
b. soft powdery lime: aggregates, larger than ca-specks;
c. soft powdery lime containing hard, white ca-nodules or ca-granules.

The occurrence of ca-specks is limited to the B horizon - and mainly the upper part of it - of the lower-rainfall Vertisols. These fine ca-mottles first appear in a zone of the profile where surface soil and subsoil form a network of tongues and intrusions (A/B and B/A horizons). The ca-specks occur in the intrusions of B soil material (dark grayish-brown clay) in this zone, whereas the tongues of A soil material (dark brown clay) lack carbonate concentrations (cf. section 4.4.3). Larger aggregates of soft powdery lime appear at depths between 65 and 165 cm, and mark the beginning of the C horizon (see above). Sometimes the aggregates of soft, powdery lime contain hard, white ca-nodules and -granules.

Ferri-manganiferous mottles and coatings

The presence of fine metallic-bluish manganiferous coatings on slickensided ped surfaces, and occurring as cutans/neocutans around grey carbonate nodules (distinct in thin sections, see section 7.5.) indicate that pedoturbation is absent, incomplete or very slow. These soft concentrations of ferric and manganese oxides are a substratum feature in all Vertisols; in some of the higher-rainfall Vertisols they are also found in the solum.

Manganiferous coatings are also present on the few, large slickensides in the half-ripe subsoil of El Gelhak, and throughout the Hadeliya profile (an Entisol). They form in a relatively short period of time, and their presence is not incompatible with (slow) pedoturbation.

7.3.3 Discussion: pedoturbation, structure formation and depth of cracking

We have seen that Vertisols from the lower-rainfall clay plains are made up of three horizons/layers of contrasting colour, whereas in the higher-rainfall Vertisols there are only two such horizons/layers: solum and substratum. In the lower-rainfall sites present pedoturbation is restricted to the 10YR 3-4/3-4 surface soil,as this is the only part of the solum that has a uniform colour. However, the bicuneate structure usually continues throughout the deep zone of transition between this surface soil and the 10YR 3/2 subsoil, and below, into the C horizon. Besides, it is generally the lower part of the B horizon, where shiny ped faces are distinct. Vertic structure in what has been described as B and C horizons must be due to former pedoturbation, or at least to former soil movement. As far as the A/B-B/A-zone of the lower-rainfall soils is concerned, it is unlikely that there is no soil movement at present: cracks penetrate well into this zone and below it (Zein el Abedine et al. 1971), and the depth below which the moisture condition throughout the year remains constant is at about 120 cm in Gezira soils (Farbrother 1972). So, the surface soil and the transitional A/B-B/A-zone must be subject to swell/shrink cycles as a consequence of present-day cycles of wetting and drying. There is,however, in this horizon no complete mixing, as the A and B soil materials are tonguing and interfingering (Fig. 7.1). Swell and shrink of the soil material in this section of the profile do not lead to pedoturbation, but they do result in soil movement. In this manner a vertic structure is formed without mixing. We must thus assume a process of soil heaving and sinking without a net displacement after a complete wetting/drying cycle.

Zein el Abedine et al. (1971) ascribe the tongues with A soil material protruding into the B horizon as crack infillings; cracks were found to coincide with the larger tongues and they reach to the bottom of the A/B-B/A-zone. The intrusions ('inverted tongues') of B soil material into the A horizon would be thrust-up portions of B soil.

This theory is not at variance with our hypothesis; in fact, crack infillings are perhaps the prime mechanism for creating an A/B-B/A transitional zone in soils of the northern part of the clay plain. Soil stress results from the infilling of cracks, and this is sufficient to create a bicuneate structure and soil heaving, but does not lead to complete pedoturbation. There may have been a deeper pedoturbation in previous, wetter climates, contrasting with a relatively shallow pedoturbation at present.

Wilding (1985) and Wilding and Tessier (1988) suggested that in addition to Vertisols with a complete pedoturbation of the solum, there are others that show a distinct zonation with depth notwithstanding the presence of a vertic structure; there would be soil heaving and sinking without pedoturbation,and each portion of soil would return to its starting position after one wetting/drying cycle. This 'soil mechanics model', rather than the 'pedoturbation model', would apply to the lower-rainfall Vertisols of the Sudan. In the higher-rainfall Vertisols one would expect a stronger pedoturbation because of deeper and more intense wetting during a longer rainy season. But whether or not the soil mechanics model would be active here cannot be ascertained as any tongues of A-horizon-soil and intrusions of B-horizon-soil would have the same colour. Fine ca-specks - which, in addition to colour, are reliable indicators of B material in the lower-rainfall Vertisols - are absent in the higher-rainfall soils. This could imply that not enough finely divided lime is present to form such ca-specks, but it could equally well imply that a deeper pedoturbation as compared to the lower-rainfall Vertisols, prevents their formation.

In Chapter 8 we will see to what extent the laboratory data support either the pedoturbation or the soil mechanics model.

Finck (1961) suggested that the higher chroma of the surface soil in the lower-rainfall Vertisols is due to a process of rubefaction following a change towards a drier climate. The lack of a colour difference between A and B horizons in the higher-rainfall areas would indicate the absence of rubefaction, whereas the similarity of subsoil colours in both lower-rainfall and higher-rainfall clay plains, suggests that prior to the assumed rubefaction stage all Vertisols of the plains had the same surface solour, i.e. 10YR-2.5Y 3/2. Observations in the Khashm el Girba area (section 6.5.1) are in line with Finck's hypothesis.

In section 4.4.3 we have related the rubefaction of the surface soil to the period 3,500 BP till present, under climatic conditions similar to those of today, and much drier than those of the preceding period (3,500 - 6,000 BP; section 4.3).

Vertic structure and slickensided ped faces often continue well into the subsoil, where the presence of large aggregates of soft, powdery lime and of ferri-manganiferous mottles and coatings shows that pedoturbation is not an active process. The presence of soil structure in a section of the profile that otherwise qualifies as a C horizon, shows that this structure is a fossil feature. Either an alternation of periods of sedimentation and of landscape stability with soil (structure) formation must have existed, or a very gradual building-up of the sediment with annual wetting-and-drying cycles.

Some of the Vertisols in the higher-rainfall clay plain sites do not contain soft aggregates of lime, at least not within the depth of the profile pit, whereas other Vertisols have soft lime aggregates beginning at a depth of 90 to 100 cm. If we consider the presence of soft aggregates of lime to indicate a C horizon, then there is not much difference between depth of solum in lower-rainfall and higher-rainfall clay plains. If, however, we consider the presence of any form of soft lime (whether ca-specks or soft aggregates of lime) as an indication of the C horizon, then there would be a difference: rather shallow soils (40 to 65 cm depth) would occur in the lower-rainfall zone, and deep soils (100 to 150 cm depth) in the higher-rainfall zone.

There remains the question of the slickensided ped surfaces. In the A/B-B/A-zone of the lower-rainfall profiles there is a bicuneate structure, but the ped faces lack glossiness. Could this imply that, at least at present, there are no soil movements? This is unlikely with a view to the reverse case: many true C horizons that at present lack pedoturbation have distinctly slickensided ped surfaces. An interesting observation in this respect is that all vertic ped faces are glossy when viewed by binocular microscope with magnifications from 10 to 50x, even the finest parallelepipeds (section 7.4).

7.3.4. Conclusions

Vertisols of the clay plains show differences in morphology that are related to a north-south gradient in annual rainfall and to differences in origin and nature of the parent materials. Residual or colluvial soils (Khadiga, Boing, Er Rawashda) and soils of ponded sites (Khashm el Girba 238, Sennar 71, Tozi, El Gelhak, Seinat B55) are different from clay plain soils on datum sites. The following observations have been recorded:

- The boundary between Vertisols with and without a gilgai microrelief is along the 600 mm isohyet; north of this line there is no gilgai, south of it round or normal gilgai is common on level terrain and wavy gilgai on gentle slopes.
- A well-developed surface mulch is present, except for soils with deviating surface material. Jewitt et al.(1979) observed a decreasing trend of mulch development with increasing rainfall, and they related this to a similar trend in the amount of free carbonates present. This trend is not confirmed in our reference profiles, but from roadside observations it was evident that maximum mulch formation is in the Butana clay plain.
- A horizon sequence of the type A-A/Bwk-B/Awk-B/Cwky-C/Bwky-Cky-Ck occurs in areas with rainfall below 500 mm. A horizon sequence of the type A-Bw-(Bwk)-BCwk-Ck occurs in areas with rainfall of 500 mm or above. The C

horizon is defined on a difference in colour with the B horizon (see below) and/or on the presence of aggregates of soft powdery lime. Abundant gypsum occurs in the upper part of the C horizon in the lower-rainfall region.

- Surface soil colours north of latitude 13°30'N are 10YR 3-4/3-4 and subsurface colours are 10YR 3/2, 3/1, 2/2. South of this latitude soil colours are usually uniform throughout the solum, at 10YR-2.5Y 3/2. Observations along the road show that north of the Sennar-Gedaref railway aggradational plains have surface soils with chroma 4, sometimes 3, degradational plains have chroma 2. Latitude 13°30'N and the Sennar-Gedaref railway are roughly between the 500 and 600 mm isohyet.
- Soil structure is bicuneate throughout the solum, or this type of structure begins at shallow depth. It often extends well into the C horizon. Shiny ped faces usually begin deeper than where the vertic structure begins. The soil below the present zone of pedoturbation often shows both bicuneate structure and shiny ped faces.
- Shiny or slickensided ped faces visible to the naked eye begin at depths between 20 and 160 cm, and extend into the C horizon. In the lower-rainfall soils shiny ped faces begin at depths between 90 and 160 cm; in the higher-rainfall soils at depths between 20 and 60 cm.
- The appearance of soft powdery lime marks the lower boundary of the zone of pedoturbation. The presence of ca-specks in a transitional A/B horizon with tongues and intrusions, indicates soil movement (and formation of bicuneate peds) which is only partly, if at all, accompanied by pedoturbation.
- Manganiferous coatings and mottles - with or without ferric iron - occur more frequently in the substratum than in the solum. They occur mainly, but not exclusively, in the zone below present pedoturbation.
- Soil movement without pedoturbation is likely to occur in the subsoil horizons of lower-rainfall Vertisols, and it should not be excluded in the higher-rainfall Vertisols.

7.4 Stereomicroscopic studies

7.4.1 Material and methods

Undisturbed soil samples - fragments or large peds - were studied by means of a Leitz Greenough stereomicroscope, using magnifications of 10x and 50x. Special attention was given to the surfaces of structural aggregates, and to the occurrence and position in the matrix, of ferric, manganiferous and carbonate concentrations. The terms used are not according to a standard terminology.

For the stereomicroscopic observations a selection was made of samples from some of the representative profiles listed in Table 7.1., viz. Khashm el Girba 213, 215, 251, 238 and 256, Jebel Qeili, Er Rawashda, Sennar 49 and 71, Jebel Abel, Tozi, Damazeen, Ulu and Renk.

For a detailed study of soil structure the 10x and 50x magnification provided an optimum scale of observation. The study of carbonate concentrations and some other pedological features revealed the position of these features in the soil matrix better than either the field or the thin section observations.

7.4.2 Observations and discussion

Soil structure

The finest wedge-shaped peds (parallelepipeds) have transparant glazed surfaces; they appear as microslickensides. This is a general observation on all peds that have a double-wedge shape. Surfaces of larger wedge-shaped peds show the transparant glazed surfaces even more distinctly. Sometimes a distinction can be made between natural surfaces that are glazed, and surfaces of clods or fragments that are rough. The ped faces have distinct parallel grooves. Larger grooves form a pattern, which on cross-section shows a certain wavelength, whereas on some surfaces finer grooves also occur. The latter are at a shorter mutual distance, and they form a superimposed pattern with a shorter wavelength. In a number of samples slickensided ped surfaces carry root prints.

Carbonate concentrations

The various forms of carbonate concentrations known from field descriptions can be clearly distinguished. The scale of magnification also allows identification of the types A through E of the thin section descriptions (section 7.5). The ca-specks of the field descriptions appear to be concentrations around fine biopores; this is type B of the thin section classification.

Manganiferous or ferri-manganiferous mottles, coatings and nodules

These concentrations appear more often in the stereomicroscopic descriptions than in field descriptions of corresponding soil horizons. However, the general picture that these features occur in the B/C and C horizons, is confirmed.

There are some interesting observations from separate samples or specific profiles. These are given below together with relevant field observations (see Appendix 2 for the profile descriptions):

a. Streaks of reddish soil are often found in B/C and C horizons. They are described in the field and are distinct under the stereomicroscope. They have been recorded in Khashm el Girba 213 and 215, Jebel Qeili, Sennar 49 and 71, Jebel Abel and Tozi. The streaks occur in a zone where pedoturbation is incomplete or absent. The origin of the reddish soil could be:

- surface soil fallen into cracks;
- burnt earth from bush or grass fires fallen into cracks.

It should be noted that the reddish streaks are found mainly in soils that have an A horizon which has a more reddish colour than the B horizon (the exception is Tozi).

This observation suggests that the reddish streaks are pockets of surface soil. If this is a correct hypothesis, it also explains why this feature is not found in the higher-rainfall soils. The presence of reddish soil pockets at great depths suggests that cracking goes much deeper than the depth of the homogeneous surface soil.

b. Khashm el Girba 215 has a silt loam substratum with abundant fine pores coated with carbonate (type B of the thin section classification). A similar observation was made in the silty substratum of Khashm el Girba 238. The fine pores could be root pores of a vegetation that flourished during the interval between the deposition of the substratum and that of the dark grayish brown surface deposit (cf. Chapter 4 and section 6.5.1).

c. Hadeliya, the profile from the Gash delta, is a uniform clay profile, but not a Vertisol. Below a finely stratified surface deposit of 3 cm, the soil is apparently structureless. However, the field description mentions darker-coated surfaces of weakness along which the soil parts into fine peds when a fragment is taken from the profile wall.

Stereomicroscopic observation reveals a fine lamination with incipient ped surfaces that appear as glazed microslickensides, often with a (ferri-)manganiferous coating. There is, apparently, a predisposition for a parallelepiped structure. The Hadeliya soil may be in the process of developing into a Vertisol, and could be designated a 'proto-Vertisol'.

As already stated in section 7.1, stereomicroscopic observations are a link between field observations and thin section studies. They do not provide a set of observations in their own right, but clarify observations made in the field and in thin sections.

The observation that all bicuneate peds have a glazed surface is specific for the stereomicroscopic study.

7.5 Thin section studies

7.5.1 Material and methods

Thin sections of undisturbed samples were prepared according to the method described by Jongerius and Heintzberger (1975). They were of three sizes: sections with a diameter of about 2 cm from samples collected in small tins; sections with a diameter of about 5 cm from samples taken in Kopecki rings, and sections of variable size (up to 15 cm) from undisturbed soil aggregates or fragments.

The thin sections were studied by means of a Leitz Ortholux Pol microscope in plain and in polarized transmitted light. For the study of the plasmic fabric circular polarization was sometimes used. Most observations were done at magnifications of 31x, 79x and 125x, in some cases up to 200x.

The thin sections were described according to Brewer (1964), unless otherwise stated. Poor quality impregnation, often resulting in unequal thickness of the slice, prevented consistent observation in a number of thin sections. These sections had been prepared at a time that impregnation of swelling clay soils met with great difficulties.

The thin sections are from the 24 Vertisol profiles and the 'proto-Vertisol' Hadeliya. Nineteen of the Vertisols are from clay plain locations (including two profiles from the Damazeen site), and fourteen of these have been sampled throughout the profile. The present discussion is restricted to the fourteen fully sampled clay plain Vertisols. Some of these have been the subject of earlier micromorphological investigations (Blokhuis et al. 1968/1969; 1970).

7.5.2 Selection and general description of relevant micromorphological features

The micromorphology of Vertisols in general has been described and discussed by Nettleton and Sleeman (1985), Mermut et al. (1988) and Blokhuis et al. (1990). In the present study we have focussed on Vertisols that cover a large, more or less continuous clay plain, and on their differentiating characteristics. We have, therefore, concentrated on features that could serve as parameters for processes that distinguish, in a consistent manner, between profiles, or between horizons within a profile. The selected features are: plasmic fabrics, planar voids, carbonate and ferri-manganiferous plasma concentrations, clay illuviation cutans, papules, and intercalary crystals of carbonate and gypsum.

7.5.2.1 PLASMIC FABRICS

The plasmic fabrics in Vertisols can be assigned to three categories (Blokhuis et al. 1990):

1. Surface-related plasma separations. These are of two types:
- **vosepic plasmic fabric,** which is normally present along the planar voids between structural aggregates.
- **skelsepic and glaesepic plasmic fabric.** Striated extinction patterns are found around skeleton grains (Photo 62) and hard, discrete glaebules. They result from pressure and shearing of the swelling clays in which the grains and glaebules are embedded.

2. Subcutanic plasma separations. These are banded areas with a striated extinction pattern, and they occur unrelated to voids: **masepic plasmic fabric** (Photo 63). Vosepic-bounded planar void surfaces along a closed void, or an extension of such striations into the soil matrix (De Vos and Virgo 1969) were also described as masepic fabric. Brewer (1964), and Sleeman and Brewer (1984) found that masepic fabric forms upon shearing of clay-size soil materials.

3. Unrelated plasma separations. These occur in the soil matrix irrespective of surfaces, and are also referred to as matrix plasmic fabric. There may be a flecked

orientation pattern (**asepic**), or the clay domains occur oriented and form striated extinction patterns (**sepic**). As the soil material contains much clay, all asepic fabrics are **argillasepic**. The areas with striated extinction patterns may occur as separate islands in the matrix (**insepic**), or they adjoin each other (**mosepic**); in rare cases all of the plasma consists of oriented clay domains (**omnisepic**).

Lattisepic plasmic fabric has been described in swelling clay soils other than Vertisols by McCormack and Wilding (1974), and these authors assumed that it may also develop in Vertisols. Brewer (1964) considers lattisepic fabric as a variant of bi-masepic fabric (i.e. masepic plasmic fabric occurring in two sets of subparallel zones, in two defined directions). As, however, there are no clear criteria to distinguish between lattisepic and (bi-)masepic plasmic fabric, we have classified all banded striations that are not surface-related as masepic.

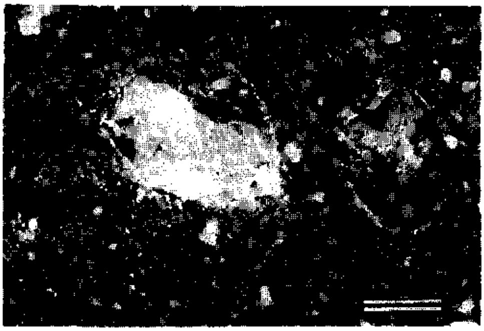
Results of an earlier study on the micromorphology of Sudan Vertisols (Blokhuis et al. 1970) showed that skelsepic plasmic fabric is a regular feature in Vertisols of the Central Clay Plain which have a soil matrix with sepic forms of plasmic fabric. Skelsepic plasmic fabric may even occur in a soil matrix with an asepic fabric. It is more strongly developed when the mineral grains are larger.

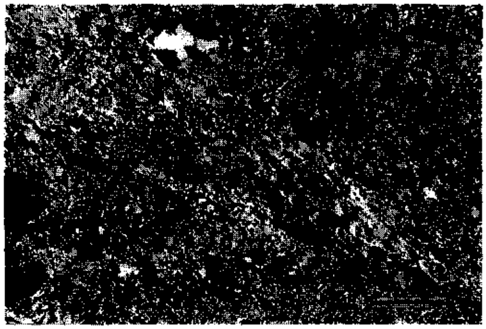
Blokhuis et al. (1970) found that (a) the width of the planar vosepic plasmic fabric, and (b) the fraction masepic fabric of the total plasma, could be used as parameters for vertic processes, in a quantitative way. This was criticized by Osman and Eswaran (1974) who argued that the expression of plasmic fabric was a function of the free-iron-content as well, and was probably also related to the ratio of skeleton grains to plasma; the features mentioned could, however, together with other characteristics, be used as parameters in a qualitative manner.

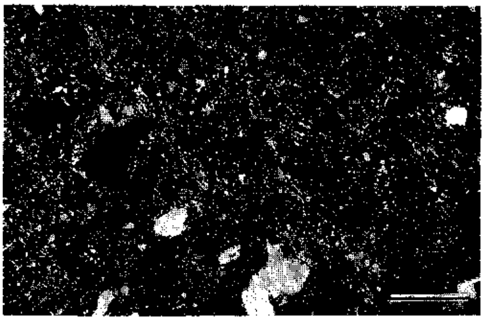
It was also found (Blokhuis et al. 1970) that the width of the zone of oriented clay domains around skeleton grains and hard glaebules, and the distinctness of this zone, was influenced not only by the intensity of the vertic processes, but also by the size of the mineral grain or the glaebule. Skelsepic and glaesepic fabric thus appeared unsuited as parameters for the quantification of vertic processes, unless grains of the same size would be considered. We have, therefore, omitted a systematic description of these types of plasmic fabric.

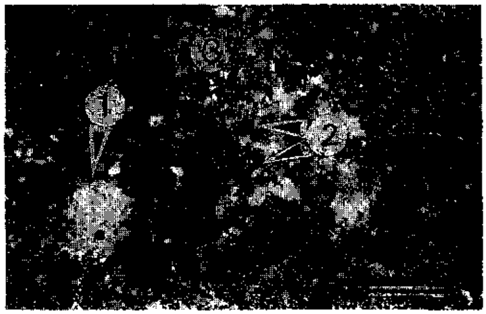
7.5.2.2 VOIDS

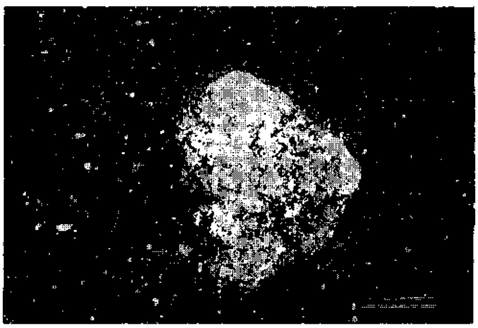
The description of voids was restricted to what have been called accomodating voids: voids between opposite and parallel ped surfaces (Bullock et al. 1985). Brewer (1964, p.197) uses the term 'joint planes' for planar voids that traverse the soil material in some fairly regular pattern, such as parallel or sub-parallel sets, and 'skew planes' for planar voids that traverse the soil in an irregular pattern. The morphology of Brewer's joint and skew planes is the same, and we therefore prefer to use only one term: **skew planes** (Photo 64). When the planar voids form (sub)parallel sets we have used the term **joint skew planes.**











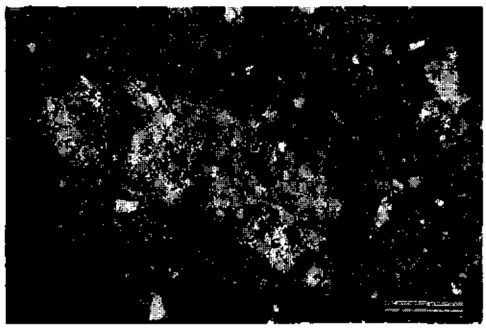


Photo 62: Skelsepic plasmic fabric; profile Boing; crossed polarizers; bar represents 120 µm.

Photo 63: Masepic plasmic fabric; profile El Gelhak; crossed polarizers; bar represents 160 µm.

Photo 64: Skew planes between 30 and 60 cm depth; profile Bozi (nr.15); crossed polarizers; bar represents 350 µm.

Photo 65: Type A diffuse carbonatic nodule (1), void calcitans (2) and intercalary calcite crystals (3); profile Er Rawashda (nr.7); crossed polarizers; bar represents 200 µm.

Photo 66: Type D carbonatic concentration with manganese impregnation; profile Er Rawashda; crossed polarizers; bar represents 500 µm.

Photo 67: Type E carbonatic nodule with mangan/neomangan; profile Er Rawashda, 120 to 140/160 cm depth; crossed polarizers; bar represents 160 µm.

The third type of planar voids, as defined by Brewer, the craze planes, do not have parallel walls - they are not accomodating - and we have considered them to be unrelated to vertic processes. The same applies to vughs and to channels. Craze planes, vughs and channels are common in all Vertisols. Channels are found in almost all thin sections. They occur more often in surface soils than in deeper horizons. Relatively wide channels are the result of faunal activity; they often contain matrix fecal pellets and (sub)angular soil fragments. Root channels are generally narrower, less curved and have smoother walls. We have not consistently described planes, vughs and channels, and will not further consider these voids.

7.5.2.3 CARBONATE CONCENTRATIONS

Carbonate concentrations are a regular feature of all Vertisols of the Central Clay Plain. They belong to four different categories of pedological features cf. Brewer (1964), viz. cutans, glaebules, crystallaria and subcutanic features. Chemical analyses of carbonate glaebules from different areas in the Central Clay Plain showed that these were calcitic (Blokhuis et al. 1968/1969; Kerpen et al. 1960).

In our descriptions we have chosen for a classification that has more genetic implications for vertic processes than Brewer's. The classes are, however, described in Brewer's terminology. A first sub-division was made between carbonate concentrations that have developed 'in situ', and others that have been transported. The latter may be relatively pure or they may be impregnated by sesquioxides. It has also been considered whether the precipitation of sesquioxides followed carbonate precipitation or preceeded it, or whether both components precipitated simultaneously or alternately. The morphological classification presented below is based on these considerations; it is a simplification of the classification by Blokhuis et al. (1968/1969). Five forms have been distinguished:

- Type A: diffuse, normal nodules, apparently not associated with voids; with an irregular boundary (Photo 65).
- Type B: carbonate concentrations, associated with voids (neocalcitans, sometimes calcitans) and invariably occurring in a soil matrix that also contains (clusters of) intercalary crystals (Photo 65).
- Type C: discrete, normal nodules, usually well-rounded; apparently not related to voids.
- Type D: like C, and containing impregnations of ferric and or manganese oxides (Photo 66);
- Type E: like D, and a mangan/neomangan ties nodule and surrounding s-matrix together (Photo 67).

In the earlier classification, type A was called type II, type B was IV, and type C was III. Types D and E were sub-types of type III.

The genetic implications of the forms A to E are:

- Type A is formed 'in situ' as evidenced by diffuse boundaries. - Type B is, without doubt, a formation 'in situ'; absence of transport is also shown by the clusters of intercalary calcite crystals in the soil matrix.
- Types C and D have been transported. Type D nodules are assumed to have developed from type C by receiving a secondary impregnation by ferric iron and/or manganese; a precipitation simultaneously with that of calcite is evident in several nodules.
- Type E has also been transported, but the mangan/neomangan has formed at its present location.

7.5.2.4 FERRI-MANGANIFEROUS CONCENTRATIONS

Ferric glaebules and other forms of concentrated ferric oxides occur in the s-matrix as translucent yellowish-brown or reddish-brown spots. Colour differences between ferric concentrations may be due to differences in iron content and in mineralogy (Brewer 1964, p.262). Manganiferous glaebules and other forms of manganese concentrations occur as dark-brown to black spots in thin sections. Such dark-coloured, opaque bodies may, however, contain 60 to 80% Fe_2O_3, with only a minor portion being manganese oxide (Blokhuis et al. 1990). Dark-coloured dendritic forms, on the other hand, consist mainly of manganese (Blokhuis et al., 1968/1969). For this reason we did not distinguish between ferric and manganiferous, but grouped them together as **ferri-manganiferous concentrations.**

The classification that we applied - and which is partly based on an earlier study (Brouwers 1969) - aims at recognizing categories that reflect different environments and, consequently, allow the interpretation of soil processes that are or have been active. We have distinguished the following types:

- Type 1: neoferrans, neomangans and neoferri-mangans (associated with voids) (Photo 68) and diffuse ferri-manganiferous nodules (apparently not associated with voids). Manganiferous concentrations are often in a dendritic pattern.
- Type 2: diffuse ferri-manganese concretions. Successive concentric bands differ in colour and this may reflect differences in concentration or in nature of the compounds.
- Type 3: discrete ferri-manganese concretions (Photo 69). Differs in thin section from type 2 only in the sharpness of the outer boundary.
- Type 4: discrete nodules, mainly ferric.
- Type 5: glaebules that differ from the s-matrix of the surrounding soil material in being largely or entirely impregnated by ferric iron and/or manganese. These 'matrix glaebules' are discrete and well-rounded to angular.

The genetic implication of this differentiation is as follows. All types indicate temporary hydromorphism, especially the concretions (types 2 and 3). Types 1 and 2 are formed 'in situ'. Types 3 and 4 have formed 'in situ' or have been transported. Type 5 has been transported, either by water (rounded glaebules) or by gravity (material falling into desiccation fissures: angular glaebules).

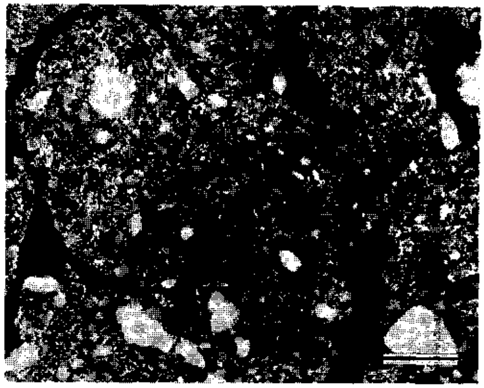


Photo 68: Type 1 FeMn concentration: neoferri-mangan, associated with voids; profile Damazeen A (nr. 14); crossed polarizers; bar represents 150 µm.

7.5.2.5 OTHER PEDOLOGICAL FEATURES

Clay illuviation cutans (**argillans**) and dislodged fragments of argillans (**papules**) are exceptional features in Vertisols. **Intercalary gypsum** crystals are found in a number of thin sections. Their distinct crystal shape and colour make identification simple (Photo 70). The micromorphological observations generally confirm the field observations. **Intercalary calcite crystals** (Photo 65) are often found in association with type B carbonate concentrations.

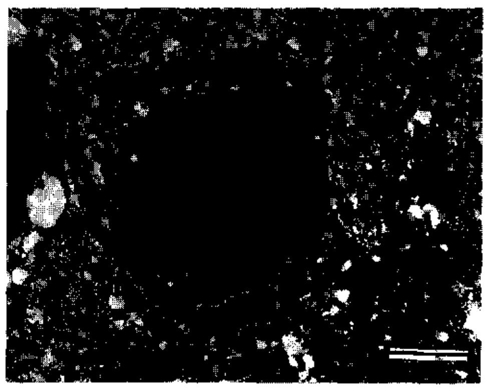


Photo 69: Type 3 FeMn concentration: discrete ferri-manganese concretion; profile Boing, at 85 cm depth; crossed polarizers; bar represents 150 µm.

7.5.3 Observations and discussion: clay plain sites

Table 7.3. gives a qualitative and, for some features, a semi-quantitative inventarization of the thin sections studied.

7.5.3.1 PLASMIC FABRICS

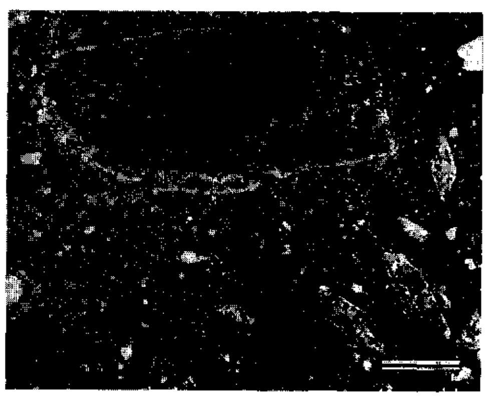


Photo 70: Intercalary gypsum crystals; profile Simsim B27 (nr.21), 130/140 to 175 cm depth; crossed polarizers; bar represents 425 µm.

Most thin sections have a non-uniform pattern of asepic and unrelated sepic plasmic fabrics. Within a single thin section some areas may have argillasepic, others mosepic plasmic fabric, and there are transitional areas between them. When the unrelated plasmic fabrics (section 7.5.2.1) are strongly developed, the surface-related and subcutanic fabrics are also strongly developed. The unrelated plasmic fabrics are mainly insepic or mosepic. Omnisepic plasmic fabric is rare; it is found in the 100-140 cm sample of the Bozi profile. Between soils the degree of orientation of anisotropic domains in the s-matrix varies considerably. It is at a minimum in Khashm el Girba 215 and 251, and in both Damazeen profiles; these profiles have argillasepic to insepic plasmic fabrics.

In thin sections that have areas with masepic plasmic fabric, the dominant fabric of the s-matrix is usually mosepic; both types indicate a moderate to strong orientation of clay domains. There is a slight tendency for masepic fabric to be more strongly developed in the subsoil than in the surface soil. Masepic zones often occur in areas with distinct joint skew planes that have associated vosepic plasmic fabric (see below). The heterogeneous pattern of surface-related and subcutanic plasma separations in most thin sections show that soil stress is not a continuous feature.

In most profiles there is no distinct depth trend: the proportion of oriented clay domains may vary between horizons, but it remains at the same general level. In some soils orientation of the domains increases with depth, then decreases below 100 to 150 cm (Jebel Abel, Seinat B55). This trend matches the general trend with depth in the development of the bicuneate structure (section 7.3). The Ulu profile shows a decrease with depth. Khashm el Girba 238 and Bozi have fewer oriented clay domains in the BC horizon.

No relation to either rainfall zonality or variation in soil parent materials appears when the reference profiles are grouped according to differences in the plasmic fabrics of the s-matrix.

7.5.3.2 SKEW PLANES IN RELATION TO SEPIC PLASMIC FABRICS

The occurrence of skew planes is a general feature: there is no thin section without skew planes. However, in only a few samples do we find skew planes as the dominant void type (in estimated total length); these are mainly from B horizons at depths between 60 and 160 cm, and this coincides with the zone of maximum macrostructure development.

Joint skew planes are common; they form one, seldom two, sub-parallel sets. They occur both in the surface soil and at greater depths. Joint skew planes are absent in several thin sections that contain skew planes as the dominant void type.

Almost invariably the skew planes carry a brim of vosepic plasmic fabric that is generally most distinct along the finest skew planes. The occurrence of skew planes as the dominant void type, however, is not always matched by a maximum development of vosepic plasmic fabric. Broad areas of vosepic plasmic fabric occur along slickensides that are on the surface of large, undisturbed structural aggregates.

Both Damazeen profiles have many skew planes. However, sepic plasmic fabrics, including vosepic fabric, occur in relatively few areas or are weakly expressed. It is surprising that in these profiles, taken from a site with a distinct gilgai microrelief, the orientation of clay domains is so weak.

Of the 69 samples from the 14 fully-sampled profiles, 33 contained mosepic plasmic fabric, 38 masepic, and 32 had joint skew planes; 48 samples had one or more of these features. The combination of all three features occurred in 13 samples, that of mosepic + masepic in 13 samples, the combination mosepic + joint skew planes in 2, and that of masepic + joint skew planes in 4 samples. Mosepic alone occurred in 5, masepic alone in 8, and joint skew planes alone in 3 samples. There appears to be a certain parallelism in the occurrence of mosepic and masepic plasmic fabrics, and joint skew planes.

7.5.3.3 CARBONATE CONCENTRATIONS

Of the five types of carbonate concentrations that have been included in Table 7.3, we will restrict the discussion to B, D and E, for two reasons: firstly, only these three types can be identified beyond doubt, and, secondly, these types, more than types A and C, have specific and mutually exclusive genetic implications.

Type B occurs in 13 out of 14 fully-sampled Vertisols from clay plain sites, and always in at least the lower subsoil and the substratum. Abundant occurrences of type B are always below 75 cm depth, and often below 120 cm. In four profiles this type is also found in the surface soil. The six profiles that have type B in abundance in one or more horizons, neither belong to a particular rainfall zone, nor to a specific geographic region. The observations show that type B is a typical substratum feature, it occurs below the present zone of pedoturbation.

Type D concentrations, the 'grey nodules' of the profile descriptions, occur concentrated in the surface soil and on the soil surface, where they also reach their greatest dimensions. They decrease in number and size with depth. In some soils small-size 'grey nodules' are common in the substratum. In thin sections of clay plain Vertisols type D is found in the surface soil, subsoil and substratum of most profiles. In Damazeen A (gilgai depression) type D is lacking, and in Khashm el Girba 238, Jebel Abel, Damazeen B (gilgai mound) and Renk grey nodules are scanty. The observations show that type D carbonate concentrations are common, but not ubiquitous in clay plain Vertisols.

Type E is a substratum feature. It is generally restricted to depths below 75 cm and that is, in most cases: below the presumed present zone of pedoturbation. Type E nodules are found in eight Vertisols of clay plain sites. Of these, two have a rainfall of 800 mm, one of 600 mm and the remaining five of 450 mm or less. This distribution pattern shows that type E occurs more widespread in the lower-rainfall than in the higher-rainfall regions. It is interesting to note that thin sections containing type E carbonate nodules always have, in addition, type D and also type 1 ferri-manganiferous concentrations. This suggests that some of the type D nodules have received a mangan/neomangan in an environment that was favourable to precipitation of ferric and manganiferous oxides.

7.5.3.4 FERRI-MANGANIFEROUS CONCENTRATIONS

Ferri-manganese concretions (types 2 and 3) are found in five reference profiles of the clay plain Vertisols. Usually both types are found, but Seinat B55 has only type 2. Type 2 may occur in one horizon, type 3 in another horizon of the same soil, and they may occur together in still another horizon (for example in Ulu and Damazeen B). This pattern of occurrence suggests that the two types do not differ as far as their genesis is concerned.

The five soils with ferri-manganese concretions are from different pedogeomorphic units, but have in common the fact that their sites receive an annual rainfall of 800 mm or more. The occurrence of these concretions can not be tied to a specific section of the soil profile.

The morphology of type 1 suggests formation 'in situ'. Type 1 is found in all fourteen clay plain profiles that were sampled over their entire depth; in six of these its occurrence is restricted to depths below 60 cm depth. In the eight other profiles type 1 occurs throughout; all of these are from the rainfall zone of 600 mm or above: Damazeen A, Bozi, Ulu, Simsim B27 and Seinat B55, with one exception: GARS 141.

We may conclude that type 1 occurs in all Vertisols: in the higher-rainfall soils throughout the solum and in the substratum, and in the lower-rainfall zones in the subsoil and substratum only. The boundary line between the two types of occurrence is at about 600 mm annual rainfall.

The occurrence of type 1 ferri-manganiferous concentrations indicates that hydromorphic soil conditions are or have been present. The question now arises whether hydromorphism in the dry region Vertisols is an actual substratum and subsoil feature, or a palaeofeature that has persisted in the lower parts of the profile, whilst it has disappeared from the upper parts of the solum due to pedoturbation. In higher-rainfall areas type 1 is present in the surface soil, that is: in the zone of actual pedoturbation. This shows that type 1 can form rapidly. Its absence in the surface soil in the lower-rainfall areas cannot, therefore, be assigned to present-day pedoturbation. Neither can its presence in the substratum be assigned to present-day hydromorphism, as wetting/drying cycles do not now penetrate into the substratum in the lower-rainfall profiles. And even if periodic wetting were to reach the substratum, it would be localized around deep cracks and not cause the ubiquitous presence of type 1 ferri-manganiferous concentrations. This means that the occurrence of type 1 in the substratum of lower-rainfall Vertisols is an indication of former hydromorphic conditions. We have seen in section 7.5.3.3 that in these soil horizons type 1 ferri-manganiferous concentrations are always accompanied by type E carbonate nodules. Both features, then, are to be assigned to former hydromorphic conditions. Besides, once formed such accumulations of sesquioxides can be very well preserved, as was shown by Kooistra (1982) for some soils of India.

The shape and colour of most occurrences of type 1 ferri-manganiferous concentrations, and of mangans/neomangans associated with type E carbonate concentrations, suggest that these consist mainly or entirely of manganese oxides. Nettleton and Sleeman (1985) in their study on the micromorphology of Vertisols, including that of the Sudan clay plains, stated that a distinct accumulation of ferri-manganiferous concentrations, in combination with a relative scarcity of ferric-iron accumulations shows that actual or former reducing conditions were never strong. These authours studied a Torrert and an Entic Chromustert in the lower-rainfall region of the Central Clay Plain. In the Torrert they found a distinct accumulation of nitrate in the 60 to 105 cm horizon. The nitrate would suggest that the Mn-coated and -impregnated carbonate nodules in the soil are relics of a more humid environment of the past, or are formed today during wet cycles. The authors conclude that both the Torrert and the Chromustert must have formed during a more humid time. We have, along different pathways, reached the same conclusion (Chapter 4).

Discrete (ferric) nodules belonging to type 4, are more often found at sites that have a rainfall of 600 mm or above, than in drier regions. Of the 14 fully-sampled clay plain Vertisols, discrete ferric nodules are not found in Khashm el Girba 215 and 238, Renk, and Jebel Qeili, and they are rare and restricted to a few samples in Khashm el Girba 213, Sennar 49, Jebel Abel and Damazeen B (mound site). Once again there is the difference between higher- and lower-rainfall regions.

'Matrix glaebules' (type 5) occur in all clay plain Vertisols with a rainfall of 600 mm or above, and are absent in all lower-rainfall soils.

7.5.3.5 ARGILLANS AND PAPULES

Argillans are only found in two samples, both of them, surprisingly, from the surface soil: Khashm el Girba 238 (0-30 cm) and GARS 141 (0-46 cm).

The argillans in the Khashm el Girba sample have a pale-yellowish colour. Stratification is weak, which is probably due to lack of ferric iron oxides (M.J.Kooistra, personal communication). These are, nevertheless, true illuviation cutans, formed under hydromorphic conditions. It should be recalled that Khashm el Girba 238 represents the wadi variant of the Asubri series (section 6.5.1). The Gezira sample contains a distinct channel argillan.

The two above samples also contain papules. These are also found in the lowest horizon of Khashm el Girba 238 (255-300 cm) and in Damazeen B at depths of between 90 and 180 cm. The papules are probably dislodged fragments of argillans. Nettleton and Sleeman (1985) observed papules that they identified as pseudomorphs of biotite, not fragments of argillans, in the Bw horizon of Vertisols.

The few argillans and papules that we observed, do not permit a pedologic interpretation. On the other hand, their scarcity is not surprising in Vertisols that, conceptually, lack clay translocations.

7.5.3.6 INTERCALARY GYPSUM CRYSTALS

Gypsum crystals are very conspicuous in thin sections. They are also distinct in the field, and generally field and thin section observations are in accordance. The occurrence of gypsum crystals is restricted to soils of the lower-rainfall areas, with a few exceptions, e.g. Simsim B27 (130/140-175 cm). Gypsum may have developed from a specific type of parent material in such cases (cf. Chapter 6).

7.5.4 Observations and discussion: other sites

The micromorphological features of five Vertisols from non-clay plain sites and the Gash delta soil (Hadeliya) are included in Table 7.3. Two of these, Er Rawashda and Boing, have a distinct vertic macrostructure, one, El Gelhak, is a shallow Vertisol in a ripening alluvial sediment, whereas the remaining two profiles, Khadiga and Seinat B7, have weakly developed vertic characteristics. Argillans, papules and intercalary gypsum crystals do not occur in this group. The micromorphology of the soils from non-clay plain sites will be compared with that of the clay plain soils.

7.5.4.1 MATRIX PLASMIC FABRIC

The 'proto-Vertisol' Hadeliya has mainly an argillasepic matrix fabric. The Vertisols have insepic to mosepic plasmic fabrics; Khadiga and Seinat B7 mainly insepic, the others relatively more mosepic, especially Boing and Gelhak. The Gelhak 60-90 cm sample has omnisepic plasmic fabric. The weakest development of unrelated plasma separations is in two soils with weakly developed vertic characteristics: Hadeliya and Khadiga.

In most of the thin sections from clay plain Vertisols that have areas with masepic fabric, the dominant plasmic fabric of the soil matrix fabric was found to be mosepic (section 7.5.3.1). This also applies to well-developed Vertisols from other sites: Er Rawashda, Boing and El Gelhak. In Hadeliya, Khadiga and Seinat B7, however, masepic plasmic fabric occurs in combination with argillasepic or insepic plasmic fabric in the matrix. (Seinat B7 is a rather sandy Vertisol, with 42-49% clay and 24-30% sand; it has a weaker vertic structure than clay plain Vertisols in the same area).

7.5.4.2 SKEW PLANES IN RELATION TO SEPIC PLASMIC FABRICS

Except for two samples, all thin sections have both vosepic plasmic fabric and skew planes; this was also found in most clay plain Vertisols. One of the conclusions from section 7.5.3.2 was: skew planes covered by a vosepic plasmic fabric are typical characteristics of Vertisols. However, these two features, in combination, are also found in the three profiles with weakly developed vertic characteristics: Hadeliya, Khadiga and Seinat B7. On the other hand, the strongly developed gilgaied clay plain Vertisol Damazeen has only weak vosepic plasmic fabric. The stress features found in the field do not, apparently, always have a simple relation with those observed in thin sections.

Joint skew planes are only found in Er Rawashda and Boing. In all samples from these two soils, joint skew planes occur in a matrix with both mosepic and masepic plasmic fabric. A similar observation was made in clay plain Vertisols (section 7.5.3.2). Among the non-clay plain Vertisols, Er Rawashda and Boing have the strongest vertic properties when voids and plasmic fabric are taken as yardsticks; both are Typic Pellusterts, very-fine, montmorillonitic, isohyperthermic family. So, it is perhaps the combination of mosepic + masepic + joint skew planes that could serve as a parameter for vertic processes.

7.5.4.3 CARBONATE CONCENTRATIONS

In accordance with the discussion of clay plain Vertisols (section 7.5.3.3) we will only comment on the occurrence of types B, D and E carbonate concentrations. Er Rawashda is similar to most of the lower-rainfall clay plain Vertisols: types B, D and E are present, and B is abundant in the lower horizons. Seinat B7 contains types B and D in the subsoil. No carbonate concentrations are found in Khadiga and El Gelhak, whereas in Hadeliya and Boing only type B occurs. The absence of types D and E in these four soils seems to reflect their relative youth. The deeper strata of El Gelhak (below 240 cm) - that were not sampled for thin sections - do contain ca-nodules and soft powdery lime with hard ca-nodules (cf. the profile description in Appendix 2). The Gelhak soil has probably formed in a soil material that contrasts with the deeper-lying strata. In Seinat B7 carbonate concentrations occur below a depth of 190 cm; this may reflect a relatively stronger leaching in this gravelly and sandy clay soil.

7.5.4.4 FERRI-MANGANIFEROUS CONCENTRATIONS

All five types of ferri-manganiferous concentrations occur in all samples of the Boing profile, and in some samples of Seinat B7. In Boing and Seinat B7 some of the features that were identified as ferri-manganiferous concentrations may in fact be weathering rock or mineral fragments. Type 1 is present in all six soils.

7.5.5 Conclusions

Of the micromorphological features described, none have the quality of differentiating between geographic regions, but some clearly differentiate between higher- and lower-rainfall regions, and, sometimes, also between depth zones in an individual profile. Other features show no relation to a rainfall gradient; they are common to all Vertisols, and some of these show a trend with depth. Some generalizations can be made. They refer to the clay plain Vertisols, but are also valid for well-developed Vertisols in colluvial or residual positions (Er Rawashda and Boing), but not for the immature or 'proto' Vertisols (Hadeliya and Khadiga).

Plasmic fabric of the s-matrix shows no distinct trend with depth in most soils: the proportion of oriented clay varies between horizons or increases or decreases with depth. The s-matrix usually has an insepic to mosepic plasmic fabric with asepic areas. Two samples (Bozi, 100-140 cm, and Gelhak, 60-90 cm) have omnisepic plasmic fabric, together with vosepic and masepic. The Gelhak profile also has a unique macromorphology: the soil is a half-ripe mud with few, distinct slickensides. The morphology is unrelated to annual rainfall or geographic region, and is largely defined by hydromorphic conditions.

Skew planes are a general feature. They occur in all soil horizons, but are most distinct in the lower subsoil and the substratum. All thin sections in which they are the dominant type of void, are from depths below 60 cm. Joint skew planes occur in both the solum and the substratum, often in horizons that have a relatively strong development of sepic plasmic fabrics (for example, mosepic plasmic fabric throughout the s-matrix, and common masepic striations).

Vertic processes are most clearly revealed by the presence of joint skew planes and an abundance of oriented clay domains, of which at least a part forms masepic zones with a striated orientation.

Carbonate concentrations are of a different type in different depth zones of the profile. Neocalcitans and diffuse nodules that are associated with voids (type B) form 'in situ' below the present zone of pedoturbation. Hard discrete nodules, either with or without secondary ferruginous and/or manganiferous impregnations (types C and D) are found in many soils, without a significant relation to certain depth zones. However, field observations show that hard grey nodules (type D) are most abundant and largest on the surface and in the surface soil. Hard discrete nodules with a mangan/neomangan that has formed 'in situ' (type E) are restricted to samples from the substratum; type E occurs most widespread in areas with an annual rainfall of 450 mm or less.

Ferri-manganiferous concentrations show a clear relation to annual rainfall. Mottles (type 1) occur throughout the profile in soils that receive a rainfall of 600 mm or more; in lower-rainfall regions type 1 is restricted to the substratum and the lower solum. Concretions (types 2 and 3) are only found when the rainfall is 800 mm or above. Ferric nodules (type 4) are more often found at sites that have a rainfall of 600 mm or more, than in drier regions. Matrix glaebules (type 5) are restricted to soils that receive an annual rainfall of 600 mm or more.

In the substratum of the lower-rainfall Vertisols we found type 1 ferri-manganiferous concentrations and type E carbonate concentrations, and have suggested (section 7.5.3.4) that both the mangans/neomangans and the ferri-manganiferous concentrations type 1 indicated a past or present mobility of manganese. Mobility of manganese and lack of mobility of iron would be typical of weak hydromorphic conditions.

Some of the higher-rainfall Vertisols contain both type D carbonate and type 1 ferri-manganiferous concentrations, whereas type E carbonate concentrations are absent. Examples are: Ulu, 0-110 cm; Simsim B27, 5-130/140 cm. In these cases, pedoturbation may prevent the formation of mangans/neomangans around type D carbonate concentrations, but not the formation of type 1 ferri-manganiferous concentrations. The latter apparently are more rapidly formed. The limited number of observations does not allow a firmer statement.

7.6 Summary

The observations, reported in sections 7.3, 7.4 and 7.5 show a gradient in some morphological and micromorphological soil properties from north to south, in accordance with an increase in rainfall and a lengthening of the rainy season in that same direction. The changes in this north-south gradient are gradual, and no distinct boundary line between a northern and a southern Central Clay Plain can be traced. However, a border zone between the isohyets of 500 mm and 600 mm separates the clay plain into two sub-regions with Vertisols - on datum sites - that are different in several morphological properties. North of this zone we find:

- no gilgai;
- type A-A/Bwk-B/Awk-B/Cwky-C/Bwky-Cky-Ck horizon sequence (with ca-specks and gypsum);
- 10YR 3-4/3-4 surface soil; 10YR 3/2 subsoil;
- shiny ped faces beginning between 90 and 160 cm;
- type E carbonate concentrations are common in the substratum;
- type 1 sesquioxidic concentrations occur only in the substratum, types 2, 3 and 5 are absent; type 4 is rare.

South of this zone we find:

- gilgai;
- type A-Bw-(Bwk)-BCwk-Ck horizon sequence;
- 2.5Y-10YR 3/2 throughout the solum;
- shiny ped faces beginning between 20 and 60 cm;
- type E carbonate concentrations are rare in the substratum;
- type 1 sesquioxidic concentrations occur throughout the solum and in the substratum; types 4 and 5 occur frequently; types 2 and 3 occur only when rainfall is above 800 mm.

There is a poor correlation between the occurrence of macroscopically visible shiny ped faces, and the occurrence of vosepic plasmic fabric in thin sections: vosepic fabric is observed more frequently in thin sections than shiny ped faces in the corresponding soil profile, especially at shallow depth. The stereomicroscopic observation that all bicuneate ped faces are slickensided is apparently more in line with the thin section descriptions than with the field descriptions.

Chapter 8

Mineralogical, chemical and granulometric investigations

In addition to field observations we have used laboratory data from selected soils to differentiate between specific areas of the apparently featureless Central Clay Plain, with special emphasis on soil parent material and soil forming processes.

8.1 Selection of profiles and samples, and of soil characteristics to be investigated

Of the 27 representative profiles (Table 6.1) 23 were sampled for mineralogical, chemical and granulometric analysis.

The mineralogical composition of the samples was determined by optical mineralogical investigation of the heavy and light minerals of the sand fraction, and by X-ray diffraction of the clay. The methods are described in sections 8.2.1 and 8.3.1, respectively.

The following chemical characteristics of the soils were determined: pH-H_20, pH-$CaCl_2$, contents of $CaCO_3$ and of organic carbon, cation exchange capacity and exchangeable sodium. The granulometric composition of the soil was determined in the same samples.

Additional analyses were conducted in some selected profiles. Electrical conductivity of a soil/water extract, anions and cations in that extract, and the amount of gypsum were determined in some soils of the northern part of the clay plain. The total chemical composition of the soil and of the clay fraction was determined in samples from selected profiles. The methods for chemical and granulometric analysis are described in Appendix 1.

8.2 Optical mineralogical investigations of sand and silt

The mineralogical composition of the sand fraction of a soil reflects the parent material in which the soil developed, whether a saprolite, a colluvial or colluvio/alluvial sediment derived from weathering of the local rock, or an alluvial sediment containing the weathering products of geological formations in the river catchment areas.

In the Central Clay Plain four types of parent material can be distinguished:

a. Fluviatile and semi-lacustrine deposits of the Blue Nile and its tributaries and the Atbara river (aggradational clay plains);

b. Colluvial and colluvio/alluvial deposits derived from the weathering of local rocks (degradational clay plains);

c. Saprolite derived from weathering 'in situ' of intermediate to basic igneous rock;

d. Alluvium of the White Nile.

In the Central Clay Plain some of the boundaries between pedogeomorphic units, notably between an aggradational and a degradational plain, are diffuse in the landscape, and not very clear in the morphology of the soils. The mineralogy of the sand fraction reveals the differences better as they are related to the soil parent materials: the Blue Nile catchment has volcanic, metamorphic and plutonic rock, the Atbara catchment has volcanic rock only, the White Nile catchment has metamorphic and plutonic, but only little volcanic rock, whereas plutonic and metamorphic rocks underly most of the Butana, Kenana and Southern Gedaref degradational clay plains.

8.2.1 Material and methods

The fractions 50 to 250 µm (very fine and fine sand) and 250 to 500 µm (medium sand) were investigated with a petrographic microscope and with a binocular microscope. The fractions were obtained by sieving, after removal of free ferric oxides, soluble minerals and organic matter, and separated into a heavy and a light fraction using bromoform.

Some or all of the heavy fraction was used to prepare slides for inspection. In each slide, 100 to 200 translucent grains were identified; the number of opaque grains was expressed as a percentage of the total number of grains counted. Some samples contained so little sand that only one slide of the entire 50 to 500 µm fraction could be prepared. In other samples the number of grains in the heavy fraction of the coarse sand was insufficient to count a representative number of grains.

Light minerals were counted in a limited number of the 50 to 250 and 250 to 500, or the 50 to 500 µm size class. Each sample was separated into three parts, coloured for the presence of potassium feldspars and plagioclases as described by Doeglas et al. (1965) and Van der Plas (1966).

Data of four Vertisols analysed by the Royal Tropical Institute, Amsterdam, have been included. Heavy and light minerals were counted in the 20 to 50 µm coarse silt and the 50 to 500 µm sand fractions.

Thin sections from the parent rock of four residual soils and from one soil profile were investigated quantitatively by microscope.

8.2.2 Results and discussion

In Table 8.1 the contents of heavy minerals are given as mass fractions of the total particle-size class.

Samples from clay plain sites have 0.7 to 6.1% heavy minerals in the 50 to 250 µm particle-size class, and 0.2 to 1.0% in the 250 to 500 µm class. The medium sand fraction is generally poorer in heavy minerals than the fine + very fine sand fractions.

The non-clay plain sites are more diversified. Heavy mineral percentages of between 16 and 26 are found in Er Rawashda, Boing and in a sample of the Blue Nile

Table 8.1: Mass fractions of heavy minerals in different particle-size classes

profile nr.	sample nr.	profile name	depth (cm)	mass fraction (%) of heavy minerals in particle-size class (μm):			
				32-50	50-250	250-500	50-500
	clay-plain sites						
5	-	Khashm el Girba 256	155-180	2.7	3.3	2.4	
6	871/872	Jebel Qeili	140-200		1.9	0.6	
10	278	Sennar 49	85-130		2.0	0.2	
12	283	Jebel Abel	60-90		5.3	0.7	
	286	do	150-190		6.1	1.0	
13	340	Tozi	60-90		6.0	0.6	
14	289/290	Damazeen A	30-90		3.9	0.5	
	292/293	do	120-180		3.7	0.5	
15	855	Bozi	60-100		4.4	1.1	
21	750	Simsim B27	0-50				0.5
	753	do	130/140-175				0.6
26	787	Seinat B50	90-130		0.7	0.7	
	790	do	400-470		0.7	1.0	
27	761	Seinat B55	30-90		1.9	0.3	
	other sites						
7	564	Er Rawashda	35-75				26.0
	566	do	120-150				24.7
18	557	Boing	0-40		15.9	8.8	
	560	do	100-125/140		24.9	26.4	
20	575	El Gelhak	60-90		1.2	0.2	
22	851	Seinat B7	100-150		1.4	1.6	
25	772	Seinat B48	60-85		0.7	0.1	
		Blue Nile riverbed	'sand'		21.3	3.3	
		do	'silt'		15.2	4.3	

riverbed at Wad Medani, containing mainly sand. This result is not surprising: the samples are from residual soils on basic rock or from fresh Blue Nile sediment. Low percentages are found in El Gelhak - a Vertisol in White Nile alluvium - , in Seinat B48 - a rather strongly weathered Paleustalf - and in Seinat B7 - a Vertisol with considerable sand and gravel.

Table 8.2 shows the heavy mineral assemblage of the sand fractions. The columns represent separate minerals or groups of related minerals or minerals occurring in the same geo-environment. The column 'opaque' includes a few 'alterites' in the counts by the Royal Tropical Institute, Amsterdam. The group 'rutile/anatase' usually contains only a few anatase grains; exceptions are Seinat B7 (10% rutile; 38% anatase) and Seinat B48 (11% rutile; 6% anatase). The group 'staurolite' includes kyanite, andalusite and sillimanite which form a polymorphic group with the same chemical composition, Al_2SiO_5. With staurolite they indicate regional metamorphism of argillaceous sediments. The group 'epidote' includes zoisite, and aggregates some of which are hydrothermal alteration products ('saussurites') of calcic plagioclases, whereas others consist of small crystals of epidote, chlorite and actinolite, derived from greenschist metamorphic rocks. The amphibole group is represented by the 'hornblendes', including a few grains of basaltic hornblende and actinolite. The pyroxene group is represented by 'augite', including enstatite, hypersthene and titanaugite.

In most clay plain Vertisols the most common minerals of the heavy fraction are epidote and hornblende. Some soils are particularly rich in augite, one (Er Rawashda) in titanaugite, and one (Ulu) in titanite. Zircon and garnet are common in a number of soils. Minerals such as tourmaline, titanite and staurolite occur frequently, but usually in minor amounts.

Heavy minerals in the 50 to 250 μm and 50 to 500 μm size fractions

In the 50 to 500 μm fraction of profile GARS 141 - representative of the Gezira fan - hornblende percentages are up to 58, and epidote percentages are between 27 and 64. Augite percentages are between 3 and 12.

In the soils developed in Blue Nile alluvium, represented by the profiles Sennar 49, Jebel Abel, Tozi and Damazeen, hornblendes take 33 to 49% of the 50 to 250 μm fraction, and epidote between 45 and 53%. The two Blue Nile riverbed samples of the 50 to 250 μm fraction contain 41 and 18% hornblendes, respectively, whereas epidote percentages are 38 and 51. In the soil samples hornblendes and epidote together cover 80 to 96% of the heavy 50 to 250 μm fraction; in the samples from the Blue Nile riverbed these figures are 79% ('sand' sample) and 69% ('silt' sample). Augite is rare in the soil except for one sample from Damazeen A (4%) and all samples from GARS 141 (3 to 12%). Blue Nile riverbed samples, however, contain 13 and 21% of augite. Other heavy minerals are present in small quantities. The mineral assemblage indicates a mixed metamorphic-volcanic-plutonic origin of the parent materials of the soils.

The Atbara clay plain is represented by the profiles Khashm el Girba 213 and 215. If we compare the Atbara clay plain soils with those from the Blue Nile alluvium, we observe lower contents of epidote and hornblende, and much higher contents of augite (32 to 78%) in the 50 to 500 μm fraction. The composition of the heavy mineral fraction indicates a mainly volcanic origin of the Atbara alluvium.

Table 8.2: Mineralogy of the sand fractions and some silt fractions (coarse silt, 32 - 50 µm)

profile and laboratory nr.	profile, horizon nr. and depth (cm)	size fraction (µm)	% of heavy fraction	heavy fraction; transparent minerals in mutual percentages											light fraction; minerals in mutual percentages			
			opaque	tourmaline	zircon	garnet	rutile/anatase	titanite (sphene)	staurolite	epidote	hornblende	augite	other minerals	unknown minerals	potassium feldspars	plagioclases	concretions, etc.	others, mainly quartz
1	Khashm el Girba 213																	
251	1 0-40	50-500	5		1	2	1			12	6	78			4	1		95
255	5 130-155	do	10		3	+[1)]	+			17	11	69			2	1		97
257	7 175-200	do	13		3	1	+	+	1	30	11	54			6	2		92
259	9 240-300	do	6	1	1	3				34	29	32			5	2		93
2	Khashm el Girba 215																	
260	1 0-35	50-500	12		1	3				29	6	61			4[2)]	1		95
263	4 85-120	do	10		+	4		+	+	32	11	53			5	3		92
267	6 190-220	do	15		1	1	+	+	1	27	10	60			6	2		92
269	7 245-265	do	29		1	5		1	+	26	10	57			2	1		97
3	Khashm el Girba 251																	
242	1 0-30	50-500	23	4	5	14	3	1		45	8	20			4	1		95
245	4 115-140	do	18		1	28		5	+	50	4	12			3	2		95
247	6 175-205	do	35	1	1	21		1		56	6	14			4	2		94
248	7 205-235	do	33	1	4	13	1		1	64	9	7			2	1		97
250	9 310-350	do	32	2	3	18	1	3	+	65	5	3			2	1		97

(To be continued)

(Continued)

profile and laboratory nr.	profile, horizon nr. and depth (cm)	size fraction (µm)	% of heavy fraction	heavy fraction; transparent minerals in mutual percentages											light fraction; minerals in mutual percentages			
			opaque	tourmaline	zircon	garnet	rutile/anatase	titanite (sphene)	staurolite	epidote	hornblende	augite	other minerals	unknown minerals	potassium feldspars	plagioclases	concretions, etc.	others, mainly quartz
5	Khashm el Girba 256																	
	7 155-180	32-50	55	1	7	2	5			57	19	4	1[3]	4	5	33		62
		50-250	17	3	3	6	2	1	1	64	13	7			6	16		78
		250-500	27			2			1	84	8			5	3	22		75
6	Jebel Qeili																	
871/872	6/7 140-200	50-250	16	1	5	2	+		1	71	9	5	1	5[4]	3	6		91[5]
		250-500	5							99		1			1			99[6]
9	GARS 141																	
139	1 0-2	50-500	16		+	5	1	1	+	28	55	11			6	2		92
140	2 2-40	do	17		1	4	1	+	2	40	45	7			9	2		89
141	3 40-60	do	10	+	+	1	1	1	2	36	47	12			10	4		86
142	4 60-90	do	4	+	+	+	+	+	1	46	46	7			21	7		72
143	5 90-110	do	12		+	2	+	3	1	35	54	5			11	6		83
144	6 110-130	do	12	+	+	1	+	1	2	27	58	11			9	3		88
145	7 130-165	do	15	1	+	2	+	1	2	38	51	5			12	3		85[7]
146	8 165-185	do	14		1	+	1	2	2	35	56	3			11	1		88[8]
147	9 185-220	do	6		2	1	1	+	+	34	53	9			14	4		82
10	Sennar 49																	
278	5 85-130	50-250	26	2	4	4	4		4	47	33	+		2	6			94
		250-500	++++[9]	+	+	+			+	+					2			98

(To be continued)

(Continued)

profile and labora-tory nr.	profile, horizon nr. and depth (cm)	size fraction (μm)	% of heavy fraction	heavy fraction; transparent minerals in mutual percentages											light fraction; minerals in mutual percentages			
			opaque	tourmaline	zircon	garnet	rutile/anatase	titanite (sphene)	staurolite	epidote	hornblende	augite	other minerals	unknown minerals	potassium feldspars	plagioclases	concretions, etc.	others, mainly quartz
12	Jebel Abel																	
283	4 60-90	50-250	13		1	1		1	1	45	48			3				
		250-500	+[9]			+			+	++	+++	+		++[10]				
286	7 150-190	50-250	10			1		1		47	49			2				
		250-500	+++[9]						+	+++	++	+		++				
13	Tozi																	
340	4 60-90	50-250	14		2	3	1			49	41							
		250-500	+[9]	+		+			+	+	++	+		+				
14	Damazeen A																	
289/290	3/4 30-90	50-250	18			4	1			53	41							
		250-500	83	+	+	+	+		+	+	+							
292/293	6/7 120-180	50-250	13		2	2				53	42			1				
		250-500	46	1		11	+	+	3	44	32	5		4				
15	Bozi																	
855	3 60-100	50-250	12		1	9	3	6	1(?)	63	14				1	11	2	86
		250-500	25			16			4	64	2		12	2	3	2		95

(To be continued)

(Continued)

profile and laboratory nr.	profile, horizon nr. and depth (cm)	size fraction (µm)	% of heavy fraction	heavy fraction; transparent minerals in mutual percentages											light fraction; minerals in mutual percentages			
			opaque	tourmaline	zircon	garnet	rutile/anatase	titanite (sphene)	staurolite	epidote	hornblende	augite	other minerals	unknown minerals	potassium feldspars	plagioclases	concretions, etc.	others, mainly quartz
16	Ulu																	
85/95	2 30-70	50-250	35		7	9	9	52		3	20							
		250-500	[9]	+		+		+										
85/97	4 110-150	50-250	49		1	13	3	46	1	3	33							
		250-500						+			+	+						
21	Simsim B27																	
750	1/2 0-50	50-250	40	2	17	4	10		7	55	3	2						
		50-500[15]	58	3	7	2	1		1	78	7	+	9	1				
753	5 130/140-175	50-500	45	+	4	+	1		3	72	16		3[11]	1				
26	Seinat B50																	
787	3 90-130	50-250	37	4	7		3		3	80	1			2	1	1	2	96
		250-500	100												1		1	98
790	6 250-470	50-250	42	1	12		3		5	74	3		1[12]	1		1	2	97
		250-500	100													1	1	98[13]
27	Seinat B55																	
761	2 30-90	50-250	59	1	7	2	3		5	29	6	43	1	3		7	1	92[14]
763	4 150-180	50-2000													1	2	++	++++
7	Er Rawashda																	
564	2 35-75	50-500	11							8	2	87	1	2[16]	3	43		54[17]
566	4 120-150	do	19							8	1	89		2	1	50		49[18]

(To be continued)

(Continued)

profile and labora-tory nr.	profile, horizon nr. and depth (cm)	size fraction (µm)	% of heavy fraction	heavy fraction; transparent minerals in mutual percentages											light fraction; minerals in mutual percentages			
			opaque	tourmaline	zircon	garnet	rutile/anatase	titanite (sphene)	staurolite	epidote	hornblende	augite	other minerals	unknown minerals	potassium feldspars	plagioclases	concretions, etc.	others, mainly quartz
18	Boing																	
557	1 0-40	50-250	11	1		1	+		+	20	75	1[19]	1	1				
		250-500	12		2	11		2	4	5	69	1		6	9	4	18	69[20]
560	4 100-125/140	50-250	9		2	2		+	+	27	67			2				
		250-500	6		2	7				5	85			1	7	6	17	70
20	El Gelhak																	
575	4 60-90	50-250	26	2	12	14	1	4	2	43	17	3			3	13		84
		250-500	++			+				++	++				5	2		93
22	Seinat B7																	
851	3 100-150	50-250	79	3	18		48[21]		9	17	2	1		2[23]	1			99
		250-500	100													8		92
23	Seinat B10																	
569	2 15-25	50-250	100															
		250-500	100															
25	Seinat B48																	
772	4 60-85	50-250	81	9	44	1	17[22]		11	7	4			7[24]	+	+		++++
		250-500	30	1		8	+		2	39	42	3	2[25]	1		1		99

(To be continued)

(Continued)

profile and laboratory nr.	profile, horizon nr. and depth (cm)	size fraction (µm)	% of heavy fraction	heavy fraction; transparent minerals in mutual percentages											light fraction; minerals in mutual percentages			
			opaque	tourmaline	zircon	garnet	rutile/anatase	titanite (sphene)	staurolite	epidote	hornblende	augite	other minerals	unknown minerals	potassium feldspars	plagioclases	concretions, etc.	others, mainly quartz
	Blue Nile riverbed																	
	'sand'	50-250	3	1				2	2	38	41	13		2	7	9		84
		250-500	5				+	?	1	22	55	7		15		14		86
	'silt'	32-50	41		3	1	1			35	35	11		14				
		50-250	25		3	1	2		1	51	18	21		3				

Notes

1) + = trace
2) light minerals of fraction 50-2000 µm
3) mica
4) 5% of an unknown metamorphic mineral
5) 2% gypsum; 89% quartz
6) about half of the grains is gypsum
7) 78 quartz; 7 anhydrite
8) 85 quartz; 3 anhydrite
9) samples with few grains; amounts are estimated as follows: ++++ abundant; +++ many; ++ common; + few
10) one mineral species, perhaps weathered epidote
11) 2 quartz; 1 pyroxene
12) metamorphic mineral
13) many ferric glaebules or ferri-coated grains sample 788 (130-200 cm), fraction 50-2000 µm, containes potassium feldspar (+); plagioclases (++); concretions (++) and other minerals (+++)
14) fraction 250-500 µm
15) a separate sample of the fraction 250-500 µm contains opaque minerals and some aggregates
16) one grain; riebeckite (?)
17) many Fe- or FeMn-glaebules, not containing carbonate
18) semi-quantitative
19) 1 colourless hornblende
20) many ferric glaebules
21) 10 rutile; 38 anatase
22) 11 rutile; 6 anatase
23) opaque may include anatase
24) includes one metamorphic mineral and one spinel (?)
25) 1 diopside; 1 pyroxene; 1 amphibole; 1 mica

The degradational Kenana plain is represented by profiles Bozi (northern part) and Ulu (southern part). Bozi shows in addition to epidote and hornblende (together 77% in the 50 to 250 μm fraction), sizeable quantities of garnet and some titanite. Ulu has about 50% titanite, 20 to 30% green hornblende, and smaller quantities of zircon, garnet, rutile/anatase and epidote. The mineral assemblage shows the absence of volcanic materials, and a strong impact of metamorphic rocks that, however, is very different between the two sites.

The degradational Butana plain is represented by Khashm el Girba 256 and Jebel Qeili, whereas Khashm el Girba 251 is transitional between Atbara clay plain and Butana pediplain (cf. section 6.5.1). In the 50 to 250 μm fractions of the former two profiles, and the 50 to-500 μm fraction of the latter, we observe high amounts of epidote (45 to 71%) and rather low quantities of hornblende (4 to 13%), and low amounts of augite (3 to 7%), except for the upper 200 cm of Khashm el Girba 251 (12 to 20%). The higher amounts of augite in Khashm el Girba 251 must be ascribed to an admixture of Atbara alluvium. This soil is also rich in garnet, a mineral characteristic of metamorphic rocks. Khashm el Girba 251 and 256 belong to different depth phases of the same soil series (Dimiat); profile 256 overlies weathering rock at 180 cm depth.

The degradational Gedaref clay plain is represented by Simsim B 27, Seinat B50 and Seinat B55. The former two soils have high amounts of epidote, and relatively high levels of metamorphic minerals such as zircon, garnet, rutile and staurolite, while hornblendes are few, and augite almost absent. Seinat B55, situated at close proximity to the footslopes of the Gedaref-Gallabat ridge, shows a strong influence of volcanic parent material; it contains 43% augite.

In all degradational clay plain soils the typical metamorphic mineral epidote is relatively more common than in the aggradational clay plain soils, whereas amphiboles are fewer.

The non-clay plain sites are represented by widely different soils: Er Rawashda, Boing, El Gelhak, Seinat B7, B10 and B48. Er Rawashda contains almost 90% augite and titanaugite in the heavy fraction, confirming the volcanic origin as inferred from field data. Boing is a residual Vertisol developed on hornblende--epidote-amphibolite, and its mineral assemblage is in line with the composition of the parent rock. El Gelhak, developed in White Nile clay, has a metamorphic mineral composition; it is low in hornblendes when compared with Blue Nile soils, and lower in augite than Atbara clay plain soils. Seinat B7, situated at the foot of Qulei'at Ed Darot, a group of hills of metamorphic rock, has unusually high zircon and anatase, and contains some rutile and staurolite. The heavy fraction of Seinat B10 - a residual soil on mica-schist - consists entirely of opaque minerals. Seinat B48, an Ultic Paleustalf, shows its advanced stage of weathering in a relative dominance of zircon in the 50 to 250 μm fraction.

Heavy minerals in the 250 to 500 µm size fractions

The mineralogy of the 250 to 500 µm fraction is very different from that of the 50 to 250 µm fraction in many samples, for example in Khashm el Girba 256, Jebel Qeili, Damazeen A (120-180 cm) and Boing. The observations, however, are too few to permit any conclusion to be drawn.

The 250 to 500 µm fraction in samples of Sennar 49, Jebel Abel, Tozi, Damazeen A (30-90 cm), Ulu and El Gelhak, was too small to count a representative number of grains. Relative proportions of the minerals found are given in Table 8.2. In Seinat B7 and Seinat B10 the 250 to 500 µm heavy fraction consists entirely of opaque minerals.

Discussion on the heavy minerals

The relatively low percentages and, in some samples, absence of augite in the soils developed in the Pleistocene Blue Nile alluvium contrasts strongly with the high percentages in the Atbara alluvial soils. The mineralogical data show that the sediments of both rivers are very much different, an observation made earlier by Hume (1925) and Shukri (1949). Even fresh Blue Nile sediment contains much less augite than the weathered Atbara alluvium in Khashm el Girba 213 and 215. If we consider the entire heavy mineral composition of the sediments of both rivers, we observe a distinct volcanic assemblage in the Atbara alluvium, and a mixed metamorphic-volcanic-plutonic assemblage in the Blue Nile alluvium. This difference can be understood from the geology of the catchment areas of both rivers. Vail's (1978) geological map shows that the Atbara in Ethiopia has an entirely volcanic catchment, only the tributary Setit is likely to contribute some material from Basement Complex rock. The Blue Nile, however, incised in both volcanic and Basement Complex areas before entering the Sudan plain. Mohr (1963) showed that the Blue Nile (or Abbai) catchment in Ethiopia has outcrops of basalt, limestone, shales, gypsites, sandstones, granites and syenites. The different amounts of pyroxenes in soils of the two areas could, however, partly be due to a difference in age of sediment and duration of weathering and soil forming processes, the Atbara clay plain being younger than the Blue Nile clay plain. Weathering 'in situ' on the clay plains of the Kenana was shown by Buursink (1971). He compared the mineralogy of Blue Nile sediment load at Damazeen with that of soils of the adjoining 'kerrib' land, and found a distinct difference in the contents of augite and titanaugite, whereas volcanic glass, labradorite, zeolite and basalt fragments present in the sediment load, had almost disappeared from the 'kerrib' soil sample. However, radiocarbon dating of shells suggested a similar age of the upper clay mantle in both areas (cf. Chapter 4), and the differences in mineralogy between the soils of the Blue Nile and Atbara clay plains must, therefore, be ascribed to a different geology of the catchment areas of the two rivers.

The differences in heavy mineral assemblage of GARS 141 and the four profiles of the Blue Nile-Dinder-Rahad clay plain - all soils being developed in Blue Nile alluvium - , could be explained by assuming a relatively restricted weathering in the Gezira fan, probably due to a lower rainfall.

If we compare the four Khashm el Girba profiles, a different origin of 213 and 215 on one side, and 251 and 256 on the other, is clearly shown by the relative amounts of augite, hornblende, epidote and garnet. The last two soils, and the Jebel Qeili profile have developed in parent material derived mainly from metamorphic rock, whereas Khashm el Girba 213 and 215 developed in alluvial clays of the Atbara river.

There is much resemblance between the heavy mineral assemblage of Seinat B55 on one side, and Khashm el Girba 213 and 215 on the other: all three soils reflect a volcanic origin of their parent material. There is no doubt, however, about their vastly different geomorphic environments.

Light minerals in the sand and coarse silt fractions

Most of the investigated sand samples have small amounts of potassium feldspars and plagioclases. Khashm el Girba 256 has high levels of plagioclases in the 32 to 50, 50 to 250 and 250 to 500 μm size classes. In this soil there is, apparently, a direct influence of the parent rock - the sample is taken from a soil horizon directly overlying saprolite - which is not found in the other Khashm el Girba soils.

The light-mineral fraction is very different between soils of the Blue Nile aggradational clay plains: GARS 141 has relatively high amounts of potassium feldspars and a low level of plagioclases, whereas most feldspars in Jebel Abel and Tozi are plagioclases. Sennar has low contents of feldspars. The Blue Nile riverbed 'sand' sample has moderate amounts of potassium feldspars and plagioclases.

A thin section of profile Jebel Abel from a depth of 150 to 190 cm, contains weathering minerals and rock fragments (granite/gneiss and basalt). The minerals include epidote, amphiboles, quartz and feldspars. The feldspars are weathering to a kaolinitic clay.

In interpreting data on feldspars in soils it should be realized that in sediments there is generally a mixed assemblage derived from various feldspar-bearing rock types. This implies that the differentiation between potassium feldspars and plagioclases is of no value in identifying the parent rock that produced the sediments of the Blue Nile river system, but it may be useful for characterizing the soil material.

Some of the other Vertisols have moderate amounts of plagioclases (Bozi, Seinat B55, El Gelhak, Seinat B7), rarely of potassium feldspars (Boing). The non-vertic soils contain very few feldspars.

The 20 to 50 μm coarse silt fraction has been investigated in three Khashm el Girba soils (213, 215 and 251), and in GARS 141 (Table 8.3). The differences between profiles 213 and 215 on one side, and 251 on the other, that were very obvious in the heavy mineral 50 to 500 μm fraction, have almost vanished. All three soils have 2 to 5% feldspars, whereas quartz ranges from 25 to 39%. The consistently high amounts of augite are remarkable: 29 to 39, 27 to 35 and 27 to 33%, respectively. A similar uniformity is shown in the epidote and hornblende figures. GARS 141 is entirely different. There is much more quartz (77 to 83%) and there are more feldspars (6 to 10%). The mineralogical composition is very different from that of the 50 to 500 μm size fraction.

Depth trends

Most of the mineralogical data discussed above do not cover complete soil profiles, and therefore cannot be used to indicate trends with depth. Only in the three Khashm el Girba soils and GARS 141 have samples from all depths been investigated (Tables 8.2 and 8.3).

Khashm el Girba 213 and 251 show decreasing amounts of augite, and increasing amounts of epidote with depth in the 50 to 500 μm fraction. A tentative explanation for 251 has already been given. The mineral assemblage of Khashm el Girba 215 is uniform with depth, despite the presence of a distinct sedimentary stratification (see Appendix 2). The light fractions of the 50 to 500 μm size class show a great deal of uniformity with depth in all three Khashm el Girba soils, and the same applies to the mineralogical composition of the 20 to 50 μm fraction.

GARS 141 shows for most minerals a great uniformity with depth. There may be some variation, for example in feldspars in the 50 to 500 μm fraction, but nowhere is there a trend with depth.

The absence of depth trends in the few soils that were investigated mineralogically over their entire depth range, must be due either to a very uniform parent material, or to pedoturbation homogenizing a non-uniform sediment. In the latter case, we must also consider a fossil pedoturbation that kept pace with sedimentation.

Mineralogy of rock samples

A semi-quantitative investigation of thin sections from the parent rock of four residual profiles gave the following result:

- Er Rawashda (nr. 7): about 50% pyroxenes, and about 50% plagioclases; some opaques, probably magnetite; rock type: plagioclase basalt.
- Khadiga (nr. 17): hornblende (dominant) and epidote; rock type: hornblende-epidote-amphibolite.
- Boing (nr. 18): amphiboles, chlorite, quartz, epidote, apatite; feldspars: sanidine, andesite, labradorite, plagioclases. There is much secondary carbonate; the calcium is assumed to be mainly derived from the weathering of epidote, clinozoisite and hornblende; rock type: hornblende-epidote-amphibolite.
- Seinat B10 (nr. 23): common quartz and opaques (probably hematite), few muscovite; rock type: mica-schist.

8.2.3 Conclusions

The mineralogical investigations give considerable support for a differentiation of the Central Clay Plain into geographic/geomorphic regions, characterized by specific geological formations and soil parent materials, as inferred from field observations.

Soil profiles developed in alluvium of the Atbara (Khashm el Girba 213 and 215) are characterized by a heavy mineral assemblage with augite (32 to 78%), epidote (10 to 33%) and hornblende (6 to 29%) in the 50 to 500 μm fraction. This is in

Table 8.3: Mineralogy of the coarse silt fraction (20-50 μm) of GARS 141 and three Khashm el Girba profiles (analyses by H. Kiel, Royal Tropical Institute, Amsterdam)

Profile nr.	sample nr.	profile name	depth (cm)	potassium feldspars	plagioclases	quartz	tourmaline	zircon	garnet	rutile	titanite	kyanite	sillimanite	epidote	zoisite	saussurite	hornblende	augite	ore
1	251	Khashm el Girba 213	0-40	2	1	37		1	1	+				9	1		7	39	2
	255	do	130-155	1	2	28		1	+	1				18	2		16	30	1
	257	do	175-200	2	+	39		+	+	1				12	3		5	37	1
	259	do	240-300	3	2	27		1	+	1				17	3		15	29	2
2	260	Khashm el Girba 215	0-35	2	1	32		1		+				20	4	+	13	27	+
	263	do	85-120	1	+	37		1		1				14	3		10	31	2
	267	do	190-220	2	1	29		+		1				26	1		11	28	1
	269	do	245-265	3	2	33		+		1				13	4		9	35	+
3	242	Khashm el Girba 251	0-30	1	2	25		1	1	1				20	1	+	17	31	+
	245	do	115-140	1	1	35		1	1	+				15	3	+	15	27	1
	247	do	175-205	1	2	28		1	+	+				17	2		13	33	3
	248	do	205-235	3	2	32		1	1	+				20	2		10	28	1
	250	do	310-350	2	1	29		1						18	3		12	33	1
9	139	GARS 141	0-2	9	1	77		+		+				4			5	2	2
	140	do	2-40	7	2	80		+		+	+			5			4	2	+
	141	do	40-60	6	1	83		+		+				4			5	1	+
	142	do	60-90	6	2	78	+	+		+		+		6			6	2	
	143	do	90-110	6	1	82		+		+				5			4	2	+
	144	do	110-130	7	2	77		+		+			+	3			8	3	
	145	do	130-165	5	1	81		+	+	+				6			6	1	+
	146	do	165-185	4	2	82		+	+	+				5			6	1	
	147	do	185-220	6	2	77		+		+	+			7			7	1	

accordance with a catchment area of the river Atbara almost exclusively on the Ethiopian volcanic plateau.

In soil profiles of the Blue Nile-Dinder-Rahad clay plain epidote and hornblende account together for over 70% of the heavy minerals. They contain little or no augite. However, the fresh Blue Nile 'sand' and 'silt' samples contain 13 and 20% of augite, respectively, in the 50 to 250 μm fraction. The difference between soil and sediment suggests that some or most of the augite has been lost from the soil due to weathering. The higher augite content in the Gezira clay (GARS 141 has up to 12% augite in the 50 to 500 μm fraction), indicates that mineral weathering in the Gezira fan was probably weaker than in the Blue Nile-Dinder-Rahad clay plain.

The Blue Nile alluvium has a metamorphic-volcanic-plutonic mineral assemblage. This can be understood from its catchment area in Ethiopia which is partly volcanic and partly metamorphic/igneous (Basement Complex).

Augite is also present in small quantities in some of the Kenana and Butana degradational clay plain soils. It is, therefore, a poor guide mineral to differentiate between soils of the Blue Nile aggradational and the Kenana degradational plains. The amount of hornblende, however, is different between Blue Nile clay plain soils (28 to 48%) and degradational clay plain soils (less than 20% and usually less than 10%). With epidote + hornblende being over 70% in both landscapes, the amounts of epidote show a reverse picture. Hornblende is known to occur in volcanic, plutonic and metamorphic rocks, epidote chiefly in regionally metamorphosed rocks (Deer et al. 1966). Higher levels of epidote in the degradational Butana and Kenana plains must be due to the relatively stronger influence of metamorphic rocks.

The Vertisols of the Southern Gedaref clay plain are comparable to those of the Butana and Kenana degradational plains in having a relatively high amount of epidote. However, the mass fraction of the heavy mineral fine and coarse sand fractions is very small (0.1 to 0.9%), and the light mineral fraction is almost pure quartz (92 to 100%). These soils are apparently more weathered than those of the Butana and Kenana. Seinat B55 differs from the other Vertisols in this region in having high augite; this can be ascribed to the proximity of the basaltic Gedaref-Gallabat ridge. The analysed Alfisol profile (Seinat B48) has a mineral assemblage with a relatively large proportion of weathering-resistant minerals, including quartz. It shows a more advanced stage of weathering when compared with the Vertisols of the Southern Gedaref clay plain.

Some colluvio/alluvial soils seem to have inherited their specific mineral composition from a local rock type; this is perhaps the case with the Ulu profile which has an unusually high amount of titanite.

8.3 X-ray diffraction of clays

Vertisols are strongly dominated by smectite clay minerals, mainly montmorillonite and nontronite. Buursink (1971) found that the specific species of smectite present in the coarse silt fraction of the Blue Nile solid sediment load (at Damazeen) contained considerable iron; the clay fraction of Vertisols of the Blue Nile alluvial clay plains contained 10 to 15% Fe_2O_3. Paquet (1970) and Trauth et al. (1967) observed that the montmorillonite found in Vertisols of sub-Saharan Africa was particularly rich in iron.

8.3.1 Material and methods

X-ray diffractograms of the clay fraction of samples from selected profiles were made with a Guinier de Wolff camera. The Guinier de Wolff technique has been described by Porrenga (1958).

X-ray diffractograms using a Philips diffractometer and CoKα radiation were made from 24 samples of 19 profiles. The clays were saturated with magnesium, and diffractograms were made before and after treatment with glycerol. As the Guinier photographs had shown that in most Vertisols the clay mineralogy did not change with depth, X-ray diffraction was in general limited to only one sample per profile. As a check all four samples of Simsim B27 were investigated. From three profiles, Khashm el Girba 213, Jebel Abel and Ulu more than one sample was analysed.

8.3.2 Results and discussion

The Guinier de Wolff photographs of Vertisols showed a great uniformity within any one profile and between profiles.

The X-ray diffractograms were interpreted semi-quantitatively in terms of relative amounts of minerals present in the fraction $< 2\mu m$. Table 8.4 shows that most clay plain Vertisols have more than 80% of smectite and less than 20% of kaolinite. An exception is Simsim B27, which apparently has a slightly smaller percentage of smectite and contains some vermiculite. The diffractograms of the four samples from this profile are virtually alike. The same applies to the three samples of Ulu, whereas there are minor differences with depth in Khashm el Girba 213 and Jebel Abel.

In Figure 8.1. examples of characteristic diffractograms are given. Most of the Vertisols have steep and distinct smectite peaks indicating a good crystallinity of the clay mineral. Jebel Qeili is a typical example. The Mg-saturated sample shows a distinct peak at 1.44 nm, which after glycerol treatment shifts towards 1.79 nm. A 'shoulder' on the smectite peak at 1.48 nm in the glycerol-treated sample indicates the presence of some chlorite as there is a third-order reflection at 0.47 nm. The presence of kaolinite is shown in a low but distinct peak at 0.71 nm.

Table 8.4: Clay mineralogy of selected samples (X-ray diffraction)

profile nr.	sample nr.	profile name	depth (cm)	phyllosilicates					non-phyllosilicates		
				kaolinite	mica	smectite	vermiculite	chlorite	quartz	goethite	feldspars
	clay-plain sites										
1	255	Khashm el Girba 213	130-155	+	(+)	++++	-	(+)	(+)	-	-
	258	do	200-240	+	-	++++	-	-	(+)	-	-
3	250	Khashm el Girba 251	310-350	+	-	++++	-	-	(+)	-	-
6	867	Jebel Qeili	25-50	+	-	++++	-	(+)	(+)	-	-
9	142	GARS 141	60-90	+	(+)	++++	-	(+)	(+)	-	-
12	281	Jebel Abel	0-15	+	-	++++[1)]	-	(+)	(+)	-	(+)
	283	do	60-90	+	-	++++[1)]	-	(+)	(+)	-	(+)
	286	do	150-190	+	-	++++[1)]	-	(+)	(+)	-	-
13	340	Tozi	60-90	+	-	++++[2)]	-	(+)	(+)	-	-
15	854	Bozi	30-60	(+)	-	++++	(+)	-	(+)	-	
16	85/94	Ulu	0-30	+	-	++++[3)]	-	-	(+)	(+)	-
	85/96	do	70-110	+	-	++++[3)]	-	-	(+)	(+)	-
	85/98	do	150-190	+	-	++++[2)]	-	-	(+)	(+)	-
21	750	Simsim B27	0-50	+	-	+++	+	-	(+)	(+)	-
	751	do	50-95/105	+	-	+++	+	-	(+)	(+)	-
	752	do	95/105-130/140	+	-	+++	+	-	(+)	(+)	-
	753	do	130/140-175	+	-	+++	+	-	(+)	(+)	-
26	787	Seinat B50	90-130	(+)	-	++++	(+)	-	(+)	-	-
27	762	Seinat B55	90-150	+	-	++++	-	-	(+)	-	-

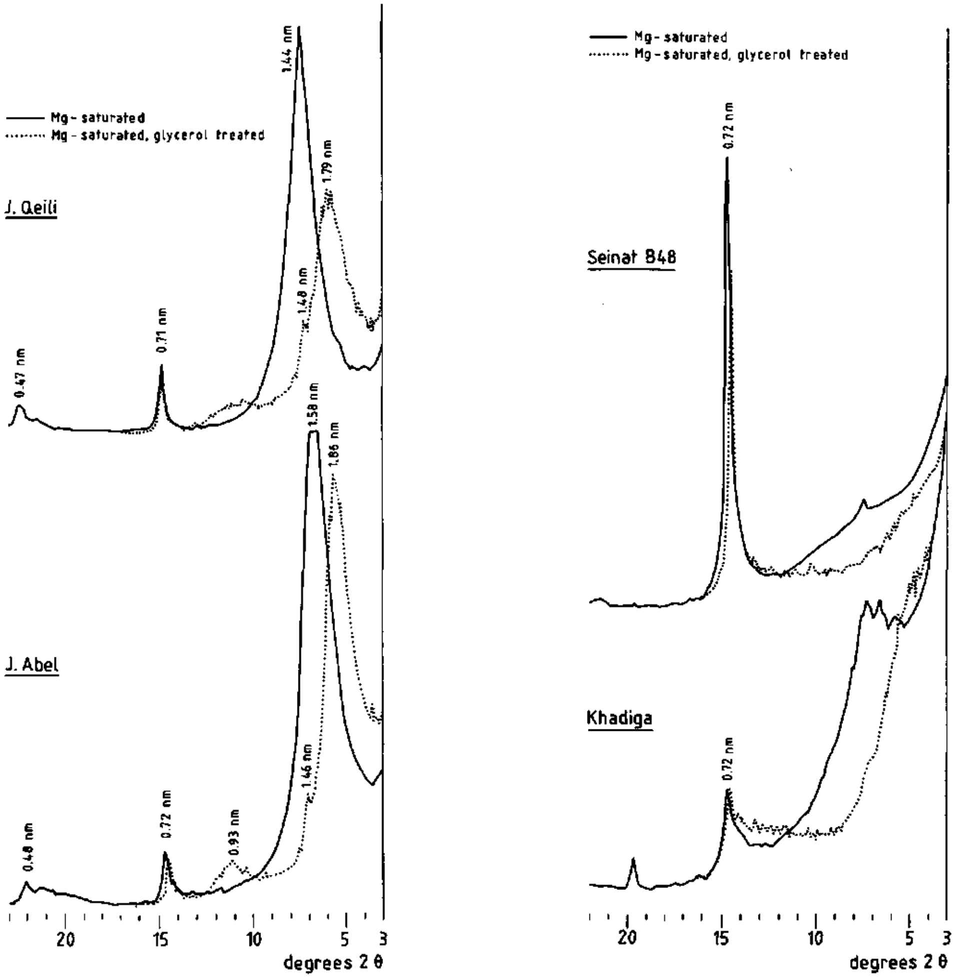
(To be continued)

(Continued)

profile nr.	sample nr.	profile name	depth (cm)	phyllosilicates					non-phyllosilicates		
				kaolinite	mica	smectite	vermiculite	chlorite	quartz	goethite	feldspars
	other sites										
7	564	Er Rawashda	35-75	(+)	-	++++	(+)	-	(+)	-	-
8	865	Hadeliya	150-180	++	+	+++	-	(+)	(+)	-	-
17	553	Khadiga	20-40	+	-	+[4]	-	-	(+)	-	-
18	559	Boing	70-100	+	-	++[4]	-	-	(+)	-	-
20	575	El Gelhak	60-90	+	-	+[4]	-	-	+	-	-
22	851	Seinat B7	100-150	++	+	++	-	-	(+)	(+)	-
23	569	Seinat B10	15-25	++	++	++[3]	-	-	(+)	(+)	-
25	771	Seinat B48	30-60	++++	(+)	+	-	-	+	(+)	-

++++ abundant (over 80%)
+++ frequent (50 - 80%)
++ common (20 - 50%)
+ few (less than 20%)
(+) rare, or presence doubtful
- not present

[1] very good crystallinity
[2] moderate crystallinity
[3] poor crystallinity
[4] poor crystallinity; amorphous minerals could be present



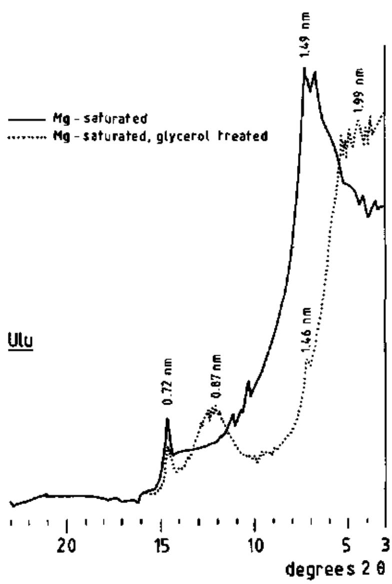


Fig. 8.1. X-ray diffractograms of samples from selected soils. Jebel Qeili, Jebel Abel and Ulu are clay-plain Vertisols; Khadiga is a Vertisol developed 'in situ'; Seinat B48 is a residual Alfisol.

The diffractograms of the Jebel Abel sample are similar to those of Jebel Qeili, but the smectite peaks are more prominent, indicating a higher degree of crystallinity of the smectite. The diffractogram of the glycerol-treated sample shows a distinct second-order reflection of smectite at 0.93 nm.

The diffractograms of the Ulu profile are similar to those of Jebel Qeili and Jebel Abel, but the smectite peaks are broader and rather ill-defined, especially after glycerol treatment. This would indicate a low crystallinity of the smectite which, however, cannot be easily related to soil or site characteristics being different from most of the other clay-plain Vertisols: the Ulu profile is a Typic Chromustert, very-fine, montmorillonitic, isohyperthermic, and is situated in a gently undulating pediplain. It is a typical Vertisol at a typical site.

Table 8.4 shows that of the Vertisols from other sites Er Rawashda has a clay mineralogy similar to that of the clay-plain Vertisols, whereas the proportion of smectite in the clay fractions of Khadiga, Boing, El Gelhak and Seinat B7 is much lower, not exceeding 50%. As an example the X-ray diffractogram of Khadiga has been given in Figure 8.1. The Khadiga clay has a smectite peak area that is smaller and more diffuse than in any of the clay plain Vertisols. This suggests very poor crystallinity and a lower amount of smectite. The kaolinite peak, at 0.72 nm is distinct, but the peak area is small. The Khadiga sample is from a relatively shallow residual Vertisol developed in epidote-hornblende-amphibolite.

As an example of a non-vertic soil, the diffractograms of Seinat B48, an Alfisol, are given. These are altogether different from those of the Vertisols. The smectite peak at 1.4 nm and the expanded peak at 1.8 nm are ill-defined. The kaolinite peak at 0.72 nm is prominent. Relatively high kaolinite is also found in the Entisol Seinat B10 and the sandy Vertisol Seinat B7 that is situated in a footslope position, halfway between an Alfisol and a Vertisol (section 6.5.2). The 'proto-Vertisol' Hadeliya has a considerable amount of smectite in the clay fraction.

Clay minerals other than smectite and kaolinite are rare, and if they occur it is only in small quantities and/or their presence is doubtful. Micas are confined to the non-clay plain sites of the Seinat area, and the Gash delta (Hadeliya). Vermiculite is found in Simsim B27 and may occur in some other Vertisols as well. A very small amount of quartz is present in the clay fractions of all samples; there is more quartz in the clays of Gelhak and Seinat B48. Goethite is present in the non-vertic soils of Seinat (especially B48) and in Ulu. Feldspars in the clay fraction are only found in the Jebel Abel profile, but in very small amounts.

Low-intensity smectite peaks in samples of the Khadiga, Boing and El Gelhak profiles may partly be the result of low levels of smectite. Similar low-intensity peaks in samples from the clay-plain Vertisols Tozi and Ulu - in contrast to the distinct peaks in most samples - however, are probably mainly due to poor crystallinity of the smectite, and/or the presence of non-crystalline clay minerals, such as allophane. Allophane contains considerable ammonium-oxalate extractable Fe, Al and Si. Of a few selected samples that did not show distinct peaks in the X-ray diffractograms, Fe, Al and Si were investigated in an ammonium-oxalate extract. The results are given in Table 8.5. The very low contents clearly show that there is no allophane in these samples.

X-ray diffraction data from several Vertisols in the Central Clay Plain have been given by the USDA Soil Survey Laboratory in Lincoln, Nebraska, USA (Soil Management Support Services / Soil Survey Administration of Sudan 1982). Relative amounts of clay minerals are given in a six-class system: 6 indeterminate, 5 dominant,

Table 8.5: Ammoniumoxalate-extractable Fe, Al and Si of some selected samples

profile nr.	sample nr.	profile name	depth (cm)	ammoniumoxalate extract		
				Fe%	Al%	Si%
16	85/96	Ulu	70-110	0.3	0.2	0.1
17	553	Khadiga	20-40	0.3	0.1	0.1
18	559	Boing	70-110	0.3	0.2	0.1
20	575	El Gelhak	70-110	0.3	0.2	0.1

4 abundant, 3 moderate, 2 small, 1 trace. In most samples relative amounts of smectite are moderate or abundant, sometimes dominant, those of kaolinite small, sometimes moderate, and there is often a trace (in some samples a small amount) of chlorite.

8.3.3 Conclusions

The X-ray diffractograms show a strong dominance of smectite and a great uniformity in mineralogical composition of the clay fraction of all clay-plain Vertisols. The Vertisols of non-clay-plain sites were found to differ markedly in the field from those of the clay plains, both in site and in soil morphology: they appear to have a somewhat different clay mineralogy and usually contain less smectite. Non-vertic soils have higher kaolinite than Vertisols.

8.4 Cation exchange capacity of the clay fraction

In landscapes with soils of highly different physical and chemical properties, the cation exchange capacity of the clay fraction (CEC-clay) can give a good indication of these differences as soil properties are generally strongly related to the clay mineralogy. In contrast to this, in landscapes dominated by soils with a smectite clay mineralogy, like the Central Clay Plain, the CEC of the clay fraction will not only show less variation, but the variations that do occur may be partly the result of properties of the clay fraction other than its mineralogy. Structural ferrous and ferric iron in smectites, for example, may affect several properties of the clay, including surface charge and CEC (Stucki 1985). In the crystal lattice reduction of ferric to ferrous, and oxidation of ferrous to ferric iron are both possible; these induce an increase and decrease, respectively, in negative charge and would, in the same way, affect CEC. But particle size and crystallinity of the clay also influence the CEC-clay. In order to understand the variation in CEC-clay between sites, their sedimentation history, mineral weathering and soil formation must be known. However, even if not fully understood, the variation in CEC-clay may contribute to the defining of regional units within the Central Clay Plain.

8.4.1. Material and methods

The CEC-clay has been calculated from the cation exchange capacity of the fine earth (CEC-soil) and the clay percentage. A correction has been made for the contribution of organic matter to the exchange capacity. Clay percentages refer to the soil free of carbonate, gypsum and organic matter. They have been corrected and expressed as percentages of the whole soil.

The cation exchange capacity of 24 profiles was determined following a method that was developed for calcareous, gypsiferous and saline soils (Begheijn 1978). It is a simple, single-step method using Li-EDTA as extractant or Li-Ba-EDTA for gypsiferous soils. The method is described in Appendix 1.

Corrections were made for organic matter, as follows:

$$CEC_{soil} = CEC_{organic\ fraction} + CEC_{mineral\ fraction}\text{, or}$$

$$CEC_{mineral\ fraction} = CEC_{soil} - CEC_{organic\ fraction}$$

In calculating the CEC of the organic fraction, it was assumed that 1 gram organic carbon equals 1.724 gram organic matter, and that 1 gram organic matter has a CEC of 2000 $mmol.kg^{-1}$. We had no data on the CEC of the organic matter in the soils studied. Scheffer and Schachtschabel (1979) consider that well-decomposed organic matter has a CEC of 1800-3000 $mmol.kg^{-1}$ at pH 8. A value of 2000 does not seem unrealistic. The CEC of the organic fraction is then:

$$CEC_{organic\ fraction} = org.C\% \times 1.724 \times 20\ mmol.kg^{-1}$$

The CEC of the mineral soil, thus obtained, is entirely ascribed to the clay fraction. As the textural classes are given as mass fractions of the soil free of carbonate, gypsum and organic matter, whereas the CEC is determined on the original samples still containing these compounds, the figures for clay percentage need to be corrected. For carbonates and gypsum the correction is as follows:

$$\text{clay\%(corr.)} = \text{clay\%(uncorr.)} \times (100 - CaC0_3\% - CaSO_4\%)/100$$

and

$$CEC_{clay} = CEC_{min.fraction} \times 100/\text{clay\%(corrected)}$$

$$= CEC_{min.fraction} \times 10^4/(\text{clay\%(uncorr.)} \times (100-CaC0_3\%-CaSO_4\%))$$

No correction has been made for: the mass fraction of organic matter in the original soil; the differences in charge related to differences in the pH of the extract (which was, theoretically, buffered at pH 8); the exchange capacity of the (fine) silt fraction. This seems to be justified: the organic matter content is usually low, and variable charge in smectitic soils is negligible compared with permanent charge. As for the contribution of the silt fraction to the exchange capacity of the soil, silt and sand fractions may posess cation exchange characteristics in exceptional cases, notably when they contain vermiculite and chlorite, and this may occur in young soils developed from basic igneous rocks (Russell 1973). These conditions do not apply to the soils of the Central Clay Plain.

8.4.2 Results and discussion

The cation exchange capacities of the clay fraction are shown in Figure 8.2. The depths indicated represent the middle of the soil horizon or layer. The grouping of the soils is according to geomorphic subunits or groups of geomorphic subunits. For the original data see Appendix 2.

It should be realized that the data on CEC-clay are subject to an accumulation of analytical errors, which could well add up to some 15% of the measured values:

1. the CEC is measured on the original sample, which was well- mixed but not ground.
2. the determination of clay fraction, carbonates and - in some samples - gypsum, is subject to inaccuracies.
3. the CEC-determination itself may be influenced by organic matter, $CaCO_3$ and $CaSO_4$, that are not necessarily at the same level at different depths.
4. the CEC of organic matter may not be 2000 $mmol.kg^{-1}$ as assumed, and it could also vary with depth in accordance with the nature of the organic compounds.

Vertisols from clay-plain sites

Gezira fan and Atbara clay plain (Fig. 8.2.a)

The three soils that represent the lower-rainfall aggradational Gezira fan and the Atbara clay plain, GARS 141 and Khashm el Girba 213 and 215, have a CEC-clay that

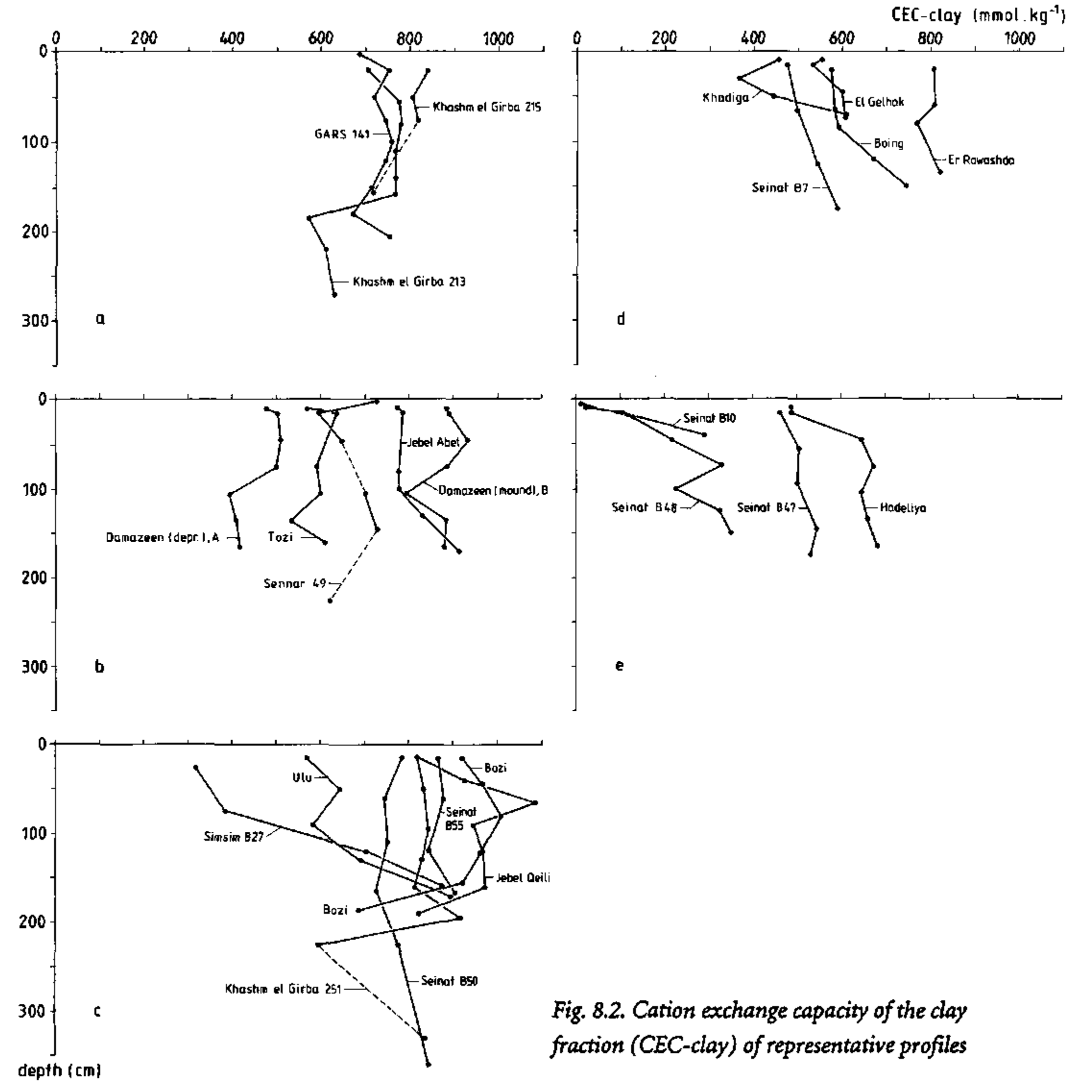


Fig. 8.2. Cation exchange capacity of the clay fraction (CEC-clay) of representative profiles

is rather uniform - approximately between 700 and 800 mmol.kg^{-1} - to a depth of about 160 cm, when there is a sudden and sharp decrease in Khashm el Girba 213, followed by a gradual increase below 180 cm. GARS 141 shows a gradual decrease from 100 to 180 cm, followed by a sudden increase. In both soils, the substratum with strong gypsum accumulation (2Cky) begins at about 160 cm depth; it has been regarded as lithologically different from the overlying solum.

Blue Nile-Dinder-Rahad clay plain (Fig. 8.2.b)

Five soils represent the large alluvial plain between the Kenana and Butana/ Gedaref degradational clay plains and more specifically the clay plain on the Blue Nile westbank. One profile (Sennar 49) is from the northern part, the four others (Jebel

Abel, Tozi, Damazeen A and Damazeen B) from the southern part. Note that not all samples of Sennar 49 have been analysed.

CEC-clay figures are different between soils: 400 to 450 $mmol.kg^{-1}$ in Damazeen A, around 600 in Tozi, 600 to 700 in Sennar 49, and 800 to 900 in Jebel Abel and Damazeen B. The great difference in CEC-clay between gilgai mound and adjoining gilgai depression at the Damazeen site, is surprising and not well-understood: there are only minor differences in the elemental composition of the soil (Appendix 2), mainly in the levels of CaO and MgO.

Kenana, Butana and Gedaref degradational plains (Fig. 8.2.c)

In the degradational clay plain soils site differences with regard to annual rainfall and parent material, are great. Three soils have a rather uniform CEC-clay with depth to about 160 cm: Khashm el Girba 251, Seinat B50 and Seinat B55 (the deeper-sampled Seinat B50 to about 350 cm). Jebel Qeili and Bozi have CEC-clay values that vary irregularly with depth. However, in both soils the elemental composition of the clay fraction (Appendix 2) remains the same throughout the profile. Ulu and particularly Simsim B27 show a distinct increase in CEC-clay with depth. This increase does not have a simple relation with the clay mineralogy which, for both profiles, is uniform with depth (Table 8.4), whereas for both soils the elemental composition of the clay (Appendix 2) does not change with depth. The depth trends in CEC-clay in these two profiles is not well-understood.

If we consider all clay plain Vertisols, we observe that CEC-clay values of around 800 $mmol.kg^{-1}$ are most common. This value changes little with depth in the upper 100 to 160 cm in the majority of the soils.

Vertisols from other sites (Fig. 8.2.d)

Er Rawashda has the same uniform CEC-clay as is often found in clay plain Vertisols, and at the same general level of 800 $mmol.kg^{-1}$.

Khadiga, Boing, El Gelhak and Seinat B7 have CEC-clay values between 400 and 700 $mmol.kg^{-1}$, which is lower than in most of the clay plain Vertisols. X-ray diffractograms (Table 8.4) show lower contents of smectite than in the clay plain Vertisols. Seinat B7 has roughly equal amounts of smectite and kaolinite; it is a sandy Vertisol with weak vertic characteristics, and has much in common with Seinat B47, a Typic Ustropept. Khadiga and Boing are residual soils developed on basic rocks. El Gelhak has developed in White Nile alluvial clay.

Non-vertic soils (Fig. 8.2.e)

In this category are three soils from the Seinat area, and one from the Gash delta (Hadeliya).

Seinat B10 and B48, an Entisol and an Alfisol, respectively, are lower in smectite and higher in kaolinite than most of the Vertisols (Table 8.4). In both soils, CEC-clay increases strongly with depth but never reaches values above 360 $mmol.kg^{-1}$, suggesting an initial formation of smectite in the weathering zone of the parent rock, and a subsequent transformation from smectite into kaolinite. This is in accordance with the observation of Kantor and Schwertmann (1974), that smectite is the first clay mineral to be formed upon the weathering of basic rock.

The CEC-clay graph of Seinat B47, an Inceptisol, is almost identical to that of Seinat B7, a sandy Vertisol. CEC-clay remains, with around 500 $mmol.kg^{-1}$ more or less at the same level. In this respect the two soils are intermediate between Seinat B10 and B48 on one side, and the well-developed Vertisols Seinat B50 and B55, on the other. This also holds true for their profile morphology, clay mineralogy and site. The Seinat soils B48, B47, B7, B50 and B55 are members of a red-black catena from Alfisol to Vertisol (cf. section 6.5.2).

The 'proto-Vertisol' Hadeliya has higher CEC-clay and more smectite than the other non-vertic soils.

8.4.3. Conclusions

a. Most of the clay-plain Vertisols have a CEC-clay of between 600 and 1000 $mmol.kg^{-1}$. In general there is a great deal of uniformity within any one profile in the surface 80 to 100 cm, and higher, lower or variable values below. The well-developed colluvio/residual Vertisol Er Rawashda conforms to this general picture of clay-plain Vertisols.

b. With the exception of Er Rawashda, the Vertisols from non-clay-plain sites have lower CEC-clay values than those from the clay plains: 400 to 700 $mmol.kg^{-1}$. This is in accordance with X-ray diffraction data showing lower amounts of smectite and higher amounts of kaolinite compared with clay-plain Vertisols.

c. In the non-vertic soils Seinat B10 and B48, the CEC-clay values are below 400 $mmol.kg^{-1}$, and there is a distinct increase of CEC-clay with depth, a trend that is also shown in some of the weakly vertic soils (Seinat B7 and B47) and in residual Vertisols (Khadiga and Boing). This depth trend may indicate higher levels of smectite nearest the weathering front, and a breakdown of some of the smectite in the surface soil to form kaolinite. Higher levels of kaolinite are also found by X-ray diffraction of some of these soils (Table 8.4).

d. There are no correlations between CEC-clay and annual rainfall, and there is no consistent difference between Vertisols on degradational and on aggradational plains.

8.5 Elemental composition of the soil and of the clay fraction

The elemental composition of the soil has been determined in 23 profiles, usually in samples from all soil horizons or layers. From most of these profiles the composition of the clay fraction has also been determined in some or all samples. Special attention has been given to the elements Si, Al and Fe, and to the various forms of Fe in the fine earth, the clay fraction and the sand + silt fraction. The element Na is considered in relation to sodicity (section 8.7). Laboratory methods are in Appendix 1.

The normative mineralogical composition of the Seinat B48, Er Rawashda and Boing profiles was calculated by Mohr et al. (1972, pp. 293-296 and 309-326), following a method developed by Van der Plas and Van Schuylenborgh (1970).

8.5.1. Molar silica/sesquioxide ratios of the clay fraction

The elemental composition of the clay fraction was investigated in 21 profiles 12 of which were from clay-plain sites. Molar sesquioxide ratios (Table 8.6) have been calculated from the data on SiO_2, Al_2O_3 and Fe_2O_3.

The SiO_2/Al_2O_3 ratio of the clay fraction of most Vertisols from clay plain sites varies from 3.5 to 4.5; lower values occur in Simsim B27, and higher values in Khashm el Girba 213 and 215. Vertisols from other sites show the same diversity: 3.6 to 4.2 in Boing and El Gelhak, and 4.6 to 5.1 in Er Rawashda. The three non-vertic soils of the Seinat area (B10, B47, B48) and the weakly developed Vertisol (B7) have lower values (3.5 to 2.7), whereas the 'proto-Vertisol' Hadeliya is no different from most of the Vertisols.

Smectites have a molar SiO_2/Al_2O_3 ratio of around 4. The strong dominance of smectite in the clay fraction of well-developed Vertisols, shown earlier by X-ray diffraction and CEC-clay, is confirmed by the values of this ratio. It is surprising that the Vertisol Khadiga has a distinctly lower SiO_2/Al_2O_3 ratio of the clay fraction than the Alfisol Seinat B48. It is to be noted that low amounts of smectite were shown in both soils by X-ray diffraction. Similarly, the relatively low ratios in the four samples of Simsim B27 are in accordance with amounts of smectite which are lower than usual in clay plain Vertisols.

There is great uniformity in the SiO_2/Fe_2O_3 ratios of the clay fraction. Values are between 9 and 12, and most of them around 10 or 11. There is but one exception: Khadiga, which with a ratio of 6, has a clay fraction relatively rich in ferric iron (compare also section 8.5.2).

Uniformity is also great in the Al_2O_3/Fe_2O_3 ratios of the clay; most of the values are between 2.0 and 3.0.

Most values of the SiO_2/R_2O_3 ratio are between 2.7 and 3.4. Distinctly lower values (2.2 to 2.7) are found in Simsim B27, in Khadiga, and in the non-vertic or weakly vertic Seinat soils.

The conclusion can be drawn that the great uniformity in clay composition of the Vertisols of the clay plains, which has been shown in preceding sections of this chapter, is confirmed by the molar silica/sesquioxide and Al_2O_3/Fe_2O_3 ratios. In most Vertisols the silica/alumina ratios are between 3.5 and 4.5, indicating a smectite clay

Table 8.6: Molar silica-sesquioxide ratios of the clay fraction

profile nr.	sample nr.	profile name	depth (cm)	SiO_2/R_2O_3	SiO_2/Al_2O_3	SiO_2/Fe_2O_3	Al_2O_3/Fe_2O_3
	clay-plain sites						
1	257	Khashm el Girba 213	175-200	3.3	4.9	10.5	2.2
	258		200-240	3.5	4.9	10.7	2.1
2	261	Khashm el Girba 215	35-55	3.4	4.9	12.0	2.4
	265		140-170	3.3	4.8	10.0	2.1
3	243	Khashm el Girba 251	30-65	3.2	4.6	10.5	2.3
	245		115-140	3.1	4.4	10.1	2.3
	250		310-350	3.3	4.5	12.8	2.8
6	867	Jebel Qeili	25-50	3.2	4.3	12.9	3.0
	869		75-100	3.3	4.3	13.6	3.2
	872		180-200	3.3	4.4	13.2	3.0
9	139	GARS 141	0-2	3.1	4.6	9.4	2.0
	140		2-40	2.9	4.1	9.4	2.3
	141		40-60	2.9	4.1	9.3	2.3
	142		60-90	2.8	4.1	9.1	2.2
	143		90-110	2.8	4.1	9.0	2.2
	144		110-130	2.9	4.2	9.3	2.2
	145		130-165	2.9	4.2	9.3	2.2
	146		165-185	2.9	4.3	9.4	2.2
	147		185-220	2.9	4.2	9.3	2.2
12	281	Jebel Abel	0-15	2.7	3.7	10.3	2.8
	282		15-30	2.7	3.7	10.3	2.8
	283		60-90	2.7	3.8	9.9	2.6
	284		90-110	2.8	3.8	10.4	2.8
	285		110-150	2.8	3.8	10.5	2.8
	286		150-190	2.8	3.9	10.8	2.8
13	340	Tozi	60-90	3.0	4.0	11.5	2.9
15	854	Bozi	30-60	3.0	4.1	10.4	2.5
	858		170-200	3.2	4.4	11.3	2.5

(To be continued)

(Continued)

profile nr.	sample nr.	profile name	depth (cm)	SiO_2/R_2O_3	SiO_2/Al_2O_3	SiO_2/Fe_2O_3	Al_2O_3/Fe_2O_3
16	85/94	Ulu	0-30	2.7	3.5	11.2	3.2
	85/95		30-70	2.7	3.5	11.3	3.2
	85/96		70-110	2.7	3.6	11.2	3.1
	85/97		110-150	2.7	3.6	11.4	3.2
	85/98		150-190	2.9	3.8	12.4	3.3
21	750	Simsim B27	0-50	2.4	3.3	9.6	2.9
	751		50-95/105	2.4	3.2	9.3	2.9
	752		95/105-130/140	2.4	3.3	9.2	2.8
	753		130/140-175	2.3	3.2	9.1	2.9
26	785	Seinat B50	0-30	2.7	3.7	10.0	2.7
	786		30-90	2.6	3.6	9.5	2.7
	787		90-130	2.6	3.6	9.6	2.7
	788		130-200	2.7	3.6	10.0	2.8
	789		200-250	2.8	3.9	10.3	2.6
	790		400-470	3.1	4.3	11.2	2.6
27	760	Seinat B55	0-30	3.1	4.3	11.2	2.6
	761		30-90 }	3.3	4.6	11.0	2.4
	762		90-150 }				
	763		150-180	3.3	4.5	11.6	2.6
	other sites						
7	563	Er Rawashda	0-35	3.4	4.6	12.1	2.6
	564		35-75	3.3	4.6	11.6	2.5
	565		75-120	3.6	5.1	12.5	2.5
	566		120-150	3.4	4.9	11.5	2.4
8	860	Hadeliya	15-30	3.1	4.4	10.7	2.4
	865		150-180	2.9	4.0	11.2	2.8
17	552	Khadiga	0-20	1.9	2.7	5.9	2.1
	553		20-40	1.9	2.9	6.0	2.1
	554		40-50/60	1.9	2.8	5.9	2.1
	555		50/60-70/90	1.9	2.8	5.7	2.0
18	557	Boing	0-40	2.8	4.1	9.3	2.3
	558		40-70	2.9	4.2	9.7	2.3
	559		70-100	2.9	4.1	10.0	2.4
	560		100-125/140	2.8	3.9	9.4	2.4
	561		125/140-125/160	2.9	4.1	10.2	2.5

(To be continued)

(Continued)

profile nr.	sample nr.	profile name	depth (cm)	SiO_2/R_2O_3	SiO_2/Al_2O_3	SiO_2/Fe_2O_3	Al_2O_3/Fe_2O_3
20	572	El Gelhak	0-15	2.8	3.6	12.6	3.5
	573		15-30	3.0	3.9	12.8	3.3
	574		30-60	2.8	3.6	12.9	3.6
	575		60-90	2.8	3.6	12.9	3.6
22	849	Seinat B7	0-30	2.2	2.9	8.7	3.0
	850		30-90	2.3	3.2	9.0	2.9
	851		100-140	2.4	3.2	9.3	2.9
	852		160-200	2.5	3.3	9.6	2.9
23	568	Seinat B10	0-15	2.5	3.3	9.7	2.9
	569		15-25	2.3	3.0	10.9	3.7
	570		25-55	2.2	2.8	11.0	3.9
24	764	Seinat B47	0-20/40	2.4	3.2	9.7	3.0
	765		40-70	2.5	3.3	9.7	2.9
	766		80-110	2.5	3.3	10.1	3.1
	767		115-170	2.6	3.4	11.0	3.2
	768		170-175	2.6	3.4	11.3	3.3
25	769	Seinat B48	0-10	2.7	3.8	9.7	2.6
	770		10-30	2.4	3.2	9.8	3.1
	771		30-60	2.6	3.5	10.8	3.1
	772		60-85	2.4	3.3	9.7	3.0
	773		85-105	2.3	3.1	8.5	2.7
	774		105-135	2.3	3.0	10.3	3.4
	775		135-160	2.6	3.2	11.8	3.7

mineralogy. The higher values in Khashm el Girba 213 and 215 (4.8; 4.9) are not matched by X-ray diffraction and CEC-clay data suggesting a clay mineralogy different from that of most clay plain Vertisols. Simsim B27 differs from most clay plain Vertisols for reasons that are not understood. The non-vertic or weakly vertic Seinat soils have silica/alumina ratios which suggest a mixed clay mineralogy. The SiO_2/Al_2O_3 ratios of Seinat B48 are unexpectedly high for a clay that is relatively poor in smectite and rich in kaolinite according to the X-ray diffraction data.

8.5.2. Forms of iron in soil, clay and non-clay fractions

The different forms of ferrous and ferric iron in the soil and in the clay and non-clay fractions are important parameters in soil-forming processes (Schwertmann

1985). Our investigations were guided by the following considerations:

- Iron in primary silicate minerals is generally ferrous iron, that in smectite clay minerals ferric iron.
- Smectites are the first clay minerals to form upon the weathering of basic rocks under semi-arid to sub-humid conditions (Kantor and Schwertmann 1974).
- Smectites in Vertisols of the semi-arid tropics are rich in iron (Paquet 1970, Buursink 1971, Fitzpatrick 1985, Kantor and Schwertmann 1974).
- Smectite formation and stability are favoured by impeded internal drainage (Borchardt 1977).
- Under environmental conditions that favour internal drainage smectites weather into kaolinite; the ferric iron and part of the aluminium are released and form oxides and hydroxides (collectively known as sesquioxides).

The above considerations are relevant to the forms of iron that are found in different soils representing different environmental conditions in the Central Clay Plain. The following hypotheses are, in this connection, to be tested:

1. Ferrous iron is present in primary minerals, and therefore almost exclusively in the non-clay fraction. Immature residual soils will be highest in ferrous iron.
2. Vertisols on very poorly drained sites, usually Pellusterts, have relatively higher silicate-bound ferric iron and lower free ferric iron than Chromusterts.
3. In residual Vertisols on basic rock, iron-rich smectites are formed in the saprolite; upon continued weathering part of the smectite is transformed into kaolinite and this transformation is accompanied by a decrease in silicate-bound ferric iron and an increase of free ferric iron in the clay fraction.
4. Non-vertic soils are more strongly weathered than Vertisols and contain relatively more kaolinite and more free ferric iron, whereas the clay fraction has less silicate-bound ferric iron. These soils have a redder hue or higher chroma or both, in comparison with Vertisols.

Ferrous iron

The contents of FeO in the soil and in the clay fraction of the analyzed samples are given in Appendix 2. Nearly all FeO mass percentages, both of the soil and of the clay, are below 0.5; a few are between 0.5 and 0.9. The one exception is the Khadiga profile, which contains 2 to 4% FeO in the soil. Khadiga is a young soil containing much unweathered and partly weathered rock debris.

The rocks underlying the residual profiles usually contain more FeO than the soil (Er Rawashda 4%, Khadiga 9%, Boing 2%). An exception is the parent rock of Seinat B10 (0.1%). This profile has developed in a mica schist rich in quartz that contains very little weatherable minerals (section 8.2). However, the low FeO contents may also reflect a rather advanced stage of oxidation of the ferrous iron to ferric iron, due to weathering.

Ferric iron

Mass percentages of total Fe_2O_3 in the soil (FeIII-soil) and of free Fe_2O_3 in the soil (free-FeIII-soil) have been used to estimate - with the aid of the clay percentages - the mass percentages of silicate-bound ferric iron in the soil (sil-FeIII-soil) and in the clay fraction (sil-FeIII-clay). In the calculations, we have assumed that in Vertisols all silicate-FeIII of the soil is contained in the crystal lattice of smectite. The calculations require of at least one sample in a profile that the mass percentage of total Fe_2O_3 of the clay fraction (FeIII-clay) be known. Data were available for 20 profiles (Table 8.7).

Calculations

The calculations that follow are restricted to samples in which clay percentage (a), FeIII-soil (b), FeIII-clay (c) and free-FeIII-soil (d) were analysed (the letters refer to the columns in Table 8.7).

The calculations are as follws:

- The percentual contribution of the clay fraction to the mass percentage Fe_2O_3 of the sample (l) equals the product of FeIII-clay (c) and clay content (a),divided by FeIII-soil (b), or **l = c x a/b**.
- Sil-FeIII-soil (f) is the difference between FeIII-soil (b) and free FeIII-soil (d), or **f = b - d**.
- In profiles in which, in addition to total FeIII-clay (c), also free FeIII-clay (e) has been analysed (Seinat B47, B48, B55), sil-FeIII-clay is calculated as **g = c - e**.
- In samples where (e) has not been determined, g is calculated as **g = f/a x 100** (based on the assumption that all sil-FeIII-soil is contained in the crystal lattice of smectite),and free-FeIII-clay (e) as the difference between FeIII-clay (c) and sil-FeIII-clay (g), or **e = c - g**.
- The clay fraction contributes to the free-FeIII of the soil by a percentage k that is calculated as follows: **k = a x e/100**. We find the contribution of the non-clay fraction to free-FeIII-soil (h) as **h = d - k**.
- The ratio (m) between sil-FeIII-clay (g) and free-FeIII-clay (e) is: **m = g/e**.

The assumption that all sil-FeIII of the soil is in the clay fraction gives erroneous results in samples that contain many unweathered or partly weathered rock fragments: lowest horizons of Khadiga and Boing, and all samples of Seinat B10. Low values for e are probably unreliable, and negative values are certainly erroneous. In samples with negative e, the values for g, h, k and m were not calculated (in Table 8.7 indicated as: n.c.). The samples concerned have in common that they contain an appreciable amount of weathering rock fragments. Although most of the iron in primary minerals is in the ferrous form, a minor part of it may be in the ferric form. It is feasible that in these samples a part of the sil-FeIII-soil is in the fragments of weathering rock.

Table 8.7: Ferric iron in soil, clay and non-clay fractions

profile nr.	sample nr.	profile name	depth (cm)	a clay	b FeIII-soil[1)]	c FeIII-clay	d free FeIII-soil	e free FeIII-clay	f sil.-FeIII-soil	g sil.-FeIII-clay	h contr. non-clay to free FeIII-soil	k contr. clay to free FeIII-soil	l % of FeIII-soil in clay fraction	m sil.-FeIII-clay/free FeIII-clay
	clay-plain sites													
1	257	Khashm el Girba 213	175-200	63.8	9.8	12.8	5.0	5.3	4.8	7.5	1.6	3.4	83.3	1.4
	258		200-240	53.4	9.2	13.0	4.8	4.8	4.4	8.2	2.2	2.6	75.5	1.7
2	261	Khashm el Girba 215	35-55	63.4	10.3	12.0	4.8	3.3	5.5	8.7	2.7	2.1	73.9	2.6
	265		140-170	45.8	9.0	13.3	4.7	3.9	4.3	9.4	2.9	1.8	67.7	2.4
3	243	Khashm el Girba 251	30-65	67.9	8.8	12.5	4.6	6.3	4.2	6.2	0.3	4.3	96.4	1.0
	245		115-140	71.9	8.8	12.6	4.7	6.5	4.4	6.1	0.0	4.7	99.6	0.9
	248		205-235	74.6	8.8	9.2	3.4	2.0	5.4	7.2	1.9	1.5	78.4	3.6
	250		310-350	72.6	10.0	10.8	4.1	[5.3]	5.9	5.5	0.3	3.8	78.4	1.5
6	867	Jebel Qeili	25-50	57.9	7.6	10.3	2.8	2.0	4.8	8.3	1.6	1.2	78.5	4.2
	869		75-100	61.2	7.4	9.8	2.5	1.8	4.9	8.0	1.4	1.1	81.0	4.4
	872		180-200	65.2	7.9	10.5	3.3	3.4	4.6	7.1	1.1	2.2	86.7	2.1
12	281	Jebel Abel[2)]	0-15	67.8	8.6	10.5	4.1	3.9	4.5	6.6	1.5	2.6	82.8	1.7
	283		60-90	71.9	8.5	10.8	3.5	3.8	5.0	7.0	0.8	2.7	91.4	1.8
	286		150-190	74.8	8.3	10.0	3.5	3.6	4.8	6.4	0.8	2.7	90.1	1.8
13	340	Tozi[2)]	60-90	62.6	6.8	10.7	2.4	3.7	4.4	7.0	0.1	2.3	98.5	1.9

(To be continued)

(Continued)

profile nr.	sample nr.	profile name	depth (cm)	a clay	b FeIII-soil[1)]	c FeIII-clay	d free FeIII-soil	e free FeIII-clay	f sil.-FeIII-soil	g sil.-FeIII-clay	h contr. non-clay to free FeIII-soil	k contr. clay to free FeIII-soil	l % of FeIII-soil in clay fraction	m sil.-FeIII-clay/free FeIII-clay
	clay-plain sites													
15	854	Bozi	30-60	70.7	9.1	12.0	3.2	3.7	5.9	8.3	0.6	2.6	93.2	2.2
	858		170-200	77.3	8.4	11.5	3.4	5.0	5.0	6.5	- 0.5	3.9	105.8	1.3
16	85/94	Ulu	0-30	60.6	8.3	11.1	3.6	3.3	4.7	7.8	1.6	2.0	81.0	2.4
	85/95		30-70	60.5	8.3	11.0	4.6	4.9	3.7	6.1	1.6	3.0	80.2	1.2
	85/96		70-110	67.2	8.3	11.2	4.1	5.0	4.2	6.2	0.7	3.4	90.7	1.2
	85/97		110-150	62.0	7.9	10.9	4.8	5.9	3.1	5.0	1.1	3.7	85.5	0.8
	85/98		150-190	55.0	7.0	10.3	4.2	5.2	2.8	5.1	1.3	2.9	80.9	1.0
21	750	Simsim B27	0-50	68.7	10.8	12.7	6.5	6.4	4.3	6.3	2.1	4.4	80.8	1.0
	751		50-95/105	73.3	11.2	13.2	7.0	7.5	4.2	5.7	1.5	5.5	86.4	0.8
	752		95/105-130/140	72.8	11.3	13.3	6.7	7.0	4.4	6.4	0.3	4.8	96.8	0.9
	753		130/140-175	68.6	9.5	13.4	5.1	7.0	4.4	6.4	0.3	4.8	96.8	0.9
26	785	Seinat B50	0-30	76.2	10.8	12.2	5.4	5.1	5.4	7.1	1.5	3.9	86.1	1.4
	786		30-90	74.9	10.9	12.6	5.3	5.2	5.6	7.4	1.5	3.9	86.6	1.4
	787		90-130	77.2	10.5	12.3	5.7	6.1	4.8	6.2	1.0	4.7	90.4	1.0
	788		130-200	77.2	10.5	12.0	5.0	4.9	5.5	7.1	1.2	3.8	88.2	1.4
	789		200-250	76.8	10.5	11.9	4.9	6.3	5.6	7.3	0.1	4.8	87.0	1.2
	790		400-470	78.0	10.5	11.5	5.0	6.0	5.5	7.1	0.3	4.7	85.4	1.2

(To be continued)

(Continued)

profile nr.	sample nr.	profile name	depth (cm)	a clay	b FeIII-soil[1)]	c FeIII-clay	d free FeIII-soil	e free FeIII-clay	f sil.-FeIII-soil	g sil.-FeIII-clay	h contr. non-clay to free FeIII-soil	k contr. clay to free FeIII-soil	l % of FeIII-soil in clay fraction	m sil.-FeIII-clay/free FeIII-clay
clay-plain sites														
27	760	Seinat B55	0-30	77.8	9.3	12.3	5.1	[6.9]	4.2	5.4	- 0.3	5.4	102.9	0.8
	761		30-90	78.5	9.3 }	12.8	6.2 }	[7.1]	3.1	5.7	0.6	5.6	108.0	0.8
	762		90-150	81.2	9.3 }		5.7 }		3.6	5.7	- 0.1	5.8	111.8	0.8
	763		150-180	79.4	9.5	12.1	5.3	[6.3]	4.2	5.8	0.3	5.0	101.1	0.9
	other sites													
7	563	Er Rawashda	0-35	79.3	8.4	11.2	4.0	5.7	4.4	5.5	0.5	4.5	105.7	1.0
	564		35-75	77.9	8.6	11.4	3.5	4.9	5.1	6.5	0.3	3.8	103.3	1.3
	565		75-120	78.7	8.9	11.1	3.2	3.9	5.7	7.2	0.1	3.1	98.2	1.8
	566		120-150	79.0	9.4	11.4	3.3	3.7	6.1	7.7	0.4	2.9	95.8	2.1
8	860	Hadeliya	15-30	48.3	8.8	12.8	3.5	1.8	5.3	11.0	2.6	0.9	70.3	n.c.
	865		150-180	54.5	9.7	11.3	3.6	n.c.	6.1	n.c.	n.c.	n.c.	63.5	n.c.
17	552	Khadiga	0-20	55.2	13.3	17.4	9.9	11.2	3.4	6.2	3.7	6.2	72.2	0.6
	553		20-40	57.3	14.7	17.8	10.1	9.8	4.6	8.0	4.5	5.6	69.4	0.8
	554		40-50/60	51.5	15.5	18.4	10.6	8.9	4.9	9.5	6.0	4.6	61.1	1.1
	555		50/60-70/90	26.9	18.0	18.4	10.2	n.c.	7.8	n.c.	n.c.	n.c.	27.5	n.c.
	556		70/90+; r		8.8^{R}									

(To be continued)

(Continued)

profile nr.	sample nr.	profile name	depth (cm)	a clay	b FeIII-soil[1)]	c FeIII-clay	d free FeIII-soil	e free FeIII-clay	f sil.-FeIII-soil	g sil.-FeIII-clay	h contr. non-clay to free FeIII-soil	k contr. clay to free FeIII-soil	l % of FeIII-soil in clay fraction	m sil.-FeIII-clay/free FeIII-clay
	other sites													
18	557	Boing	0-40	61.5	11.1	12.1	5.2	2.5	5.9	9.6	3.7	1.5	67.0	3.8
	558		40-70	63.5	10.4	12.1	5.2	3.9	5.2	8.2	2.7	2.5	73.9	2.1
	559		70-100	69.8	10.9	12.1	5.5	4.4	5.4	7.7	2.4	3.1	77.5	1.8
	560		100-125/140	75.7	11.3	11.8	5.8	4.5	5.5	7.3	2.4	3.4	79.0	1.7
	561		125/140-125/160	43.9	11.1	11.8	3.5	n.c.	7.6	n.c.	n.c.	n.c.	46.7	n.c.
	562		125/160; r		4.6[R]									
20	572	El Gelhak	0-15	80.1	8.2	10.5	3.7	4.9	4.5	5.6	- 0.2	3.9	102.6	1.1
	573		15-30	80.5	8.5	10.4	3.4	4.1	5.1	6.3	0.1	3.3	98.5	1.5
	574		30-60	76.2	9.1	9.1	3.0	1.1	6.1	8.0	2.2	0.8	76.2	7.3
	575		60-90	77.3	8.3	9.3	2.9	2.3	5.4	7.0	1.1	1.8	86.6	3.0
22	849	Seinat B7	0-30	41.8	6.7	13.9	5.0	9.8	1.7	4.1	0.9	4.1	86.7	0.4
	850		30-90	43.5	8.7	13.7	6.8	9.3	1.9	4.4	2.8	4.0	68.5	0.5
	851		100-140	44.4	9.1	13.4	7.0	8.7	2.1	4.7	3.1	3.9	65.4	0.5
	852		160-200	48.6	9.3	13.1	6.7	7.8	2.6	5.3	2.9	3.8	68.5	0.7
23	568	Seinat B10	0-15	19.7	12.5	11.2	9.6	n.c.	2.9	n.c.	n.c.	n.c.	17.7	n.c.
	569		15-25	25.2	12.0	9.8	7.8	n.c.	4.2	n.c.	n.c.	n.c.	20.6	n.c.
	570		25-55	21.5	13.3	10.0	9.7	n.c.	3.6	n.c.	n.c.	n.c.	16.2	n.c.
	571		55+; wr		12.5									
	571A		r		8.5									

(To be continued)

(Continued)

profile nr.	sample nr.	profile name	depth (cm)	a clay	b FeIII-soil[1]	c FeIII-clay	d free FeIII-soil	e free FeIII-clay	f sil.-FeIII-soil	g sil.-FeIII-clay	h contr. non-clay to free FeIII-soil	k contr. clay to free FeIII-soil	l % of FeIII-soil in clay fraction	m sil.-FeIII-clay/free FeIII-clay
	other sites													
24	764	Seinat B47	0-20/40	44.9	6.5	12.9	4.7	[9.3]	1.8	3.6	0.5	4.2	89.1	0.4
	765		40-70	39.2	5.7	13.0	4.2	[9.0]	1.5	4.0	0.7	3.5	89.4	0.4
	766		80-110	51.5	7.0	12.7	5.2	[8.7]	1.8	4.0	0.7	4.5	93.4	0.5
	767		115-170	56.3	7.1	11.9	4.9	[8.3]	2.2	3.6	0.2	4.7	94.4	0.4
	768		170-175	59.7	7.4	11.8	5.0	[7.8]	2.4	4.0	0.3	4.7	95.2	0.5
25	769	Seinat B48	0-10	4.2	1.5	13.8	1.1	[11.4]	0.4	2.4	0.6	0.5	38.6	0.2
	770		10-30	15.1	2.6	11.8	2.1	[9.4]	0.5	2.4	0.7	1.4	68.5	0.3
	771		30-60	22.7	3.1	11.6	2.8	[9.1]	0.3	2.5	0.7	2.1	84.9	0.3
	772		60-85	32.6	4.8	12.3	5.0	[9.8]	- 0.2	2.5	1.8	3.2	83.5	0.3
	773		85-105	45.1	6.1	12.2	3.9	[9.6]	2.2	2.6	- 0.4	4.3	90.2	0.3
	774		105-135	39.4	6.3	11.6	5.2	[8.9]	1.1	6.4	1.7	3.5	72.5	0.7
	775		135-160	38.6	6.0	10.7	4.7	[7.4]	1.3	6.0	1.8	2.9	68.8	0.8

[1] in this table Fe_2O_3 is indicated as *FeIII*
[2] recent chemical data, not included in Appendix 2.

Remarks: - data in columns a, b, c and d are from laboratory analyses,
- data in column e between brackets (e.g. [5.3]) are from laboratory analyses, otherwise they have been calculated.
- n.c.: data not calculated,
- r, [R]: rock,
- wr: weathered rock

The data on ferric iron show the following for clay plain Vertisols:

The total Fe_2O_3 content of the soil (b) is within the rather narrow range of 7 to 11%, whereas the free Fe_2O_3 contents of the soil (d) are between 2 and 7%.

Analytical data on FeIII-clay (c), show that between 9 and 14% of the clay fraction consists of Fe_2O_3. Free iron contents (e) are between 2 and 8%, silicate iron contents (g) between 5 and 8%.

Columns h and k show that in some clay plain Vertisols the free FeIII in the soil is more or less equally divided between clay and non-clay fractions (Khashm el Girba 213 and 215, Jebel Qeili), whereas in the other soils most of the free FeIII is in the clay fraction.

Over 75% of the total Fe_2O_3 content of the Vertisols can usually be assigned to the clay fraction (column l). Some percentages that are over 100 reflect inaccuracies in analytical data; they often occur in connection with negative values for h.

The data on the non-clay plain sites show more variation.

Er Rawashda resembles the clay-plain Vertisols. Hadeliya has a similar amount of free-FeIII-soil as most clay plain Vertisols, but there is relatively more in the non-clay fraction and less in the clay fraction. This may be due to the lower clay percentage in this soil. Khadiga is rich in ferric iron oxides: 13 to 16%. The ratio silicate-FeIII-clay/ free-FeIII-clay (column m in Table 8.7) decreases from 1.1 at 40-50/60 cm depth to 0.6 in the surface soil sample. The data show that iron-rich smectite is formed in the weathering rock; with time part of the smectite is transformed into kaolinite - compare the trends in CEC-clay (Fig. 8.2.d) - and this process is accompanied by a decrease in silicate-FeIII and an increase in free-FeIII in the clay fraction. Boing is similar to clay-plain Vertisols in contents of ferric iron oxides in soil, clay and non-clay fractions.

In the non-vertic soils a relatively larger part of FeIII-soil is in the non-clay fraction. Seinat B48 has low contents of ferric iron oxides in the surface soil, whereas the contents in the subsoil (6%) are not unlike those of clay plain Vertisols. The trend is shown in both the free-FeIII component (d) and the silicate-FeIII component (f). In the clay fraction there is relatively more free FeIII compared with silicate FeIII, and this is probably related with a more kaolinitic clay mineralogy when compared with most Vertisols, especially in the surface soil. The observations are in line with the profile morphology and with data on clay mineralogy and CEC-clay.

Conclusions

In clay-plain Vertisols between 75 and 100% of the total FeIII-soil is in the clay fraction (Table 8.7, column l). The same applies to the well-developed Vertisols Er Rawashda and El Gelhak, the major part of the Boing profile and, surprisingly, Seinat B47 and part of Seinat B48. Lower percentages are found in most soils with weaker vertic characteristics such as Hadeliya, Khadiga and Seinat B7. The clay fraction of Seinat B10 contains very little FeIII.

The clay plain Vertisols belong to a very homogeneous population:

- 7 to 11% of the soil material consists of FeIII (ferric oxides);
- over 75% of all FeIII-soil occurs in the clay fraction; - 5 to 11% of the clay fraction consists of silicate-FeIII (in the crystal lattice), and 2 to 8% of free-FeIII.

How far do our results, discussed above, confirm the statements 1 to 4, given earlier in this section?

- ad 1: Iron in primary silicate minerals is generally ferrous iron. We found FeO to be very low (< 0.5%) in almost all soil samples, whereas percentages of 2 to 9 were restricted to samples of weathering rock underlying residual soil profiles. However, samples with much saprolitic material have probably silicate-bound ferric iron in some of the primary minerals in the sand and silt fractions.
- ad 2: There are three Pellusterts among the 27 representative profiles: Tozi, Er Rawashda and Boing. The data in column m of Table 8.7 do not confirm the hypothesis that the clay fractions of Pellusterts contain relatively more silicate-FeIII and less free-FeIII.
- ad 3: The statement that free FeIII occurs in both the clay and the non-clay fraction, is confirmed.
- ad 4: The statement that non-vertic soils contain a higher percentage of free ferric iron oxides is not confirmed. However, the clay fractions of the non-vertic soils contain less silicate-bound ferric iron and more free ferric iron than the clay fractions of the Vertisols. In Vertisols most of the ferric iron of the clay fraction is silicate-bound, whereas in non-vertic soils it is free ferric iron.

8.5.3. Characterization of smectite

Data on the elemental composition of the clay fraction of some profiles (Appendix 2) have been used to calculate the approximate chemical composition of the smectite clay minerals that are strongly dominant in this fraction. Five samples from fully analyzed clay-plain Vertisols, which had in common the fact that more than 80% of the fraction < 2 mμ was smectite, were selected (Table 8.4).

In order to arrive at an approximate chemical composition of the smectite, the data have been corrected by subtracting other minerals of the clay fraction, and recalculating the elemental composition to 100%. Relative peak areas of kaolinite and silica in the diffractograms[1] were used to make an assessment of the percentual contribution of these minerals to the clay fraction. Kaolinite was estimated to be 10% in all five samples; silica (SiO_2) was negligible in three samples, and estimated to be 5% in Bozi, and 10% in Ulu. Other minerals present have been neglected, because they were 'rare' or their 'presence doubtful' (Table 8.4), or their chemical composition was unknown (vermiculite in Bozi and Seinat B50, chlorite in Jebel Qeili).

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[1] Some examples of X-ray diffractograms are presented in Fig. 8.1.

A correction was also made for all free ferric iron in the clay fraction. In the calculations in section 8.5.2, it was assumed that all silicate-bound ferric iron in the soil is part of the clay fraction, being contained entirely in the crystal lattice of smectite. The contents of silicate-bound ferric iron in the clay fraction (g in Table 8.7.) are probably the best estimate for the Fe_2O_3 contents of the smectite. No correction was made for amorphous aluminosilicates as these are probably low in all samples (compare also section 8.3.2 and Table 8.5).

The results are given in Table 8.8. The calculated smectites are similar in chemical composition. They show some variation in the three main composing elements: SiO_2 (50-57%), Al_2O_3 (16-26%) and Fe_2O_3 (7 to 11%). The Fe_2O_3 contents are around 10% in the three soils from the northern part of the clay plain, and 7.5% in the two profiles from the southern part. We will now compare the composition of Sudan clay plain samples with some that have been reported from elsewhere.

Weaver and Pollard (1973) gave the chemical composition of 17 smectites, 14 of which have Fe_2O_3 contents lower than 4%, whereas three other smectites have percentages between 7 and 12. Wilson and Mitchell (1979) found that the smectite in a Vertisol from the Guneid area (Sudan, Blue Nile clay plain) had a beidellite composition (ferriferous beidellite). Fe_2O_3 contents were around 8% in the < 0.5 μm size fraction of the soil, with SiO_2 47%, and Al_2O_3 18%, which is similar to our data. Smectites in Udic Pellusterts in Kenya (Kantor and Schwertmann 1974) had a similar composition, with Fe_2O_3 contents around 8%. Mermut et al. (1984) found that smectites in fine-textured lacustrine deposits in South-Saskatchewan (Canada) were iron-rich montmorillonites. Trauth et al. (1967) found that smectites in 'Vertisols lithomorphes' - comparable with those on footslope positions in red-black soil catenas - were ferriferous, an observation also made by Paquet (1970) and by others (cf. section 8.5.2).

The often reported ferriferous nature of the smectites in Vertisols in semi-arid environments is supported by our observations.

Table 8.8.: Calculated approximate chemical composition of smectite in five samples of clay-plain Vertisols

sample nr.	profile, and depth of sample	SiO_2	Fe_2O_3	Al_2O_3	TiO_2	MnO	CaO	MgO	Na_2O	K_2O	FeO	P_2O_5	H_2O+	sum
258	Kh. el Girba 213, 200-240 cm	57.1.	9.9	16.0	1.3	0.1	0.5	3.7	1.4	tr	0.6	0	9.4	100.0
867	Jebel Qeili, 25-50 cm	51.3	9.5	17.9	1.4	0.1	0.3	1.9	0.1	0.6	0.2	0.1	16.4	99.8
854	Bozi, 30-60 cm	49.2	10.6	20.4	1.5	0.1	0	3.5	0.3	0.3	0.4	0.3	13.8	100.4
85/98	Ulu, 150-190 cm	48.3	7.4	25.6	2.0	0.1	0.3	2.6	tr	0.1	0.3	tr	13.0	99.7
787	Seinat B50, 90-130 cm	50.5	7.5	22.1	1.6	tr	tr	2.3	0.1	tr	0.8	0.2	14.9	100.0

8.6 Pedogenic carbonate, granulometric composition and organic carbon: laboratory data compared with field observations

8.6.1 Pedogenic carbonate

Pedogenic carbonate occurs in most Vertisols of the Central Clay Plain in the form of intercalary crystals, cutans and neocutans, and soft and hard glaebules. X-ray diffraction and chemical analysis have shown that in all forms of pedogenic carbonate the dominant mineral is calcite (Blokhuis et al. 1968/69; Kerpen et al. 1960). Finely divided calcium carbonate as well as soft and hard glaebules could be identified in the field using hydrochloric acid.

In the laboratory carbonates were determined by treatment with hydrochloric acid and measuring the volume of carbon dioxide produced (Scheibler method; cf. Appendix 1). As all laboratory determinations were done on the fine earth fraction (< 2 mm), some of the hard glaebules were removed as gravel.

Discrepancies found between field observations and laboratory determinations could be due to unequal distribution of the carbonates in a particular soil horizon. Field identification of carbonates, for example, was not confirmed in the laboratory in Hadeliya, Seinat B7, Seinat B47 and Simsim B27. Micromorphological identification of carbonates in some of these profiles shows a closer agreement with laboratory data. The absence of free carbonates in El Gelhak, Seinat B10 and Seinat B48 can be understood from their site and genesis, as previously discussed.

8.6.2 Granulometric composition

The classes of soil separates as given in Appendix 2 are those of the US Department of Agriculture (see, e.g. Soil Survey Staff 1951, page 207): clay, silt, and five sand fractions. In several samples from Vertisols, the sand fraction was so small that no sub-division was made. Extremes are Er Rawashda (sand percentage 0.9-1.1) and Seinat B55 (sand percentage 0.7-2.1). The soil textural classes as used in the field descriptions are generally in agreement with classes based on the granulometric composition as measured in the laboratory.

The most striking aspect of the granulometric composition of the clay-plain Vertisols is the great uniformity. The variation in sand, silt and clay separates within any one profile is small, and often negligible, and between Vertisols of different sites the granulometric composition of the soil is very similar: clay percentages of between 60 and 80, sand percentages of between 10 and 20, and silt percentages of between 20 and 30. There are no systematic differences that can be related, for example, to a climatic gradient, or differences in either soil parent material or in landscape formation.

Textural variation in some of the soils of the aggradational plains is due to sedimentary stratification, for example in Khashm el Girba 213 and 215, and in Jebel Abel. Other aggradational clay plain soils, however, have a uniform soil texture or show gradual changes. The most uniform soil textures are usually found in Vertisols of the degradational clay plains (Khashm el Girba 251, Bozi, Seinat B50 and B55); here we also find some of the highest clay percentages (Seinat B50 and B55: 75 to 80%). The paucity of sand in Seinat B55 may be due to a strong volcanic component in its parent material.

The Vertisols from non-clay-plain sites have less uniform textural profiles. Khadiga and Boing are residual Vertisols on basic weathering rock. The AC and C horizons of these soils have a much lower clay content than the A and B horizons, indicating ongoing weathering and clay formation in the solum. El Gelhak has an unusually low silt percentage (6 to 10%), and this may well reflect the more strongly weathered sediments of the White Nile compared with those of the Blue Nile and tributaries. Er Rawashda, a residual/colluvial soil on basalt, is almost devoid of sand.

The granulometric composition of four non-vertic soils can be understood from site, parent material and soil-forming processes.

In the Hadeliya profile is evidence of some mass movement in the soil as shown by cracks and occasional sinkholes. Micro-shear is shown by an incipient vertic structure. However, in order to arrive at a complete post-depositionary mixing of the sediments, pedoturbation should have been stronger, and continuous through the entire soil. The distribution of organic matter (section 8.6.3) is also evidence of a lack of homogenization. The uniformity of soil texture in Hadeliya may therefore be inherited from a homogeneous sediment. Seinat B 10 is a very young, shallow soil on a rocky hill. The parent rock contains a considerable amount of quartz, in addition to minerals that weather into silt and clay. The soil contains about 50% sand, 30% silt and 20% clay.

Seinat B48 has the typical low silt content of a strongly weathered tropical soil (Van Wambeke 1962). The clay increase with depth is due to illuviation (there is an argillic B horizon), but perhaps also to stronger weathering in a lower part of the profile that retains more moisture than the surface soil. Seinat B47 has some vertic characteristics between 30 and 170 cm depth (profile description). The higher sand content in the surface soil is a result of sandy overwash (section 6.5.2). The silt fraction does not change with depth; it is larger than in Seinat B48 but lower than in most Vertisols.

A common observation in Vertisols is the presence of stones and gravel on the surface of a soil that has a solum free of stones (Dudal 1965; Johnson et al. 1962; Schlichting 1968; Yaalon and Kalmar 1971). This feature has been explained from the pedoturbation of the soil mass: an upward movement with the swelling soil is incompletely balanced by a downward movement when the soil shrinks, because the majority of the desiccation cracks are too narrow for the coarse fragments to fall back to their former position. Springer (1958) and Jessup (1960) demonstrated the movement of gravel embedded in swelling clay material in laboratory experiments. On the degradational clay plains of the central Sudan stones are often found on the surface of stone-free Vertisols at sites well away from rocky inselbergs (section 6.4). Schlichting (1978) observed a decrease in sand and an increase in clay with depth in Vertisols of Australia, and in Pelosols from SW Germany. Of several hypotheses put forward, Schlichting considered a selective ejection of sand and coarse silt the most likely explanation. Yaalon and Kalmar (1972) also ascribe an upward movement of sand grains to vertic processes.

In the Central Clay Plain we find an upward coarsening of the soil texture in a number of profiles. In some of these soils, most clearly in GARS 141, silt contents remain the same with depth. If pedoturbation had moved (coarse) sand upward, we should find a proportional reduction in both silt and clay towards the surface. And a number of Vertisols, as we have seen, have uniform percentages of sand, silt and clay throughout the profile. It appears that our data are insufficient to either reject or confirm Schlichting's, and Yaalon and Kalmar's hypotheses. Besides, any effect of pedoturbation may be counteracted by other processes, such as deposition of windblown sand, or a preferential clay formation in the subsoil due to a relatively moister environment during most of the year. However, the latter process is more likely to bring about a shift from silt to clay, than from sand to clay.

8.6.3 Organic carbon

The data for organic carbon are in Appendix 2. With a few exceptions the values are below 1.0%. Higher values occur in Ulu, Boing and Seinat B10. In many Vertisols, the organic carbon percentages fluctuate with depth (Damazeen A and B), in others they remain at the same level (GARS 141) or decrease with depth (Ulu, El Gelhak).

In several of the Vertisols, we find no difference in organic matter content between A and B horizons, whereas the BC has a lower amount, and the C the lowest: Khashm el Girba 213, 215 and 251, Sennar 49, Khadiga, Boing, Seinat B55. Such organic matter profiles suggest that pedoturbation has homgenized the solum. But if these data indeed demonstrate the process of pedoturbation, one wonders why other, equally well-developed Vertisols, do not conform to this pattern.

Of the non-vertic soils, the Hadeliya profile shows the typical organic-matter profile of a Fluvent: a level that fluctuates but that does not decrease with depth, whereas Seinat B10 shows a 'classic' organic-carbon profile, with higher levels than are common in soils of the Central Clay Plain, and a distinct decrease with depth.

In Vertisols the organic matter occurs bounded to the large surface area of the smectite clays, and so small amounts of organic matter have a strong pigmenting effect. This explanation of the dark (low value) colour of the Vertisols has been generally accepted. However, the values of the soil colours in the Vertisols of the Central Clay Plain have no consistent relation with organic matter contents.

8.7 Salinity and sodicity

8.7.1 Saline and sodic Vertisols in the Central Clay Plain: a review

In the lower-rainfall regions of the Central Clay Plain saline and sodic Vertisols occur under natural conditions. Most of these soils are saline-sodic, some are nonsaline-sodic, and a few are saline-nonsodic. The terms saline and sodic are used here according to the definitions of the US Salinity Laboratory (Richards 1954), on the understanding that the term sodic is used instead of 'alkali' for soils having a high percentage of exchangeable sodium.

Saline soils have a conductivity of the saturation extract (ECe) of > 4 mS/cm (mmhos/cm) at 25°C., and the exchangeable sodium percentage (ESP) is less than 15. Saline-sodic soils have ECe > 4 mS/cm, and ESP > 15. Nonsaline-sodic soils have ECe < 4 mS/cm, and ESP > 15. The pH-H_2O is generally < 8.5 in saline soils, and between 8.5 and 10 in nonsaline-sodic soils. The pH-value in saline-sodic soils is determined by the CO_2-HCO_3-CO_3-equilibrium in the soil, and on the amounts of dissolved salts. When the soils are strongly saline, the pH is usually below 8.5, whereas upon leaching, the salinity may decrease and pH-readings may rise above 8.5.

Purnell et al.(1976) consider an ESP-value of 15 too low to differentiate between non-sodic and sodic Vertisols. They suggest limits of 25 for slightly sodic, and 35 for strongly sodic. This is based on the observation that excellent cotton crops are grown under ESP's well above 15. In Australia, however, Vertisols with ESP in the range 8 to 14 are considered sodic (MacGarity 1985); they have a crusty (mazic) surface and a massive soil structure.

Salinity and sodicity in Vertisols of the Gezira, the Northern Kenana and the northern parts of the Butana and the Rahad-Dinder-Blue Nile Gezira, have been reported by several authors. Van der Kevie and Buraywah (1976) describe saline-sodic Entic Chromusterts near Jebel Qeili and Sufeya Ed Derishab (Northern Butana), with ESP 18 to 26 and ECe 3.4 to 8.5 mS/cm. The salinization is mainly of a sodium chloride type. Gypsum occurs in the Sufeya profile. A Vertisol in the Khashm el Girba sugar estate (15°28'N-35°33'E) that contained gypsum, has ESP 22 below 25 cm depth, and ECe 12 in 80-120 cm. The salinization is mainly due to sodium chloride and sodium sulphate.

Purnell et al.(1976) report on saline and sodic Vertisols in the lower-rainfall regions of Khartoum and Blue Nile Provinces. Subsurface soils are usually both saline and sodic. The soluble salts are dominantly sodium salts, mainly chlorides in the driest regions, and sulphates more to the south. A relatively high amount of sodium carbonate causes high levels of pH (1:5 soil/water ratio), up to 9.2. Data on an Entic Chromustert in the Gezira Scheme are given in Table 8.9. Additional data on this profile show that Na and Ca are the dominant cations in the saturation extract, and SO_4 is the dominant anion. HCO_3 is low and constant at 1.2 to 1.9 meq./l. Gypsum occurs below 100 cm depth. There is no chloride salinity. Salinity is strongest in the subsurface soil (30 to 100 cm), and much less below. Sodicity is severe below 65 cm. The general observation in saline-sodic soils that pH-levels are highest when salinity is relatively low and sodicity relatively high, is not evident in this soil.

Table 8.9: ESP, ECe and pH-H_2O (1:5) of an Entic Chromustert in the Gezira area (after Purnell et al. 1976)

depth (cm)	pH-H_2O (1:5)	ESP (CEC by NH_4OAc)	ECe (mS/cm)
0-15	8.3	0	5.8
15-30	8.2	0	4.3
30-65	8.3	10	6.2
65-100	9.2	32	6.6
100-125	9.0	60	1.8

Nachtergaele (1976) observed that the main water-soluble anion at ECe-levels of 0.4 to 0.5 mS/cm in Suleimi soils (Entic Chromusterts in the Gezira Scheme) is bicarbonate. With depth EC increases, bicarbonate decreases and sulphate becomes the dominant anion. Chlorides are few.

Salinity and sodicity data of a profile near the GARS 141 site, an Entic Chromustert belonging to the Suleimi series - are given in Table 8.10 (Soil Management Support Services/Soil Survey Administration of Sudan 1982). The data confirm Nachtergaele's observations. Tables 8.9 and 8.10 both refer to Entic Chromusterts in the Gezira clay plain. Salinity and sodicity appear to be quite different between these two soils.

Table 8.10: Water-extractable ions (from a saturated paste), ECe, ESP and pH-H_2O of a Vertisol of the Suleimi series (Gezira) (after Soil Survey Administration 1982)

depth (cm)	cations (mmol/kg)					anions (mmol/kg)						ECe mS/cm	ESP	pH H_2O (1:1)
	Ca^{2+}	Mg^{2+}	Na^+	K^+	sum	CO_3^{2-}	HCO_3^-	Cl^-	SO_4^{2-}	NO_3^-	sum			
0-5	2.6	0.4	8.8	0.1	11.9		8.3	0.9	1.3		10.5	1.1	2	8.5
5-23	0.6	0.1	7.9	tr	8.6		6.9	0.6	0.8		8.3	0.8	15	8.8
23-45	0.4	0.1	8.4	tr	9.3		6.5	0.4	1.0		7.9	0.8	20	8.8
45-70	0.4	0.1	9.1	tr	9.6		6.6	0.8	1.3	0.6	9.3	0.9	23	8.9
70-90	2.3	0.6	20.8	tr	23.7		4.0	2.1	15.8	2.1	24.0	2.4	22	8.4
90-122	23.2	7.2	59.4	0.1	89.9		2.3	7.7	74.2	10.7	94.9	6.8	21	7.9
122-165	22.7	8.0	59.5	0.1	90.3		2.2	9.0	71.2	11.5	93.9	6.8	20	7.9

Greene (1928) found that Gezira soils with a low salt content and without gypsum mainly had a Na_2CO_3 salinization, whereas those with high salt content and with gypsum accumulation, mainly had Na_2SO_4.

Several authors have observed that both salinity and sodicity in the Gezira are highest in the north; they gradually decrease - with increasing rainfall - towards south.

Surprising are the extremely high ESP-values recorded in some irrigated Vertisols of the Gezira/Manaqil Scheme (Buringh 1969; Robinson et al. 1970; Purnell et al. 1976). Buringh refers to Vertisols in parts of the Central Clay Plain that are nonsaline, have a pH > 8.5, and ESP 40 to 80. Morphologically these soils are not different from nearby nonsaline-nonsodic Vertisols, and no reference is made of differences in site characteristics. It is likely - but as yet there are no data to prove it - that the presence of the Na-zeolite analcime is the cause of the high measured exchangeable sodium (section 8.7.5).

Robinson et al. (1970) gave average values of ESP and ECe from a large number of Vertisols from various parts of the Gezira/Manaqil Scheme. The data are from three depth classes, 0 to 30, 30 to 60 and 60 to 90 cm, and show the following:

a. In the depth class 0 to 30 cm there is a wide range of ESP (5 to 27), in combination with a low level of ECe (below 1).

b. In the depth class 30 to 60 cm there is also a wide range of ESP, but at a higher level (18 to 35), and accompanied by higher ECe (1 to 4); there is a weak positive correlation between EC and ESP.

c. In the depth class 60 to 90 cm ESP ranges from 21 to 43, and ECe from 4 to 9, but there is no correlation.

Buringh (1969) observed that most sites with sodic Vertisols in the Central Clay Plain occur south of the Gezira. Chromusterts usually had lower ESP than Pellusterts, and Buringh ascribed this to the poorer drainage of the latter.

Strmecki (1971) studied the soils in a 25 to 50 km wide strip on the Blue Nile westbank between Sennar and Roseires. The soils are Chromusterts and Pellusterts. Salinity is low, and restricted to the lower soil horizons (ECe 2 to 4 mS/cm at 150-200 cm depth). Sodicity is also low. Both salinity and sodicity increase with depth. Pellusterts tend to be more strongly saline and sodic than Chromusterts, and sometimes contain gypsum. An investigation of the surface 50 cm in 67 Chromusterts and 44 Pellusterts showed a linear relation between EC and ESP; highest values for EC and ESP in the Chromusterts were 0.7 and 18, respectively, and in the Pellusterts 1.0 and 36. The relation between EC and ESP is more distinct than in the Gezira soils.

Bunting and Lea (1962) found for Vertisols in the same area that with a change in chroma of the soil colour, marking the transition from Chromusterts to Pellusterts, the Na-value (exchangeable + water-soluble Na in meq./100 g soil), the percentage of soluble salts, P_2O_5-Truog and percentage $CaCO_3$ increased.

An Entic Pellustert, situated in the lowest, treeless part of an elongated depression that runs parallel to the Blue Nile westbank between Singa and Roseires (FAO 1970b), showed an ESP increasing with depth from 12 to 40, in combination with a low salt content (ECe increasing with depth from 0.9 to 2.4); the pH (1:5 soil/water ratio) was

9.6. Our reference profile Tozi, that has similar values for pH and ESP, is situated in a slightly higher-lying part of the same depression, which carries a vegetation including *Acacia seyal, Acacia fistula* and other tree species. Profile Tozi is discussed below in sections 8.7.2.2, 8.7.3 and 8.7.5.

The following conclusions can be drawn from the above review:

1. Salinity and sodicity usually occur together in Vertisols of the arid parts of the Central Clay Plain.
2. Salinity and sodicity decrease with increasing rainfall, and - within any soil profile - increase with depth.
3. Moderately high and high salinity levels are paralleled by a visible gypsum accumulation in the soil; some of the salinity measured is due to the appreciable solubility of gypsum.
4. In most of the Vertisols where high levels of salinity and/or sodicity are reached below depths of 60 to 100 cm, both salinity and sodicity are weak in the rooting zone of most crops.
5. In closed depressions in the western Kenana, sodicity is higher than in the surrounding clay plains, whereas salinity is low. The soils in the depressions are nonsaline-sodic Entic Pellusterts, those outside the depressions Chromusterts. Other Pellusterts in the area, however, are saline-sodic.
6. At low salinity levels, the dominant watersoluble anion is bicarbonate, at higher salinity levels it is sulphate. Chloride salinzation occurs in the northern part of the Central Clay Plain. The dominant cations are calcium and sodium.
7. Nonsaline-sodic Vertisols usually have a high pH (>8.5) and a dominance of bicarbonate anions in the soil solution.

8.7.2. Salinity, sodicity and pH in nine clay-plain Vertisols

8.7.2.1 METHODS

The electrical conductivity of a soil:water extract was used as a parameter for soil salinity in a number of soils. The profiles selected were those that had an exchangeable sodium percentage >15 in any horizon, and/or had a visible accumulation of gypsum. The selection was based on the observation (section 8.7.1) that salinity is often accompanied by sodicity and by the presence of gypsum. It has been recommended (Richards 1954) that the conductivity should be measured in a saturation extract (ECe). However, in several Vertisols it was difficult to extract sufficient water from a saturated soil paste, to enable a conductivity measurement to be taken. Therefore, soil:water extracts were made in the ratio 1:1, 1:1.5 or 1:2, mixing 10 grams of soil with 10, 15 or 20 ml water, respectively, whatever ratio was required to obtain, after centrifuging, 5 to 10 ml extraction liquid. As the same quantity of water was obtained after centrifuging the same amount of soil, it is clear that the different amounts of water required for obtaining 5 to 10 ml extraction liquid, reflect the different amounts of water held by the clay against the centrifuging force. The extract was also used to measure water-soluble sodium by flame photometer.

Salinity and sodicity occur in the following representative profiles: Khashm el Girba 213, 215 and 251; Jebel Qeili; GARS 141; Sennar 49; Jebel Abel; Tozi and Bozi. These soils are on sites with an annual rainfall of 600 mm or less. The data on salinity and sodicity are plotted against depth in Figures 8.3 and 8.4.

8.7.2.2 RESULTS

Figure 8.3 gives the electrical conductivity profiles of the nine soils. Salinity increases, gradually at first, then steeply, with depth. Khashm el Girba 215 shows a lower salinity in the 140 to 170 cm sample, which also has a much lower clay percentage. Jebel Abel and Tozi have low salinity throughout. A few soils (Khashm el Girba 213 and 251, Sennar 49) were sampled to depths below 180 to 200 cm, and these show a decrease in soil salinity with greater depth.

Figure 8.4 gives the exchangeable sodium percentages of the same profiles. Note that in some profiles (Khashm el Girba 213 and 215, Jebel Qeili, GARS 141, Jebel Abel, Tozi and Bozi) more horizons have been analysed on ESP than on EC. The ESP increases with depth in all profiles, and at a given depth the ESP values are very much alike, except for Jebel Qeili and Bozi which follow this trend at lower ESP levels. ESP-values range from 4 to 10 near the surface, to values of between 24 and 36 at depths of about 160 cm. A reverse trend at greater depth is noted in GARS 141, Khashm el Girba 213 and 251, in the latter two profiles at the same depth where the EC also shows a reverse trend. Tozi stands apart, with a very steep increase in ESP to levels between 48 and 53 at depths of between 75 and 160 cm. In Figure 8.3 we have seen that Tozi has a low and constant EC at 0.8 mS/cm.

Figure 8.5 gives the pH-H_2O of a 1:5 soil/water extract. In most soils the pH values remain at the same level throughout the profile, whereas the mutual differences between soils are small: pH varies between 7.6 and 8.7. Jebel Abel and Tozi have higher pH in the subsurface soil: 8.4 to 9.0, whereas Bozi, and especially Jebel Qeili, have an irregular depth trend. The pH value of 9.5 in sample 5 of Jebel Qeili is not matched by high sodicity and very low salinity.

Some general trends emerge:

a. Salinity is low in the surface soil. At a certain depth salinity increases steeply. This 'saline horizon' begins deeper and the maximum EC is lower, accordingly as the rainfall at the profile site is higher. In the lower subsoil or the substratum there may be a decrease in salinity.

b. The percentages of exchangeable sodium follow the EC trend, but the increase is more gradual. There is a remarkable uniformity in both the ESP-values and their depth trend in most Vertisols. The exceptions are Jebel Qeili and Bozi, the two profiles that, in contrast to the other sodic Vertisols, are from degradational clay plains.

c. The Tozi profile with low salinity, high ESP and high pH is a typical nonsaline-sodic soil. It is characteristic of soils in depressions in the NE Kenana. These sodic Vertisols are usually Entic Pellusterts, with a soil colour that has both low chroma and low value.

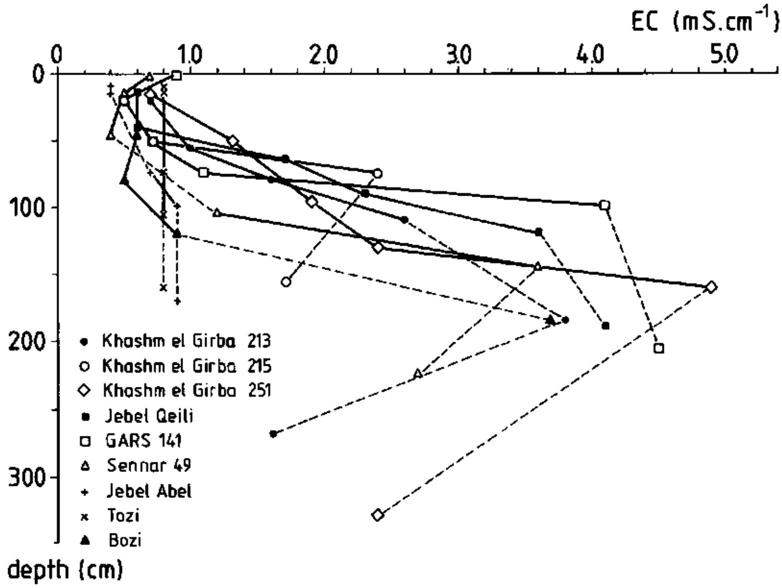

Fig. 8.3. Electrical conductivity of clay plain Vertisols with rainfall 600 mm/ annum or less

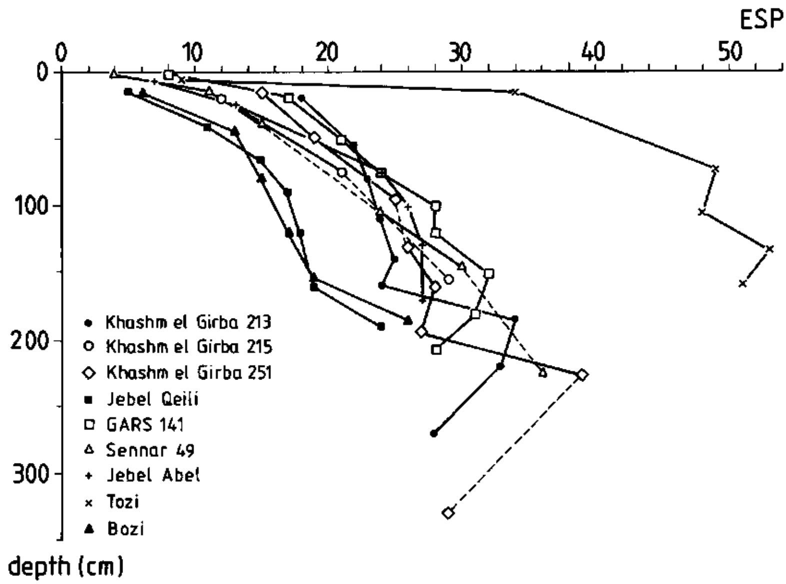

Fig. 8.4. Exchangeable sodium percentages of clay plain Vertisols with annual rainfall of 600 mm or less

Table 8.11 gives, for three profiles (Sennar 49, Jebel Abel and Tozi) the anions and cations in the soil:water extract in which the electrical conductivity was also measured. Data on ESP and pH-H2O have been added for comparison. Sennar 49, below a depth of 55 cm, is a sodic soil, with mainly sodium sulphate salinization; it also contains chlorides and bicarbonates of sodium, calcium and magnesium. Jebel Abel, with low salinity, has dominantly sodium bicarbonate and sodium sulphate salinization. It is surprising that the Tozi sample, from a sodic Entic Pellustert with an ESP of 49 and a pH of 8.8, has Na_2SO_4 rather than Na_2CO_3 salinization. The subsurface soil horizons of all three soils are sodic, Tozi most strongly so.

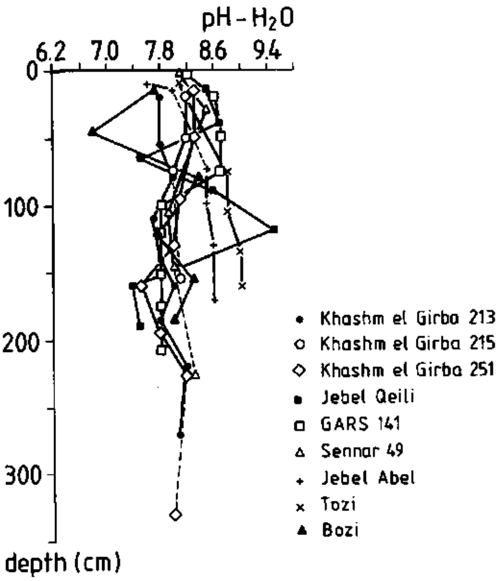

Fig. 8.5. pH-H_2O of clay plain Vertisols with rainfall 600 mm/annum or less

8.7.3 ESP provinces in the Central Clay Plain

The exchangeable sodium percentage was calculated in samples from all 23 analysed profiles, and we have used these data to make a geographic differentiation based on classes of ESP values. The control section of depth was 0 to 150 cm.

The profiles have been grouped in classes according to the highest ESP values in the control section. Six classes have been defined in this way. The classes and the profiles belonging to each class are given below:

1. ESP >30: Tozi.
2. ESP 20-30: Khashm el Girba 213, 215 and 251; GARS 141; Sennar 49; Jebel Abel.
3. ESP 15-20: Jebel Qeili; Bozi.
4. ESP 10-15: Er Rawashda; Seinat B50.
5. ESP 5-10: Damazeen A; Simsim B27; Seinat B47; Seinat B55.
6. ESP <5: Hadeliya; Damazeen B; Ulu; Khadiga; Boing; El Gelhak; Seinat B7, B10, B48.

Two trends come out clearly. Firstly, Vertisols on sites with a relatively high rainfall have lower ESP than sites with relatively low rainfall. Secondly, Vertisols on degradational clay plains and residual Vertisols have, under the same rainfall conditions, lower ESP than those on aggradational clay plains. The Blue Nile dissolved load has apparently been an important source of sodium to the clays of the aggradational plains.

The Tozi profile stands apart due to its specific site.

Table 8.11: Soluble anions and cations, EC, ESP and pH-H_2O in three Vertisols of the Gezira/Kenana

sample nr.	profile name and number	depth (cm)	soil-water extract (mmol/kg)										EC mS/cm	pH-H_2O	ESP
			cations					anions							
			Ca^{2+}	Mg^{2+}	Na^+	K^+	sum	CO_3^{2-}	HCO_3^-	SO_4^{2-}	Cl^-	sum			
275	Sennar 49 (10)	0-3	4	1	7	1	13	1	19	0	1	21	0.7	8.1	4.1
276/277		3-55	1	0	15	0	16	1	21	2	1	25	0.4	8.5	13.3
278		85-130	42	20	110	0	172	0	8	151	19	178	1.2	7.9	24.1
279		130-160	23	14	100	1	138	0	7	124	15	146	3.6	8.0	30.1
280		190-260	5	3	66	0	74	0	12	46	17	75	2.7	8.3	36.1
281	Jebel Abel (12)	0-15	1	0	9	0	10	0	8	2	0	10	0.4	7.6	7.0
283		60-90	1	0	17	0	18	2	10	6	0	18	0.7	8.5	24.2
286		150-170	1	0	17	0	18	2	9	7	0	18	0.9	8.6	26.5
340	Tozi (13)	60-90	1	0	16	0	17	3	2	12	0	17	0.8	8.8	48.5

8.7.4 Salinity and sodicity in Khashm el Girba South

Soil profile and site descriptions, and laboratory analyses were available from almost 200 soil profiles in the Khashm el Girba South soil survey area (section 6.5.1). By means of DBASE-II a data set of profiles was obtained, with horizon and site characteristics (Van den Broek 1986). Two salinity groupings were distinguished, with soluble salts percentages >0.15, and >0.35, respectively. For sodicity the Na-value (exchangeable + water-soluble Na, in meq./100 gram clay) was used as a parameter. There were two sodicity groupings, with Na-value >15 and >35, respectively. The boundary values for soluble salts percentage (0.15 and 0.35) and for Na-value (15 and 35) conform to those of the soil suitability classification for irrigated cotton cultivation, in use at the time (Blokhuis 1963): Class I, good, has soluble salts <0.15 and Na-value <15, whereas Class II, medium, has soluble salts 0.15 to 0.35, and/or Na-value 15 to 35; Class III, unsuitable, has higher values. Other criteria for this suitability classification were depth to salt accumulation horizon and clay percentage (Finck and Ochtman 1961).

A salt percentage of 0.15 roughly equals an ECe of 4, and a percentage of 0.35 an ECe of 8, for soils with mainly chloride salts or sodium sulphate (Soil Survey Staff 1951, p. 360; Richards 1954, p. 11), and these are the common types of salinity in the semi-arid parts of the Central Clay Plain (section 8.7.1). It was also found (Blokhuis 1963) that sodium values above 15 usually correspond with ESP-values above 15, the boundary value for sodicity in the classification of the US Salinity Laboratory (Richards 1954).

Of a total of 1258 samples, 54 had a Na-value above 35, 1024 of between 15 and 35, and 180 had a Na-value under 15. A soluble salts percentage between 0.15 and 0.35 occurred in 837 samples. The data show that moderate salinity and sodicity are common, and occur mostly in the same samples. Such parallelism does not occur with the higher Na-values and soluble salts percentages: of the 54 samples that have a Na-value >35, only 21 have soluble salts >0.35, whereas the entire data set contains 416 samples with soluble salts >0.35%. Salinity appears to be more widespread than sodicity in this area.

Of the 54 samples with Na-value >35 the sodium value was plotted against percentage soluble salts (Fig. 8.6). To each sample location the pH (1:5 soil/water ratio) was added. The soil series to which the samples belong (section 6.5.1) were also given.

The plotted data show some relation between pH and salinity/sodicity:

- the pH is below 8.5 when the percentage of soluble salts is over 0.50, and the Na-value is 35 to 38.
- the pH is 8.5 to 9 when the percentage of soluble salts is 0.25 to 0.50, and the Na-value is 35 to 42.
- the pH is above 9 when the percentage of soluble salts is below 0.25, and the Na-value is 35 to 60.

These results are in accordance with what has often been observed in saline-sodic soils: high amounts of soluble salts tend to lower the pH, whereas high amounts of exchangeable sodium are often accompanied by high pH's. It is also shown that at a relatively high and constant level of the Na-value (34 to 40), the salinity shows a wide variation.

It is interesting to note the differences between the three soil series:

- The Asubri series has low soluble salts (0.11 to 0.28%), in combination with some of the highest Na-values found (48, 52, 58, 75, 91).
- The Khashm el Girba series has a wider range of soluble salts (0.26 to 0.96%), in combination with a very narrow range of Na-values (35 to 43).
- The Dimiat series - represented with only four samples - is similar to the Khashm el Girba series: soluble salts 0.45 to 0.54%, and Na-values of 35 to 37.

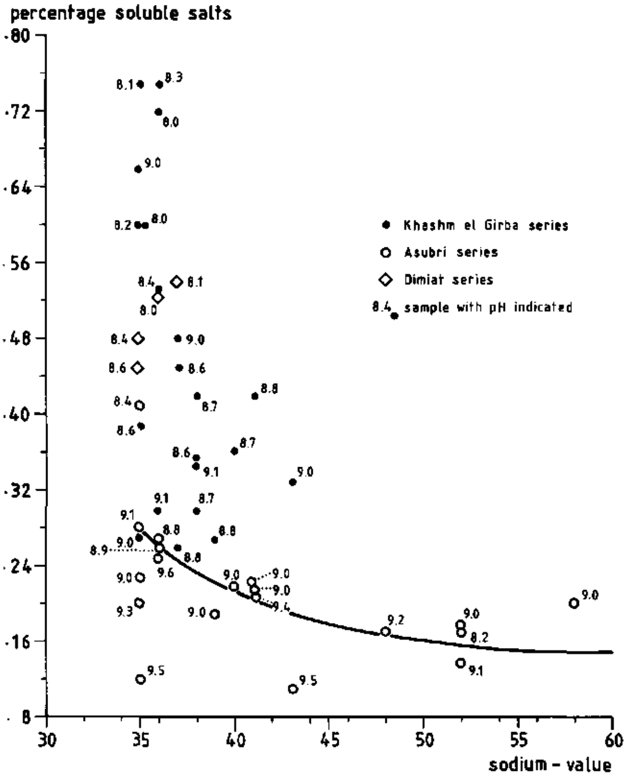

Fig. 8.6. Khashm el Girba samples with Na-value > or = 35, in their relation to percentage soluble salts and pH-H_2O

8.7.5 Salinization and sodication in Sudan Vertisols

The observations reported in the preceeding sections can be related to some specific salinization/sodication processes. We distinguish the following situations:

1. The common pattern in Vertisols in regions with 400 mm or less annual rainfall, is a weak salinity and sodicity in the surface soil, increasing rather abruptly to higher levels at a certain depth. Lower values are sometimes found in the substratum. Free carbonates and gypsum are present in the subsurface soil and in the upper part of the substratum. This pattern is common in both alluvial (Khashm el Girba 213, GARS 141) and colluvio/alluvial soils (Khashm el Girba 251, Jebel Qeili), under natural

conditions. The weaker salinity in the surface soil and the sudden increase in salinity in the subsurface soil is probably due to a leaching-cum-accumulation process. It is probably mainly due to the presence of deep and wide cracks in the dry season that some leaching is possible in these impermeable soils: salts concentrate on the surface of cracks during the dry season, and are washed down by the first rains.

2. The low-salinity high-sodicity depressions with Entic Pellusterts in the aggradational Blue Nile clay plain between Sennar and Roseires contrast strongly with the adjoining nonsaline-nonsodic datum sites with Typic Chromusterts. It is feasible that during the final stages of clay aggradation the closed depressions not only had higher sodicity, but also higher salinity compared with the surrounding clay plain. Excess floodwater must have accumulated in these depressions, where it eventually evaporated. Chemical analyses of the dissolved load of the Nile system, reported by Buursink (1971, p.52), show that the water consistently contains less Ca+Mg than HCO_3. This implies that the evaporating solution has a positive residual alkalinity, i.e. it contains more alkalinity than divalent cations, or:

$$(HCO_3^-) + 2(CO_3^{2-}) + (OH^-) > 2(Ca^{2+}) + 2(Mg^{2+}),$$

where brackets denote molar concentration (Van Breemen and Brinkman 1976).

Upon evaporation of a solution with residual alkalinity, calcium carbonate precipitates until most of the dissolved Ca^{2+} has disappeared, while dissolved sodium bicarbonate and carbonate increase. The high (Na^+) and low (Ca^{2+}) contents of the soil solution causes the displacement of some of the exchangeable Ca^{2+} by Na^+, with a subsequent ongoing precipitation of $CaCO_3$. Under the present climatic conditions flooding (by rainwater) must have lowered the concentration of the soil solution in the surface soil. The sodium absorption ratio (SAR) will decrease, but only slightly, as the soil solution is relatively rich in Na^+ and relatively poor in Ca^{2+}. With high SAR, the ESP will be maintained at a high level, even when the salinity is low.

However, it should be realized that usually the trends in salinity and sodicity are parallel: with increasing salinity (higher EC), the sodicity increases also (higher EC) (see also the conclusions of section 8.7.1). Evaporation of a solution with residual alkalinity would normally result in an increased concentration of any NaCl and Na_2SO_4 present, and so both salinity and sodicity would increase.

The Vertisols of the closed depressions in the western Kenana, however, show a reversed pattern. Lowering the concentration of the solution would yield a higher SAR, but it remains difficult to understand the combination of a very low salinity with a very high sodicity in these soils. Another hypothesis is presented here, considering:

a. a marshy vegetation and anaerobic conditions in these sites for at least part of the year.

b. floodwater with appreciable amounts of sulphate in addition to sodium and calcium.

Under these conditions sulphate reduction could have occurred (Whittig and Janitzky 1963), as follows:

Na_2SO_4 (aq.) + 2 $CH_2O \rightarrow H_2S \uparrow + 2HCO_3^- + 2Na^+$, and

$CaSO_4$ (aq.) + $2CH_2O \rightarrow H_2S \uparrow + CaCO_3 \downarrow + CO_2 + H_2O$
(CH_2O stands for organic matter).

With volatilization of H_2S, immobilization of Ca (and Mg) as carbonates, the concentration of both HCO_3^- and Na^+ ions in the soil solution would increase, and the higher Na/Ca ratio would result in a partial replacement of Ca on exchange sites by Na. The original sodium sulphate salinization would thus be changed into a bicarbonate salinization, characterized by a high ESP and a high pH (Van Breemen 1987). The absence of gypsum in these depressions and the strong accumulation of $CaCO_3$ are in accordance with the presumed processes.

3. In the Khashm el Girba area there is a striking difference in salinity and sodicity between the Khashm el Girba series and the Asubri series. The Asubri soils have low soluble salts, high pH and high Na-value. As salt percentages are usually below 0.2%, the contribution to the Na-value of sodium ions in solution is probably small in comparison with the contribution of sodium ions on exchange sites.

The higher sodicity in the substratum, compared with that of the Khashm el Girba series, could be explained by assuming a higher initial (sodium) salinity (sulphates, carbonates, bicarbonates), perhaps caused by a secondary enrichment from saline groundwater. Such an enrichment from groundwater is not feasible in the clayey substratum - with probably a very low hydraulic conductivity - of the Khashm el Girba series. In addition, the relatively thin clay mantle of the Asubri series could have allowed a leaching of salts to the underlying coarser-textured substratum, whereas such leaching is not feasible in deep Vertisols like Khashm el Girba 213. Subsequent leaching of the saline-sodic Asubri series substratum, would have yielded the present strongly sodic and weakly saline soil.

However, a sulphate reduction as suggested for the closed depresssions in the Kenana, may also have taken place here. There is, indeed, locally an indication that marshy conditions have existed during the interval between the semi-lacustrine deposition of the upper clay mantle, and the meandering-river type sedimentation of the substratum (section 6.5.1). This is notably the case in the snail-bearing soil profile described in section 4.4.4. However, similar accumulations of shells have not been found in the other Asubri profiles.

4. There is no simple relation between sodium in the soil solution and sodium on exchange sites. Data by Robinson et al. (1970) showed a great variation in ESP at low levels of salinity, whereas in the Khashm el Girba area (Fig. 8.6) soils with a relatively high Na-value had very different salinity.

5. The observation that Vertisols in the Gezira area with ESP values in the range of 40 to 80 (Buringh 1969) had a morphology and a cotton production similar to adjoining low-ESP soils, suggests the presence of zeolites in the high-ESP soils. The sodium in the zeolite mineral analcime is partly exchangeable by the potassium and ammonium ions conventionally used in the investigation of cation exchange capacity and exchangable ions, and so anomalously high apparent ESP-values have been obtained in samples containing Na-zeolite (Schultz et al. 1964). We did not find zeolite in our samples. However, Buursink (1971, p.46) identified zeolites, notably analcime, in the 50 to 500 µm sand fraction of a sample of the Blue Nile riverbed at Damazeen (3% of the light fraction). Whiteman (1971, p.125) refers to observations showing that zeolites are common in Gezira clays.

6. As far as the relation between sodicity and soil structure is concerned, a collapse of soil structure as is often reported for sodic soils, is not evident in Gezira Vertisols. This is probably due to the mode of structure formation in Vertisols, which is an annual process following the desiccation and shrinking of a wet soil. Purnell et al. (1976) ascribed the absence of soil structure deterioration in sodic Vertisols of the Gezira to the high plasticity of the soils. The subsoil would, regardless of ESP, be impermeable due to the overburden of the surface soil.

However, there are other observations, showing a relation between sodicity and soil physical characteristics. Mukhtar et al. (1976) found that in Vertisols with moderate ESP-values (10 to 25), soil swelling and shrinking - and hence structure formation - is stronger than in Vertisols with lower ESP. In soils with very high ESP-values (> 25), the hydraulic conductivity decreased and structural aggregates were dispersed. Nachtergaele (1976), studying the Suleimi series in the Gezira - to which GARS 141 belongs - found that ESP-values below 5 had an adverse effect on the physical characteristics of the soil (low air/pore space, low aggregate stability and low available moisture). ESP-values above 25 had similar consequences, and in addition resulted in a lower hydraulic conductivity and in toxicity of the sodium ion for plant growth.

8.8 Summary

The pedogeomorphic map 1:2 000 000 of the Central Clay Plain (Chapter 6 and Appendix 4) was based on differences in site (geomorphology, soil parent material, vegetation/land use, climate) and in soil morphology. A detailed study of the morphology, including the micromorphology, of 27 representative profiles, revealed that some - but not all - of the differences between soils correlated with different mapping units and, on the other hand, that soils could be very much alike between mapping units.

In Chapter 8 we have discussed analytical data from laboratory investigations. We have differentiated between Vertisols from clay plain sites, other Vertisols (residual soils and Vertisols in red-black catenas) and non-vertic soils. One objective was to ascertain to what extent the analytical data would support the field and micromorphological observations. Another objective was to support hypotheses on soil forming processes. The main conclusions from this chapter are the following.

The optical mineralogical investigations of sand and silt (section 8.2) revealed major differences between aggradational and degradational clay plains. Differences between the Atbara and the Blue Nile-Dinder-Rahad aggradational clay plains could be related to the catchment areas of the rivers, but post-sedimentary weathering of the deposits had also to be taken into consideration.

The variation in parent materials, as shown in the mineralogy of the silt and sand fractions does not recur in the clay fractions (section 8.3). X-ray diffraction of the clay shows the mineralogy to be strongly smectitic for all clay-plain Vertisols, and less smectitic (due to poor crystallization of the smectite, or due to a greater proportion of other clay minerals) in some of the Vertisols developed 'in situ', especially when they are pedogenetically young. The non-vertic soils have a mixed or kaolinitic clay mineralogy, in accordance with greater permeability of the soil material and sites that allow runoff of excess water.

Most of the clay-plain Vertisols have a cation exchange capacity of the clay fraction (CEC-clay) at around 800 mmol. kg^{-1}, with a range from 600 to 1000. The great uniformity in clay composition of clay-plain Vertisols is only partly confirmed by the cation exchange capacity of the clay fraction (section 8.4). The clay mineralogy of Vertisols from other sites, and of non-vertic soils is more varied. It should be realized that within a rather homogeneous population of clayey smectitic soils, variations in the CEC of the clay fraction occur as a result of size of clay particles, crystallinity of the clay, exchange cations and ferrous/ferric iron in the crystal lattice. Neither X-ray diffraction, nor CEC-clay data could be related to rainfall regime at the site, or nature of the parent material.

The smectitic nature of the clay is illustrated by the molar silica/sesquioxide ratios of the clay fraction (section 8.5.1). Ferrous iron is present in primary minerals. Most of the ferric iron compounds of the Vertisols are in the clay fraction, and this includes both free and silicate-bound ferric iron (section 8.5.2). The clay fractions of the non-vertic soils contain less silicate-bound ferric iron than the clay fractions of the Vertisols. Differences in soil colour and drainage conditions between Chromusterts and Pellusterts were not matched by systematic differences in the silicate/free ferric iron ratio of the clay fractions.

Data on the elemental composition of the clay fraction of some profiles were used to calculate the approximate chemical composition of the smectite clay minerals that dominate this fraction (section 8.5.3). The calculated smectites were similar in chemical composition; they contained 7 to 11% ferric iron, confirming the ferriferous nature of smectites in Vertisols of semi-arid environments, often reported in the literature.

Data on pedogenic carbonate, granulometric composition, and organic carbon (section 8.6) generally confirm the uniformity in composition of the clay-plain Vertisols.

Vertisols in regions with an annual rainfall of 600 mm or less are weakly saline and sodic in the surface soil; in the lower part of the solum they are moderately saline and sodic (section 8.7). The distinct and abrupt increase is probably due to a leaching-cum-accumulation processes. Closed shallow depressions in the aggradational Blue Nile plain between Sennar and Roseires have nonsaline-sodic Entic Pellusterts, in marked contrast with adjoining sites having nonsaline-nonsodic Typic Chromusterts. Sodicity and high alkalinity in these soils may have been the result of evaporation of excess flood water with a positive residual alkalinity, whereby calcium carbonate precipitates and dissolved sodium bicarbonate and carbonate increase. In an alternative hypothesis, it is suggested that with a marshy vegetation and anaerobic conditions during part of the year, and floodwater containing appreciable amounts of sulphate in addition to sodium and calcium, sulphate reduction has lead to the formation and subsequent volatilization of H_2S, immobilization of Ca (and Mg) as carbonates, and an increased concentration of both HCO_3^- and Na+-ions in the soil solution.

Deterioration of soil structure due to a high percentage of exchangeable sodium is not evident in Vertisols. Both very low (<5) and very high (>25) ESP-values have an adverse effect on several physical soil characteristics.

Chapter 9

Aspects of soil genesis, classification and survey

The main subject of this chapter is a discussion on soil forming processes in Vertisols of the Central Clay Plain. Emphasis will be on those aspects of soil genesis that are different between soils from different parts of the plain.

Prior to a discussion on soil-forming processes, attention will be given to the nature and origin of the clays that are the parent materials of the Vertisols. The discussion on soil formation will be focussed on Vertisols of clay-plain sites, closed depressions, and red-black soil catenas. Special attention will be given to soil colour, a soil property that is closely related to environmental factors such as annual rainfall, nature of parent material, drainage conditions of the site, and permeability of the soil material. Finally, the validity of the concept of pedoturbation - at one time considered to be the essential process in Vertisol formation - will be reviewed.

The subgroup and soil family names according to the US Soil Taxonomy (Soil Survey Staff 1990), show the great uniformity of Vertisols in the Central Clay Plain (Table 6.1). Such differences as occur - and were found to be of importance in the area under consideration - do not feature as differentiating characteristics on the family and higher levels of Soil Taxonomy. The International Committee on Vertisols, ICOMERT (one of several Committees that are to make recommendations for updating Soil Taxonomy) has made suggestions for suborders, great groups and subgroups of the Vertisol order. These are in part based on other diagnostic features than those given in the present version of Soil Taxonomy. The new names proposed by ICOMERT in August 1990, will be compared with those of the present version of the classification system. Suggestions by ICOMAQ, the International Committee on Aquic Soil Moisture Regimes, which are relevant for the classification of Vertisols with hydromorphic characteristics, are also taken into consideration. The discussion will include the naming of Vertisols in the FAO/Unesco-system of 1974, and in the revised version of 1988.

Soil surveys in level, featureless clay plains are faced with difficulties not usually encountered. The great uniformity of soils and landscape, and the diffuse horizon boundaries call for a regular grid pattern of soil observations, and for a profile description with standard depth sections. Geostatistics on lateral and vertical variability of soils could provide optimum mapping, description and sampling methods.

9.1 Origin and formation of the clays

9.1.1 Aggradational clay plains

Parent materials of the Vertisols on the aggradational clay plains are river sediments, dating back to the period between approximately 12 000 and 5 000 BP. The deposits that now form the upper clay mantle can be related to different river regimes. The Gezira clay plain and the northern part of the Blue Nile-Dinder-Rahad clay plain (Adamson et al. 1982) have the characteristics of an alluvial fan. The central and southern part of the Blue Nile-Dinder-Rahad clay plain is a river floodplain with backswamps, levees and silted-up meanders. The Atbara clay plain has a uniform upper clay mantle of 1 to 3 m thick, overlying sediments of a river floodplain landscape. Post-sedimentary weathering of the deposits has produced additional clay. Buursink (1971) showed that from 11 to 40 % of the currently present clay fraction in the soils of the Blue Nile clay plain, has been derived from 'in situ' weathering of silt-size minerals. This hypothesis finds support in the mineralogical composition of the sand fraction of the present Blue Nile sediment load, compared with that of the Blue Nile clay plain soils (Table 8.2).

The mineralogy of the sand fractions shows a different provenance for Blue Nile and Atbara clays. The Atbara clay soils have a higher proportion of minerals from volcanic rocks, notably augite. This has been explained by assuming a different stage of weathering, the Atbara clay plain being younger than the Blue Nile clay plain (Ruxton and Berry 1978; compare also Buursink's above statement). Besides, the clay deposits in Gezira and Blue Nile-Diner-Rahad clay plains are much thicker than in the Atbara clay plain. However, radiocarbon dates of mollusc shells in Gezira and Atbara clay plains, from the same depth and having the same stratigraphic position, showed the same age (Chapter 4).

Since 5 000 BP the climate has fluctuated, but has never been as humid as during the last stage of deposition on the clay plains. Leaching of solutes, and migration of colloidal weathering products must have been limited under these climatic conditions. Leaching was further restricted by the smectitic clayey soil material, whereas the level topography prevented loss of soil compounds by runoff. The conditions must have been optimal for the formation of smectite, and for its stability.

The Gezira fan fades out in the north; the clay mantle gets thinner and is increasingly mixed with windblown sand from nearby Nubian Sandstone outcrops and from 'kerrib' land. The same applies to the Atbara west bank deposits north of Qoz Regeb.

The White Nile clays are lake-bottom deposits, and they are still flooded for long periods each year.

9.1.2 Degradational clay plains

In the aggradational clay plains there has been geomorphic stability since the end of deposition (ca. 5 000 BP), whereas geomorphic instability has continued in the degradational plains. This is shown by the presence of low hills with wide sandy pediments that have not yet reached the ultimate stage of planation (e.g. between Sufeyah and Husheib on the Blue Nile/Atbara watershed).

Clays in the degradational plains have formed from rock weathering on hillslopes and pediments, with migration of solutes and fine-textured colloidal weathering products. The processes are further discussed in section 9.1.3. which deals with Vertisols as members of a soil catena.

The northern boundary of clay formation in the degradational plains is reached when the annual rainfall is insufficient for chemical rock weathering to take place. Ruxton and Berry (1961) have set the boundary at 300 mm annual rainfall; with lesser rainfall there are no clay plains, but plains mantled with silt and fine sand. This 'natural' northern limit of the degradational clay plain can only be traced in areas where the underlying Basement Complex rock continues north of the 300 mm isohyet. This is the case in mapping unit 511 between Jebel Qeili and Abu Deleiq.

A soil profile near Abu Deleiq is situated in a clay flat between areas with sandy and gravelly surface soils, in mapping unit 511. The Abu Deleiq profile has a silty clay loam surface soil, merging with depth into a clay. The horizon sequence is A (0-60 cm), A/Bwky (60-90 cm), B/Awky (90-135 cm), B/Cwky (135-160 cm) and C/Bwky (160-190 cm+). The surface is finely cracked, whereas a vertic soil structure is restricted to the profile section between 60 and 160 cm. Carbonate nodules and fine specks of soft, powdery lime, as well as gypsum crystals are found in the A/B and deeper horizons. The rainfall is 200 mm. The horizon sequence, and the colours of A, B and C soil material (10YR 3/3, 10YR 3/2 and 7.5YR 4/4, respectively) are similar to those of the Khashm el Girba series (the C horizon is rather unlike that of the Dimiat series described in section 6.5.1). Low clay contents of the surface soil apparently prevent the formation of deep cracks and a vertic structure in the A horizon. The low clay content of the surface soil is probably due to an admixture of sandy and gravelly material from elsewhere, but could also be the result of a rather limited clay formation at this low-rainfall site. Similarly, the higher clay content of subsoil and substratum could be due to clay migration in the profile or to weathering and soil formation in a former, more humid environment. The climatic shifts, described by Warren (1970) for the 'qoz' area west of the White Nile, have also moved over the Central Clay Plain area.

Differences in clay composition, and in clay content of the soil, which cannot be related to a climatic zonality, could be due to different parent materials and, ultimately, to different parent rocks. Most of the parent rock is Basement Complex which consists mainly of gneiss, but more basic metamorphic rocks occur, as well as limestone and marble. The clays are thus derived from a multitude of rock types; they have been transported during landscape planation and been mixed together, so the precise origin of the parent materials cannot be traced. Some hill groups have produced considerable weathered rock material, and the soil surrounding the hills can often be mineralogically related to the rock type of the hills; this will be shown below in a few examples from the Southern Gedaref soil survey, and from the southern Kenana.

The soil parent materials in the Gedaref clay plain are derived from two sources: Precambrian Basement Complex and Mesozoic to Tertiary basic volcanics, mainly basalt (the third geological formation in the area, the Nubian or Gedaref Sandstone Formation, produces very little clay upon weathering). In most soils of the Umm Simsim and Umm Seinat soil survey areas, the influence of basaltic rock, as shown in the mineralogy of the sand fraction (section 8.2), is not evident. The Basement Complex that underlies the area and outcrops in some hills such as Qulei'at Ed Darot, has provided the parent materials for most of the soils. The mineralogy of Seinat B55 is different from all other analysed Seinat soils: 43% of the transparent heavy minerals in the 50-250 μm fraction is augite (Table 8.2); the clay content is higher than in most Seinat Vertisols and the colour of the soil tends towards Pellic. The first two properties must be ascribed to the influence of the nearby Gedaref-Gallabat volcanic ridge; the low chroma colour could be due to poor drainage (high clay content of the soil; level site), but low chroma is also a characteristic of Vertisols developed 'in situ' on basic rock (cf. section 9.2.3).

Other low chroma Vertisols occur as aprons around inselbergs of the Jebel Simsim group, sloping down towards the clay plain (Fig. 6.5, catena 3). Jebel Simsim has been mapped as solvsbergite (section 6.5.2), a hypabyssal rock composed chiefly of sodic feldspar, with some potassium feldspar, sodic pyroxene or amphibolite, and with little or no quartz. Profile Simsim B35 is representative of this fringe of low-chroma Vertisols around Jebel Simsim (it is not included in Appendix 2). The main characteristcs in which this profile differs from the surrounding clay plain Chromusterts are: colours 10YR 3-2/0.5-1; gypsum present in 80-125 cm and in 170-300 cm+; the surface is a 2-3 mm thick platy crust, which breaks easily into a very thin mulch, and there are flat stones up to 30 cm diameter on the surface. Gypsum is very rare elsewhere in Simsim and Seinat, and so are Pellic soil colours. In this case, the Pellic colour could be due to flooding by excess water draining the hillslopes, or to the nature of the parent rock, or to both (sections 6.5.2 and 9.2.3).

The last example is the Ulu profile in the Southern Kenana clay plain. Ulu is situated on a gilgai microridge in an undulating clay plain with wavy to lattice type gilgai. Ulu is the only Vertisol with a high percentage of titanite in the heavy fraction of the 50-250 μm size class. This anomaly can only be explained by assuming that rocks rich in titanite are in the area.

9.1.3 Red-black soil catenas

Clay formation in red-black soil catenas in semi-arid and sub-humid areas is primarily the formation of smectite (Kantor and Schwertmann 1974). Smectites may form directly in weathering rocks by mineral transformation of biotite, amphiboles and other weatherable minerals (Tardy et al. 1970; 1973), but in most Vertisols of Mediterranean climates and of tropical areas with alternate wet and dry aseasons, smectite is formed from ions in solution. Paquet (1970) described two different pathways for these processes. The first is an 'in situ' formation of smectite from ions that are released by hydrolysis of silicate minerals, when the weathering rock is a closed system. The process is confined to basic rock types, and the soils formed are residual Vertisols. The second pathway is an allochthonous formation of smectite, from ions in solution that have migrated downslope. Smectites form in foot slope or plain positions if the weathering solution contains sufficient silica and basic cations, and under conditions of poor drainage and with a pH in the alkaline range (Borchardt 1977). We have described Vertisols that form on these foot slopes and clay plains as colluvio/alluvial, and they occur in catenas developed from basic as well as from acid rock.

'In situ' Vertisols are limited to basic rocks; they occur on slopes (Khadiga) or on crests (Boing), or they may cover the entire catena except for steep sections of the slope that are covered by vertic lithic soils (Gedaref-Gallabat ridge). Two catenas on basalt in Israel, with an annual rainfall of 400 and 700 mm rainfall, respectively, have been described by Yaalon et al. (1966). The upper members of these catenas consist of shallow lithic, or vertic, red soils, the middle and lower members of Vertisols. The clay mineralogy is the same in all members of both catenas, with smectite dominant, and some kaolinite.

Catenas on acid and intermediate rocks occur in the Seinat area, and most of them run from non-rocky elevation to clay plain. The following members can be distinguished: Alfisols on crest or upper slope, Inceptisols with vertic subsoils on middle slopes, sandy Chromusterts with a crusty surface on foot slopes, and fine-textured Chromusterts with a surface mulch on clay plains. The Seinat soils B48, B47, B7 and B50, although not situated on one and the same hillslope, are representative of the members of such a catena. The upper member on rocky elevations such as Qulei'at Ed Darot, is a Lithic Ustorthent (Seinat B10). Seinat B55 does not belong to the catena, as its parent material is strongly influenced by basaltic rock.

The catenas to which the Khadiga and Boing profiles belong are intermediate between the catena of the Gedaref-Gallabat ridge and the Seinat catena. The entire hillslope may consist of Vertisols (e.g. Boing), or Tropepts and Alfisols occur on better drained upslope positions and Vertisols on foot slopes (e.g. Khadiga) and below. Thin sections from the weathering rock underlying the Boing profile show clay formation and some clay migration in fissures, as well as neoformation of calcium carbonate inside weathering mineral grains (Photo 71). Similar catenas occur in the Ingessana hills and in parts of the Southern Kenana clay plain, for example near Kurmuk.

The Er Rawashda soil has developed in a colluvium directly underlain by weathering basaltic boulders. The profile is situated on a long, and very gentle slope.

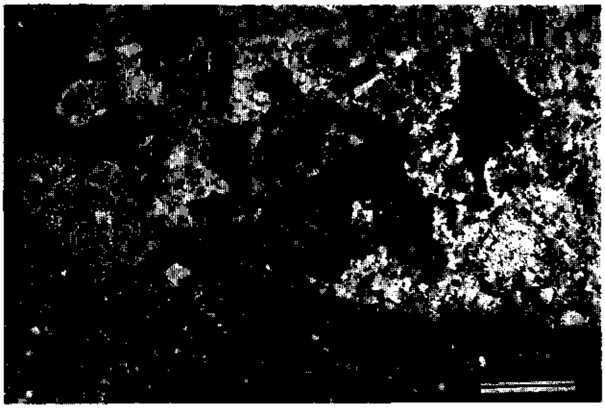

Photo 71: 'In situ' formation of calcium carbonate (grey colour) in saprolite (whitish colour) at a depth of 170 cm; the dark threads at the carbonate/saprolite boundary are manganese concentrations; profile Boing; crossed polarizers; bar represents 440 µm.

From the above discussion it can be deduced that the location of Vertisols in the degradational clay plains varies between two extremes. On one side, 'in situ' Vertisols of a dark red (5YR 3/2) colour cover basaltic hills and plateaus, whereas adjoining very dark grayish brown (10YR 3/2) Vertisols with a tendency towards Pellic colours, cover foot slopes and clay plains. The other extreme is a granitic landscape in the lower-rainfall region (Butana) with smooth hills surrounded by wide, sand-covered pediments, where Vertisols are only found in clay plains below these pediments. The granitic hills - for example in mapping unit 511 between Sufeyah and Husheib - are probably the remainders of the older land surface that elsewhere has disappeared due to planation. The presence of such hill groups - which are distinct from inselberg-type intrusions - shows that planation is an ongoing process in the Butana and elsewhere on degradational clay plains.

9.2 Soil formation in the Central Clay Plain

9.2.1 Soil-forming processes on datum sites (level clay plain positions)

Self-mulching Vertisols belonging to the very-fine, montmorillonitic, isohyperthermic family of Typic Chromusterts, cover nearly all level or very slightly undulating clay plain sites. Entic subgroups occur in lower-rainfall areas, and the fine particle-size class as well as the hyperthermic soil temperature class also occur. There are variations in morphology, and in physical and chemical soil properties, but these are not reflected in the soil family name. The main soil-forming process is a physical process which creates a vertic soil structure (Chapter 7). The variation in soils on datum sites is due to a north-to-south rainfall gradient.

Most sites with a rainfall of 400 mm or less have Vertisols that are slightly saline and sodic, especially in the low chroma Bw horizon and below. Detailed salinity and sodicity investigations in Khashm el Girba South have confirmed this general observation.In some soil samples salinity/sodicity is accompanied by gypsum accumulation. Gypsum occurs incidentally in higher-rainfall regions, in connection with specific parent materials (section 9.1.2).

All clay plain Vertisols contain carbonate concentrations, mainly calcium carbonate, in one of several forms. Soft powdery lime, occurring as specks or soft concentrations, marks the beginning of the substratum, which in our concept coincides with the depth of cracking and the zone of pedoturbation. The process of pedoturbation will be discussed in section 9.2.4.

There is a zonality north to south in abundance and form of carbonate concentrations. Generally speaking, the soil material is carbonatic throughout in the lower-rainfall regions, and there is an abundance of hard, grey nodules, especially in the A horizon and on the soil surface; soft powdery lime begins at about 50 cm depth, and the amounts increase with depth. In higher-rainfall regions the solum is sometimes free of carbonates, and hard, grey nodules are common to few, and sometimes absent. There are two different types of horizon sequence, with their boundary approximately at the 500 mm isohyet (Chapter 7).

With increasing rainfall there is a gradual decrease in salinity and sodicity, gypsum and finely divided lime. The swelling capacity of the soil material increases when there is less soft lime (Rimmer and Greenland 1976), and this is shown in the changing degree of expression of some physical soil characteristics: the surface mulch is more weakly developed, the vertic structure is of a coarser class, and a gilgai microrelief appears. Cracking depth and crack width on the surface are expected to increase, but these characteristics are not easily quantified: they depend on the moisture condition of the soil and thus on the date of description. This, to some extent, is also true of the soil structure.

Type and form of ferri-manganiferous concentrations also show a north-south trend. With increasing rainfall they appear at shallower depth, and occur in more forms. These concentrations reflect oxidation/reduction processes in a soil matrix without macromorphological expression of gley. Nettleton and Sleeman (1985) found that reducing conditions in some Vertisols of the Gezira area were never strong, as was shown by the presence of Mn-oxides and the lack of Fe-mottling. We have described the substrata of some soils in the Butana as having a "hydromorphic appearance", and this refers to the presence of greyish and reddish-brown mottles. However, at least some of the mottles are weathering minerals, coated with ferric iron. Hydromorphic properties, resulting from water stagnating on a perched or true water table, are alien to Vertisols; a water-table in the conventional meaning of the term, as it relates to sandy soils, is not feasible in a Vertisol profile (Brinkman and Blokhuis 1985; Blokhuis 1982).

Soil forming processes are the same in aggradational and degradational clay plains. The differences found result from the nature of the subtratum, soil depth, and possible differences in contents of soluble salts, gypsum and carbonates, and in exchangeable-sodium percentage. Ruxton (1956) summarized the differences between aggradational and degradational clay plains in the lower-rainfall area. Most of Ruxton's statements (section 5.3) on landform, parent material and thickness of the clay mantle, are confirmed by our observations and data. However, for Ruxton's statement that soils of the degradational plains have less salts, gypsum and carbonates, our data are not conclusive. Strong sodicity, on the other hand, seems to occur only in soils of the aggradational plains.

9.2.2 Soil formation in depressions on the Blue Nile westbank

Closed depressions and large level areas, as they are found on the Blue Nile west bank between Sennar and Er Roseires, cannot occur in pediplains such as the Butana and the northern Kenana. Landscape formation in the degradational clay plains creates a very gently undulating topography, with wide and shallow valleys, but without closed depressions (Fig. 2.2). Such depressions are also absent in the Gezira fan (Fig. 2.5) and the Atbara clay plain (Fig. 2.4).

The soils in the Blue Nile west bank depressions are Entic Pellusterts with a surface crust instead of the usual mulch. They have high sodicity, high pH, low salinity, and are very calcareous. In sodic clay soils, which have greater tensile and shear strength, and a greater capacity to swell than similar soils that are non-sodic, one would expect a relatively coarser class of vertic structure. Such a structure, however, does not develop, perhaps because the soils are moist for most of the year. Besides, they are calcareous and this tends to reduce shear strength. There is a characteristic vegetation of *Acacia fistula*, but the lowest parts of the depressions are treeless grass areas (section 8.7.1). As no significant differences were found in levels of pH and ESP between the two profiles in this depression - one (profile Tozi) in *Acacia* tall grass savannah, the other (described in FAO 1970b) in the treeless part - we concluded that the absence of trees in the lowest sites is due to prolonged flooding.

Comparable sites do not occur in the lower-rainfall regions, or if they do, they are flooded for such a short time that the surface soil colour is apparently not influenced. However, Vertisols in wadi beds in the Khashm el Girba area differ from the adjoining clay plain Vertisols in having a surface crust, an uneven surface that approaches a gilgai microrelief, and a relatively low-chroma surface soil. An example is Khashm el Girba 238 (section 6.5.1). These 'wadi variants' in the Atbara clay plain also have a deeper solum, whereas concentrations of soft powdery lime begin at greater depth than in datum site Vertisols. The morphology of wadi-variant Vertisols resembles that of higher-rainfall Vertisols.

9.2.3. Soil colour of Vertisols as an indicator of pedogenic processes

The colour of a soil is often an indicator of soil forming processes. Soil colours are usually described in a three-dimensional system (Munsell 1954), according to hue (the basic colour), value (degree of darkness, from black to white) and chroma (intensity of the colour).

The value of a soil colour normally changes with its amount of finely divided organic matter: A horizons have a lower value than B and C horizons. Entic subgroups of Vertisols are defined as having a colour value in the upper 30 cm that is too high (too light) to meet the criteria for a mollic epipedon. One would expect such subgroups in an arid environment, where soils have low contents of organic matter. Research in India and elsewhere has shown that the origin of the dark colours of Vertisols - which has puzzled many soil scientists, mainly because of the low organic-matter contents that go with it - is in clay-organic matter complexes that are strongly bound to external and internal clay surfaces (Singh 1954; 1956). These complexes have a strong pigmenting effect due to their large surface area, even when amounts of organic carbon are low. The implication of this is, that values of colour are not strongly correlated with organic-matter contents in Vertisols; this is also shown if one compares organic-matter contents between Entic and Typic subgroups of Vertisols in Appendix 2.

The few Vertisols in the Central Clay Plain area which are Entic often have low chromas: they are Pellusterts rather than Chromusterts (Table 6.1). Entic Chromusterts occur in the more arid parts of the clay plain; examples are Jebel Queili (nr. 6) and the Suleimi series, characteristic of most of the Gezira soils (Nachtergaele 1976).

Vertisols in the Central Clay Plain have hues of 10YR or 2.5Y; they are occasionally redder (7.5YR, 5YR) or yellower (5Y). Differences in hue between soils are usually related to amount and type of free ferric oxides: hues of 5Y reflect the absence of free ferric iron, whereas soils with, for example, hue 5YR or redder have a substantial amount of free iron.

Chromas can also be influenced by ferric iron, higher chromas (brighter colours) indicating higher free FeIII. Chromas of 2 or less, when occurring next to spots of higher chroma, or chromas of the soil matrix of 1 or less, are diagnostic criteria for defining Aquic suborders and subgroups in most orders of Soil Taxonomy (Soil Survey Staff 1990); horizons having such chromas are assumed to be saturated with water at some time of the year. Vertisols with a chroma of less than 2 are classified as Pellic great groups. Low-chroma Vertisols, according to Soil Taxonomy, occur in level areas or depressions. Watersaturation and reducing soil conditions are not specifically mentioned and, indeed, such conditions can at the most be temporary in soils that, by definition, are periodically wet and dry, and that owe their specific features to this alternation. Bunting and Lea (1962) found in the Tozi area that both low chroma and yellowish hue (2.5Y or even 5Y) indicated waterlogging.

ICOMAQ, in its Circular 11 of March 1991, proposed to replace the term 'aquic soil moisture regime' by 'aquic conditions'. Requirements are all three of:

a. redoximorphic features. There are three forms:
   - redox concentrations (zones of apparent accumulation of Fe-Mn-oxides);
   - redox depletions (zones of low chroma);
   - reduced matrices (low chroma soil matrices whose colour increases in hue or chroma when exposed to air).

b. Saturation, defined as zero or positive pressure in the soil water. Saturation implies that macropores conduct water.

c. Reduction, to be ascertained in principle by measuring the redox potential (Eh). The Eh is a function of pH.

We will now examine the site, morphology and laboratory data of the Pellusterts among our representative profiles, and ascertain whether aquic conditions, as defined by ICOMAQ, exist. This question is relevant, because:

1. Chromas of the soil matrix that in the Vertisol order are characteristic of Pellic, are diagnostic for Aquic in most other orders of Soil Taxonomy.
2. The pellic colour suggests reducing conditions.
3. Vertisols subject to flooding for several months may be saturated for a certain period and to a certain depth.

There are five Pellusterts among the representative profiles: Tozi, Seinat B55, El Gelhak, Er Rawashda and Boing. Tozi, Seinat B55 and El Gelhak are on sites that are subject to flooding. Er Rawashda is a colluvial, and Boing a residual soil from basic rock, both occurring on well-drained sites. Pellic Vertisols developed 'in situ' on basaltic rock, in well-drained positions, have been described elsewhere, for example in the Canary Islands (Quantin et al. 1977; Tejedor Salguero et al. 1978; Fernandez Caldas et al. 1981).

Boing and Khadiga have developed from the same type of rock. Even so, Khadiga is a Chromustert with a 5YR 3/2 colour, Boing a Pellustert with a 10YR-2.5Y 3/1 colour. The striking colour difference is accounted for by the amounts of free FeIII (Table 8.7): both free-FeIII-soil and free-FeIII-clay are much higher in Khadiga than in Boing. And the ratio silicate-FeIII-clay/free-FeIII-clay is highest in Boing. Boing is also richer in smectite.

One could assume that in both soils weathering of primary minerals has induced neoformation of smectite clays. In Khadiga, a more shallow soil on a well-drained site, some of the smectite may have been transformed into kaolinite, with a simultaneous liberation of Fe^{3+}-ions from the smectite lattice, and oxidation of these to ferric oxides. In Boing, on the other hand, the smectite formed has been conserved. If this assumption is correct, the question of Chromic/Pellic on well-drained sites on basic parent materials - where 'aquic conditions' are not feasible - is translated into one of smectite stability.

For Pellic Vertisols on poorly drained sites, two different modes of formation should be explored:

a. The site has 'aquic conditions' for part of the year; the Pellic colour of the Vertisols is the colour of a reduced matrix due to saturation and reduction;
b. 'Aquic conditions' as defined by ICOMAQ are not feasible, and the Pellic colour is due to stability of smectite and lack of free ferric iron.

ad a: Aquic conditions require redoximorphic features (1), saturation (2) and reduction (3).
ad a(1): Pellusterts of the Central Clay Plain have no mottles. The uniform low-chroma soil is, however, not a 'reduced matrix' because the colour does not change on exposure to air.
ad a(2): Saturation could occur in flooded Vertisols during a shorter or longer period. Saturation is normally limited to the surface soil and the soil around and at the bottom of large cracks, whereas most of the soil between the large cracks remains unsaturated. Flooding does not imply that the surface soil is saturated throughout. Bryssine (1965) characterized the moisture regime in Vertisols from Morocco as 'aéro-hydropédique', soil processes taking place in a moist but aerated environment. Reduction and gleying did not occur in these soils.
ad a(3): Reduction implies that reduced iron (Fe^{2+}) and manganese are mobile and can be transported by water.

In any saturated Vertisol mobility of water is restricted, and this prevents the concentration of soluble compounds such as ferrous iron, and the subsequent formation of redox concentrations on spots subject to oxidation. If the saturated state were to induce reduction, redox concentrations and depletions would form, not a reduced matrix: the reduced state can only be temporary in soils that by definition, are periodically wet and dry, not continuously wet. However, as we have seen under a(1) above, mottles are not formed in Pellusterts of the Central Clay Plain. We draw the conclusion that in Pellic Vertisols periodic saturation is feasible, but reduction is not.

From a chemical point of view mobility of ferrous iron is unlikely in Vertisols with a high pH. Mobility of ferrous iron, formed during reduction, is strongly pH-dependent (see, for example, Krauskopf 1967). With high pH (around 8) extremely low Eh-values, i.e. strongly reducing conditions, are required before iron is reduced.

As aquic conditions are not feasible, the low chroma of Pellic Vertisols must be ascribed to stability of smectite and a relative paucity of kaolinite and free ferric iron[1]. The question now arises: is smectite stability feasible on the sites where we find Pellic Vertisols?

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[1] Some free ferric iron is present in the Pellusterts of the Central Clay Plain, but it hardly contributes to the chroma of the soil. Whether this is due to a finely divided state of the ferric iron, to its bounding to the very large surface area of the smectite, to masking by organic matter, or to any other factor, we do not know.

The stability of smectite is promoted by a high pH, high levels of basic cations and of silica, and impeded drainage (Borchardt 1977). These conditions are fully met in Pellusterts on poorly drained sites on the Central Clay Plain; here we expect considerable stability of smectite and, consequently, low levels of kaolinite. Pellusterts developed in well-drained sites on basic rock meet the conditions for stability of smectite in much the same way as those on poorly drained clay-plain sites, the main difference being the rather rapid external drainage (run-off) on foot slope and hillslope positions. If poor drainage is a pre-requisite for smectite stability (Paquet et al. 1961), and thus for low chroma soil colours, then we must also assume poor drainage - that is: poor internal drainage - for sites like Boing. Pellic Vertisols, derived from 'in situ' weathering of basalt have a high clay percentage, and could well have very slow internal drainage.

Data on clay mineralogy (relative proportions of kaolinite and smectite, Table 8.4), on SiO_2/Al_2O_3 ratios of the clay fraction (for smectite around 4, Table 8.6) and the ratio silicate-FeIII/free-FeIII in the soil and in the clay fraction (Table 8.7) could support the hypothesis that stability of smectite is greatest in Pellic Vertisols. However, no systematic differences between Chromic and Pellic Vertisols have been found. In order to prove the hypothesis, specific research would be required, including detailed soil surveys, careful selection of sampling sites, and mineralogical, granulometric and chemical analyses. No definite conclusions on this issue can therefore be based on the current study.

The influence of various soil compounds on aspects of soil colour was tested on four soil samples from four soil profiles. The colour was recorded after successively removing organic matter, soluble minerals (salts, gypsum, carbonates), and free ferric iron (the procedures are those of the pre-treatments required for optical mineralogical investigation of sand and silt).

The treatments were as follows, in three successive steps:

a. Treatment with H_2O_2, by which organic matter is oxidized;

b. Like a, followed by treatment with NaOAc-pH5, to remove carbonates;

c. Like steps a and b, followed by treatment with sodium citrate, -bicarbonate and -dithionite, to remove free FeIII.

The results are given in Table 9.1, which also gives relevant chemical data: organic matter, $CaCO_3$ percentage, and free FeIII-soil.

The removal of organic matter gave a one unit higher value in the samples Khashm el Girba 213 and Tozi, and no change in the other two samples. There is no correlation with the amounts of organic matter. The subsequent removal of calcium carbonate had no effect on the colour, except for the Jebel Qeili sample which became slightly darker. The colour change upon removal of free FeIII is distinct in all four samples. The change is one of chroma in three of the four samples: from 3 or 2 to 1. The Tozi sample had a chroma 1 under natural conditions; this chroma did not change. Three of the four samples also showed a distinct change in hue upon removal

Table 9.1: Munsell colours of soil samples after successive removal of organic matter, soluble minerals and free ferric oxides

profile nr.	sample nr.	profile name	depth (cm)	org. C %	$CaCO_3$ %	free FeIII-soil %	Munsell colour code (moist)				
							field colour	laboratory colour prior to treatment	after removal of organic matter	after removal of organic matter and $CaCO_3$	after removal of organic matter, $CaCO_3$ and free FeIII
1	251	Khashm el Girba 213	0-40	0.4	7.8	3.7	10YR3/4	10YR3/4	10YR4/3	10YR4/3	10YR4/1
6	867	Jebel Qeili	25-50	0.8	5.7	2.8	10YR4/3	10YR4/3	10YR4/3	10YR3.5/3	5Y4/1
13	339	Tozi	30-60	nd[1,2]	nd[3]	nd[4]	10YR(-2.5Y)4/1	10YR4/1	10YR-2.5Y5/1	10YR-2.5Y5/1	5Y5/1
15	853	Bozi	0-30	0.2	2.7	3.2	2.5Y3/2	2.5Y3/2	2.5Y3/2	10YR-2.5Y3/2	5Y4/1

[1] nd: not determined

[2] in 0-30 cm: 0.8%; in 60-90 cm: 0.5%

[3] in 0-30 cm: 16.6%; in 60-90 cm: 15.5%

[4] in 60-90 cm: 2.4%

of free FeIII: from 10YR or 10YR-2.5Y, to 5Y. The Khashm el Girba sample did not show this change. It should also be noted that the changes in chroma and/or hue after removal of free iron, affect samples from poorly drained and from datum sites, and from lower- and higher-rainfall regions alike. The colour experiment clearly shows that pellic colours (low chroma) in Vertisols are due to the absence of free FeIII, regardless of whether this is caused by aquic conditions or by any other factor.

We will end this discussion on the colour of Vertisols as an indicator of soil-forming processes, with the observation that in low-rainfall areas, Vertisols on aggradational plains have a slightly higher chroma in the surface soil than those on degradational plains (section 6.4). A higher chroma of the surface soil compared with the subsurface soil occurs in all lower-rainfall Vertisols; it has been ascribed by Finck (1961) to rubefaction. Why then has this process been most intensive in the aggradational plains? Climatic and drainage conditions on both types of plain have been similar since the end of the deposition of alluvial clays (ca. 5 000 BP), so what factor or factors could have caused the difference? A possible explanation is provided by the grass patterns typical of the low-rainfall degradational clay plain of the Butana.

The Butana grass patterns (Worrall 1959) are probably due to a special type of soil creep (Ruxton and Berry 1960). This process may have mixed the surface and subsurface soil in the degradational plains more than pedoturbation in the aggradational plains did, and so rubefaction of the surface soil could have had more effect on the soil colour in the aggradational plains than in the degradational plains. But the nature of the clay and of the silt and sand fractions may also be relevant. The Vertisols in the aggradational plains have more weatherable minerals in the sand fraction than those of the degradational plains (section 8.2), and they have more free ferric iron in the surface soil (Table 8.7, columns d and e; compare the three Khashm el Girba profiles with Jebel Qeili). However, colour chroma differences in the surface soil are not convincing in this case (Table 7.1). It should be remembered that the colour chroma observations were made during journeys, and that they are not supported by laboratory determinations. The fact of the (slight) colour difference is worth recording, but any explanation given can only be speculative.

9.2.4 Pedoturbation, soil structure and gilgai

9.2.4.1 PEDOTURBATION MODEL AND SOIL MECHANICS MODEL

The concept of Vertisols as 'turning soils', is based on the process of churning or mechanical pedoturbation. Swelling and shrinking of soil materials upon changes in moisture content are at the base of structure formation. Pedoturbation seems inevitable in Vertisols that develop a surface mulch: crumbling of mulch material into cracks causes soil pressures that can only be released in an oblique upward movement of subsoil, and this should ultimately result in a complete turnover of the soil mass within the depth of cracking. Features such as the accumulation of coarse fragments on the surface, and the absence of soft powdery lime in the solum, can be understood to be a result of pedoturbation (section 7.1).

Parsons et al. (1973), however, found that the stratification of a sedimentary parent material had persisted in distinctly slickensided Vertisols in Oregon, USA. This observation shows that soil movement - manifested by slickensides - does not necessarily imply a turnover and mixing of the soil. Wilding (1985) differentiated between a pedoturbation model and a soil mechanics model in Vertisol structure formation. In the soil mechanics model there is soil movement without soil mixing.

If we assume that soil mixing by pedoturbation is an active process in Sudan clay plain Vertisols, we would require a heterogeneous soil parent material in order to show the homogenizing effect of pedoturbation. The problem in the Central Clay Plain is now precisely that, due to the very nature of its formation, the soil parent materials are very uniform. Pedoturbation in such soil materials can only be shown in soil properties that have developed after sedimentation had come to an end; such properties must be different between the churning zone (the solum) and the underlying substratum (1C horizon).

9.2.4.2 UNIFORMITY OF THE VERTISOL PARENT MATERIALS

The clay mantle of both aggradational and degradational plains is often very uniform laterally and homogeneous to a considerable depth. The Upper Clay Member of the Gezira Formation has a thickness of 7 to 45 m, and unlike the two lower units of the Formation, is very uniform (section 3.6.1). The top 150 cm of this clay cover, and similar surface clays in the Atbara clay plain, have a uniformity that can only be explained by assuming semi-lake conditions during deposition (Blokhuis et al. 1964). In the Gezira, at the location of GARS 141, it comprises the present dark-brown (10YR 3/3.5) surface clay (A horizon, 0-60 cm), the transitional horizon (60-90 cm), and the dark grayish-brown (10YR 4/1.5) subsoil (B horizon, 90-130 cm). We have considered this 130 cm clay mantle to be one deposit, laid down between 12 000 and 5 000 BP (section 4.4.3). The underlying yellowish-brown (10YR 5/3) substratum has been designated a 2C horizon; it has different properties, and we therefore have described it as a different deposit. It appears to be no less uniform than the overlying clay. Slickensides are found to a depth of 19 m; their presence suggests soil formation, alternating with or subsequent to sedimentation. We have assumed - following Finck (1961) - that the surface soil acquired a dark-brown colour after sedimentation had come to an end. This process of rubefaction was strongest in the most arid parts of the clay plain, and less distinct with increasing rainfall: in the higher rainfall areas A and B horizons have the same colour.

The clay mantle of the degradational clay plains shows an even greater homogeneity (section 8.6.2). In the process of rock weathering and planation, smectite clays formed below the pediment, where they accumulated and built up extensive clay plains. With time, these clay plains have advanced upon the pediment. Clay sediments thus formed, are bound to show a great uniformity.

The uniformity of the upper clay mantle in both aggradational and degradational clay plains is shown in various properties: the mineralogical composition of sand and silt (section 8.2) and of clay (section 8.3), the molar silica/sesquioxide ratios of the clay fraction (section 8.5.1), and the granulometric composition (section 8.6). Some relatively shallow clay soils in aggradational clay plains overly coarser-textured soil material (Khashm el Girba 215, 238, Tozi, Jebel Abel, Damazeen).

9.2.4.3. SOIL MORPHOLOGICAL DATA

Pedoturbation or churning in uniform parent materials could manifest itself in two different ways:

1. By the presence of gravelly material on the soil surface, in combination with a gravel-free solum; the substratum should contain the same type of gravel as found on the surface.The same may apply to a relatively high proportion of (coarse) sand in the surface soil (Schlichting 1978).
2. By the uniformity of a solum, contrasting with a substratum. Plasma concentrations, such as, for example soft carbonate aggregates, may be present in the substratum, whereas they are absent in the solum (in our example: carbonate may be present in the solum in a finely divided form, but not as a plasma concentration).

As in crusty Vertisols pedoturbation would normally be absent, or at least weak, we assume for both cases that surface mulch is sloughing into open cracks.

Gravel and pebbles occur on the surface of gravel-free soils in degradational clay plains on level terrain, in areas well away from inselbergs (section 6.4). Sandy and gravelly surface phases of the Ghabita and Shuheit series are bordered by non-gravelly Shuheit soils in the Seinat area (section 6.5.2). Also in Umm Seinat we find pea-iron gravel in the substratum of Seinat B48 (a Paleustalf), and in both the substratum and on the soil surface (but not in the solum) of Seinat B47 (an Ustropept). Upward churning in Seinat B47, which has a subsoil with a distinct vertic structure, would have brought the gravel to the surface. An accumulation of gravel due to soil creep and surface wash, operating over almost flat terrain and over large distances, is very unlikely: the combined transport of gravel and clay, without much sand and silt, is not feasible.

In Vertisols from the higher-rainfall part of the Central Clay Plain a uniform solum contrasts with a 1C horizon having features that require absence of soil mixing for their formation. The most common example is the presence in the substratum - and the absence in the solum - of soft aggregates of calcium carbonate. The absence of turbation in the substratum is also shown in its zonation: with depth, the soft aggregates of calcium carbonate decrease in abundance (and gypsum disappears).

Whether or not these concentrations are the result of former or of actual processes, is not relevant. The important fact is that such plasma concentrations are not found in the soil within the depth of cracking, whereas the soil compound itself (calcium carbonate) is present in a finely divided form (Chapter 7).

Elbersen (1982) described a 'striped zone' in clay soils with calcic horizons in Spain. Profile walls show a pattern of vertical stripes consisting of lime-filled cracks separated by clay pillars. The original profile at the site was thought to consist of a medium-textured surface soil overlying a calcareous horizon, which in turn overlied a smectite clay. The origin of the 'striped zone'is explained as follows. In the dry season, desiccation cracks develop in the underlying clay substratum. In the subsequent wet season, fine silt-size calcite crystals move down the cracks in suspension and accumulate at the bottom of the cracks. Calcite gradually fills the space required to accomodate the swelling of the adjoining clay pillars. As a consequence the pillars are deformed when the clay swells, they are pushed upwards and split into clay lumps. At the same time, a calcic horizon is formed in the zone where the cracks end. Elbersen refers to the process as 'subterranean gilgai'.

When we compare Elbersen's observations with the morphology of low-rainfall clay-plain Vertisols in the Sudan, there is a certain analogy, especially with profile GARS 141. This profile shows a 'striped zone' of tongues of dark-brown clay, and intrusions of dark grayish-brown clay with fine ca-specks (sections 7.2.2., 7.3 and 4.4.3). Salts have accumulated in the lower subsoil due to an accumulation-cum-leaching process (section 8.7.5), and carbonates may have concentrated and moved downward (in solution or in suspension) in a similar way, contributing to the higher carbonate content of the C horizon (4 to 5%, against 2 to 2.5% in the A and B horizons).

There are, however, marked differences with Elbersen's 'subterranean gilgai'. First, the carbonate content in the Spanish profiles is much higher than in the Gezira profile; 'calcic horizon' is rather an understatement for the soil material in Elbersen's profiles which consists for over 80% of carbonates. Second, the 'striped zone' in Elbersen's profiles consists of clay pillars embedded in a soft calcic horizon. In the Sudan profiles the 'striped zone' is one of dark-brown clay tongues and dark grayish-brown clay intrusions. The pattern is only visible in a wet soil, and we do not know what it would look like on cross-section. Third, we consider the higher carbonate content of the substratum in the Gezira profile to be a geogenic rather than a pedogenic feature; this profile has developed in two different deposits and the concentration of carbonates and gypsum at the surface of the substratum would be mainly or entirely due to flooding and evaporation of Blue Nile waters in a period of standstill in deposition (Chapter 4).

In the Sudan profiles swell and shrink affects both tongues and intrusions, in the Spanish profiles only the clay pillars and the supporting substratum are affected whereas the calcic horizon resists pressure. The ultimate effect may, however, be similar. In the Sudan profiles the process would lead to a breaking-up of both the tongues and the intrusions. One could assume that the lack of a transitional horizon with tongues and intrusions in the higher-rainfall Sudan clay-plain soils is due to stronger swell and shrink, accompanied by a complete breaking-up and mixing of the A and B horizon sections of the transitional horizon (turning an A/B horizon into an AB horizon).

The organic-carbon profiles in clay-plain Vertisols do not provide a conclusive answer to the question of pedoturbation. In several Vertisols we find the same organic carbon percentages throughout the A and B horizons, with lower amounts in the BC, and lowest in the C horizon. This suggests a homogenization of the solum. But if these data indeed demonstrate the process of pedoturbation, why then do other, equally well-developed Vertisols, not conform to this pattern?

In both aggradational and degradational clay plain soils hard, dark-grey calcareous nodules are most abundant and largest on the soil surface and in the A horizon. There is micromorphological evidence that the dark-grey skin of these nodules is a mangan that in an earlier period has formed as a mangan-neomangan below the depth of present cracking, in a zone without pedoturbation. In this zone, the present C horizon, we do find carbonate nodules with a mangan-neomangan (type E cf. section 7.5.2.3) in addition to other forms of concentration of manganese oxides. The accumulation of manganese-coated calcareous nodules on the surface could be explained by an upward movement of soil material.

Shear in Vertisols is shown by the presence of vosepic, masepic, skelsepic and glaesepic fabric (section 7.5). Such fabrics have been found in all clay plain Vertisols. It was also found that soil stress is not a continuous feature; it varies in intensity between sections of the soil (section 7.5.3.1). Soil mixing, however, cannot be demonstrated by these fabrics; this would require a detailed macromorphological and micromorphological study of uniformity in soils in which uniformity is not an inherited feature of the parent material.

9.2.4.4 EVIDENCE FROM RADIOCARBON AGE DETERMINATIONS

Radiocarbon age measurements by Adamson et al. (1982) have shown that hard, dark-grey carbonate nodules were much older than the clays in which they were found (section 4.4.3); this supports our hypothesis that their presence on the soil surface is not due to sedimentation together with the clay, a possibility that should be ruled out already on the grounds of their very different particle size.

Scharpenseel and co-workers have given radiocarbon dates of soil samples from selected profiles, including thirteen Vertisols of the Gezira area. The radiocarbon dating method provides the Apparent Mean Residence Time (AMRT) of soil organic-matter carbon (Scharpenseel 1972a). Vertisols and Mollisols were expected to give the most reliable data: although bioturbation in Mollisols and pedoturbation in Vertisols would induce rejuvenation of active organic carbon in the solum, the substratum would show little impact of the principal rejuvenation processes such as root growth, homogenization by soil fauna, and percolation of organic matter. Therefore a strong age versus depth relationship would exist in the substrata (Scharpenseel et al. 1984). In Vertisols, radiocarbon ages would be more or less the same within the depth of cracking, and increase distinctly and abruptly below this zone. Some of the age versus depth curves of 39 Vertisol profiles from Southern Europe, Tunesia, Israel, Argentina and Australia (Scharpenseel 1972b) conform largely to this model, others do not show the expected uniform radiocarbon age in the zone of pedoturbation. Scharpenseel et al. (1986) found that weakly developed Vertisols (Pelosols) from Germany had the steepest age versus depth gradient to 500 cm depth, whereas strongly developed Vertisols from Tunesia and Sudan (Gezira) had a very weak gradient. In a profile from Argentina (Scharpenseel and Pietig 1973) a distinct inflection in the age versus depth curve occurred at 80 cm, which was about the depth where the B22 changes into a BCca with abundant carbonatic concretions.

In Figure 9.1 we have plotted age versus depth graphs based on data supplied by Scharpenseel et al. (1984). Profile nr. 6 shows roughly the same radiocarbon age of 2 000 BP for the depth zone 0 to 150 cm, followed by a gradual increase (2 000 to 5 000 BP) between 150 and 300 cm. The inflection point at 150 cm could, in our opinion, mark the boundary between solum (homogenized by pedoturbation) and substratum. In most of the other profiles, however, there is a trend of age increasing with depth. A reverse trend between 150 and 200 cm depth makes a break in some of the graphs: profiles 1, 2, 3 and 11. Scharpenseel et al. (1984) suggested that such inflection points are due to modern organic matter dropping into the deepest holes of cracks, termite activity or individual deep roots.

The overall impression of Figure 9.1 is one of an increase in age with depth, and it does not allow any conclusion to be drawn on the intensity and depth zone of the pedoturbation process. From other areas (Scharpenseel 1972b) an inflection point in the curve is clear in many, but not all, Vertisols. The oldest radiocarbon ages of the thirteen Gezira profiles of Fig. 9.1, some of them till a depth of 2 or 3 m, are between 5 000 and 6 000 BP (with one sample of 10 000 BP), and this is younger than most other observations (including radiocarbon ages of shell samples) have shown (Chapter 4).

Yaalon and Kalmar (1978) found that radiocarbon ages of organic matter (Mean Residence Time) in five Vertisol profiles in Israel (Scharpenseel and Pietig 1973) increased with depth at similar rates as those in non-vertic soils.

The most important general conclusion from the work by Scharpenseel and co-authors is, that Vertisols with strong pedoturbation do exist next to those with no sign of intensive mixing.

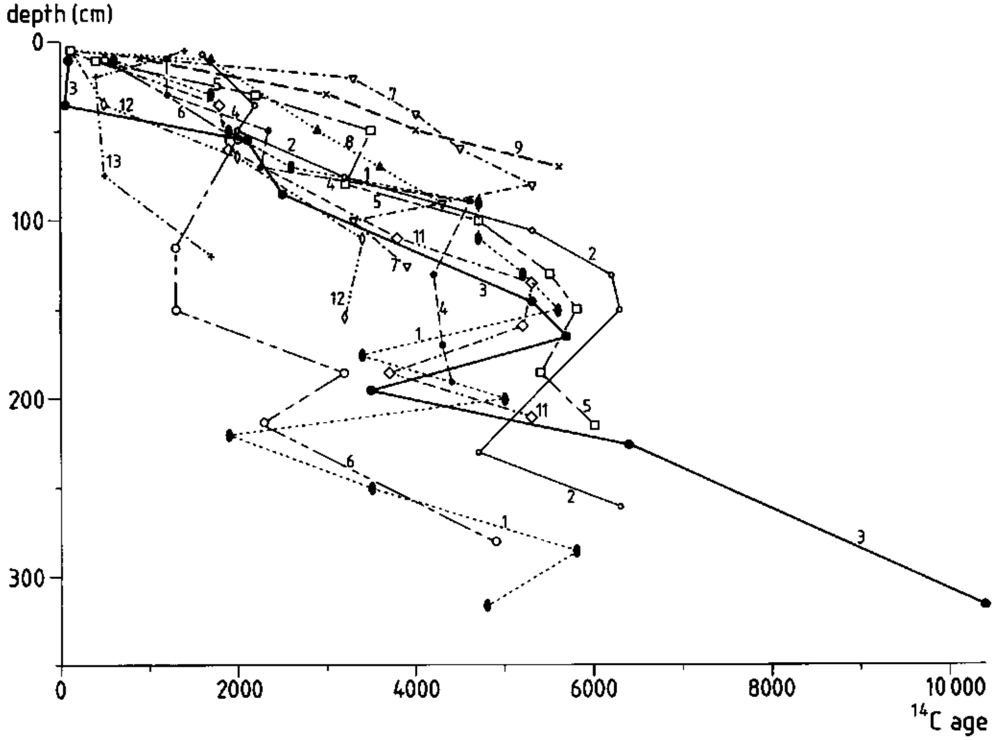

Fig. 9.1. Radiocarbon dates of 12 Vertisols in the Gezira area (data from Scharpenseel et al. 1984; numbers refer to profile numbers in this publication)

9.2.4.5 GILGAI

There is no gilgai microrelief in the lower-rainfall areas, whereas it is a general feature in the higher-rainfall part of the clay plain, i.e. in areas where depth of cracking, and with it pedoturbation, would be at a maximum. Deeper pedoturbation in the higher-rainfall areas is also suggested by the greater depth at which soft powdery lime appears.

But gilgai is not the result of surface mulch falling into open cracks; if this were so, gilgai would be strongest in the lower-rainfall areas, where mulch development is strongest. Gilgai is a consequence of subsoil and substratum forces (Blokhuis 1982). And gilgaied soils are not homogenized: there is an upward thrust of substratum material through the subsoil towards what is to become the centre of the mound - or the ridge, in linear gilgai. In Vertisols elsewhere (Morocco, India), we observed a distinct cone of strongly contrasting substratum material (described as 'mukkara' by Paton (1974)). Mixing of solum and substratum soil material is not evident, or at least it proceeds at a lower pace than the uplift of the substratum. Beckmann et al. (1984) found that churning or convection mechanisms were not necessary for gilgai development.

Piercing substratum cones are less distinct in the gilgai profiles which we observed in the Sudan clay plain, but there is some evidence of a substratum protruding into the solum in the Damazeen mound profile, and in the microridges of wavy gilgai in the Southern Kenana. The microridges are lighter-coloured than the microvalleys, and contain quartz fragments and carbonatic nodules, not usually found on the surface of the microvalleys (profile Ulu, nr. 16).

There is a contradiction between the concept of increased pedoturbation with higher rainfall (deeper cracking, greater depth at which soft powdery lime appears), and the observation that gilgai - which does not mix the soil - only occurs in the higher-rainfall areas.

9.2.4.6 EXAMPLES FROM THREE SUDAN CLAY PLAIN VERTISOLS

We have scrutinized the data of three soil profiles in order to assess which features would support the concept of pedoturbation - mixing of surface soil and subsoil, shear, formation of a vertic structure - or the concept of shear without pedoturbation - soil heaving and sinking, and formation of a vertic structure, but without mixing of surface soil and subsoil. The profiles selected are Hadeliya (nr. 8), a 'proto-Vertisol' in an inland alluvial delta; Ulu (nr. 16) and Seinat B50 (nr. 26), both Typic Chromusterts from degradational clay plains. Soil movement aspects of lower-rainfall Vertisols (such as Khashm el Girba 213, GARS 141 and Jebel Qeili) have been amply discussed in previous sections of this chapter and in preceeding chapters.

The 'proto-Vertisol' Hadeliya (nr. 8), a Typic Ustifluvent, shows the homogeneity of the parent material in profile macro- and micromorphology, and in analytical data (soil texture, pH, organic carbon, CEC-clay). There is an incipient vertic structure throughout the soil and cracks that generally reach to 40 cm depth. Conspicuous sinkholes are common, and they are associated with some of the cracks that reach to between 100 and 200 cm depth (Photo 72). There is not much evidence of soil movement in the thin sections: most of the matrix is argillasepic, with some

Photo 72: Profile Hadeliya (nr.8), showing cracks below a sinkhole. The ruler is 10 cm.

insepic, masepic and vosepic areas. There are skew planes, but no joint skew planes. The lack of pedoturbation is also shown, throughout the profile, by the presence of fine specks of soft powdery lime. A fine sedimentary stratification is only present in the upper few centimetres; it seems that vertic structure formation has disturbed the original stratification below this depth.

In short, the Hadeliya profile shows: a uniform soil parent material; incipient vertic structure formation; lack of pedoturbation. Hadeliya represents initial soil formation in a flat clayey sedimentation plain, probably not unlike the Gezira fan at the time that sedimentation had come to an end. The incipient structure formation has not prevented calcium carbonate to concentrate into specks. The anticipated development of the soil material is an increase in clay content due to 'in situ' weathering, whereas the soil profile would develop towards a Vertisol with a distinct vertic structure; the carbonate specks would disappear due to pedoturbation.

Profile Ulu (nr. 16), situated in the Southern Kenana pediplain, is from a site with wavy gilgai. The microridges have a thick mulch that contains white carbonate nodules and - sometimes - fine gravel. The microvalleys have a thin mulch and distinct, wide cracks; they lack coarse fragments.

The microridge soil is uniform to 150 cm depth: 2.5YR 3/2 soil colour; presence of carbonate nodules and granules, absence of soft concentrations of carbonate. With depth the pH increases, and the soil structure changes gradually. Thin section studies reveal that masepic and vosepic plasmic fabric occur throughout, in addition to one or more of: asepic, insepic and mosepic. There are skew planes throughout the profile, and joint skew planes between 0 and 110 cm. Type B carbonate concentrations and intercalary calcitic crystals occur between 30 and 110 cm; this is not in line with field observations that show the absence of soft powdery lime in this depth zone.

Below 150 cm depth there are 'in situ' carbonate concentrations, and the soil colour changes into 2.5Y-10YR 4/3. Soil texture, $CaCO_3$ percentage, and CEC-clay are different from the overlying soil. There are no joint skew planes. Type B carbonate concentrations and intercalary calcite crystals are present.

The microvalley soil has much less carbonate nodules and granules in 0-150 cm than the microridge soil, but below 150 cm both profiles are alike.

The following conclusions can be drawn:

1. There is a non-uniform soil parent material, which has been homogenized by pedoturbation to a depth of 150 cm.
2. Pedoturbation is weak: although no carbonate specks are found in the field, type B concentrations are observed in thin sections of the microridge profile.
3. Shear is distinct; it is shown by the presence of carbonate nodules and granules on the surface, in the solum and in the substratum at the microridge site, and their absence at the microvalley site and in the microvalley profile.

Seinat B 50 (nr. 26) is a Typic Chromustert from the Southern Gedaref clay plain; its site has normal gilgai. The surface on the mound site is covered with quartz gravel and stones, and carbonate nodules, and there is a thick mulch; the depression site has a thin mulch, and coarse fragments are lacking.

In both mound and depression profile, ca-granules and -nodules occur throughout, but in the depth range 0-130 cm they are 'common' in the mound profile, and 'few' in the depression profile. Below 130 cm there is no difference between the two profiles.

In the mound profile cracks can be traced to 60 cm depth, and a vertic structure is well-developed between 30 and 200 cm; the vertic structure is weak in the Ck horizon (200-250+ cm). Soft, powdery lime occurs in B/Cwk and Ck horizons of both profiles (130-250+ cm).

The analytical data of the mound profile show great uniformity throughout the soil to 250 cm, except for CaCO3 percentage which is highest in the Ck horizon.

Micromorphological data of the Ck horizon of the mound profile are available. The thin section shows the presence of insepic, mosepic, masepic and vosepic plasmic fabric, and there are skew planes, but no joint skew planes. Type B carbonate concentrations and intercalary calcite crystals occur.

The data of Seinat B 50 permit the following conclusions to be drawn:

1. There is a uniform soil parent material, in which soil formation has created a solum (0-130 cm) different from the original material (200+ cm), with a transitional zone (130-200 cm) between the two.
2. There is a strong vertic structure in the solum and in the transitional zone, but structure is weaker in the substratum.
3. The uniformity of the solum, contrasting with the underlying substratum in features that have developed due to soil formation, but not in features pertinent to the original material, shows that in the solum pedoturbation is an active process.

9.2.4.7 CONCLUSIONS

The validity of the pedoturbation model is not easily demonstrated in Vertisols that have developed in uniform parent materials such as the clays of the Central Clay Plain. It has become clear that a distinction should be made between soil heaving and sinking - essentially a pattern of soil movement in which, after one cycle, the soil returns to its original position - and true pedoturbation which results in homogenization of the soil to the depth of cracking. The upward thrust of sand grains and gravel is ascribed to upward directional forces but not to pedoturbation (Yaalon and Kalmar 1978; Schlichting 1978). Nor is pedoturbation seen as a required process for the formation of shear planes and slickensides (Yaalon and Kalmar 1978); our study has confirmed this observation.

Soil heaving is shown by the accumulation of gravel, pebbles, hard calcitic nodules (and coarse sand) on the surface of soils overlying gravel-free subsoils; it is perhaps also shown in the gilgai microrelief.

Pedoturbation is shown by uniformity of soil properties that are the result of post-sedimentary soil-forming processes: contents of organic matter that do not decrease with depth, radiocarbon ages that remain the same in the solum and increase sharply below, and the absence of concentrations of soft powdery lime in a soil matrix that is strongly calcareous.

9.3. Soil classification

The taxonomic names on the level of the Soil Family according to Soil Taxonomy (Soil Survey Staff 1990) have been given in Table 6.1. In this section we will discuss the classification of the Vertisols of the Sudan Central Clay Plain in two classification systems, that of the USDA (Soil Taxonomy), and that of the Soil Map of the World (FAO/Unesco 1974). The first system is now being revised, following recommendations by international committees (ICOM's) who study specific orders, or specific aspects of the system. The International Committee on Vertisols (ICOMERT) submitted its final proposals in August 1990. The International Committee on Aquic Soil Moisture Regimes (ICOMAQ) has made recommendations for classifying wet Vertisols. The FAO/Unesco classification has been revised (FAO 1988). In Table 9.2 the proposed new names according to ICOMERT and the revised names in the FAO-classification are given in addition to the present Soil Taxonomy and former FAO/Unesco names.

9.3.1 Soil Taxonomy and the proposals by ICOMERT

All Vertisols on clay plain sites in the study area are Usterts, and all except two (Tozi and Seinat B55) that are Pellusterts, are Chromusterts. Two of the four residual/ colluvial profiles are also Chromusterts, the other two are Pellusterts. The Gelhak soil, at a site subject to prolonged flooding, is a Pellustert intergrading towards a Udert; it is a Udic Pellustert. Most Vertisols of the clay plains belong to the Typic subgroup; there are three Entic Chromusterts (Jebel Qeili, Sennar 71 and Jebel Abel), whereas both Pellusterts belong to Entic subgroups.

On the family-level, most Vertisols are very-fine, montmorillonitic, isohyperthermic. Some soils have less clay, and more sand or silt (particle-size class: fine), some have a greater proportion of kaolinite in the clay fraction (mineralogy class: mixed), and some from higher latitudes have greater seasonal differences in soil temperature (soil temperature class: hyperthermic).

The classification according to Soil Taxonomy, and the diagnostic properties for order, suborder, great group, subgroup and family have been discussed in section 6.3.

In the ICOMERT proposal of August 1990 the gilgai criterion was waived in the definition of the order: gilgai is no longer a possible alternative to wedge-shaped peds

Table 9.2: Classification of representative Vertisol profiles in Soil Taxonomy (1990), ICOMERT proposals (August 1990), FAO/Unesco (1974) and FAO (1988)

profile nr.	profile name	subgroup cf. Soil Taxonomy (1990)	subgroup cf. ICOMERT proposals (August 1990)	soil unit cf. FAO/Unesco (1974)	soil unit cf. FAO (1988)
clay-plain sites					
1	Khashm el Girba 213	Typic Chromustert	Sodic Haplustert	Chromic Vertisol	Calcic Vertisol
2	Khashm el Girba 215	Typic Chromustert	Sodic Haplustert	Chromic Vertisol	Calcic Vertisol
3	Khashm el Girba 251	Typic Chromustert	Sodic Haplustert	Chromic Vertisol	Calcic Vertisol
4	Khashm el Girba 238	Typic Chromustert	Sodic or Chromic Haplustert	Chromic Vertisol	Calcic Vertisol
5	Khashm el Girba 256	Typic Chromustert	Sodic or Chromic Haplustert	Chromic Vertisol	Calcic Vertisol
6	Jebel Qeili	Entic Chromustert	Chromic Haplustert	Chromic Vertisol	Calcic Vertisol
9	GARS 141	Typic Chromustert	Sodic Haplustert	Chromic Vertisol	Calcic Vertisol
10	Sennar 49	Typic Chromustert	Sodic Haplustert	Chromic Vertisol	Calcic Vertisol
11	Sennar 71	Entic Chromustert	Sodic or Chromic Haplustert	Chromic Vertisol	Calcic Vertisol
12	Jebel Abel	Entic Chromustert	Sodic Haplustert	Chromic Vertisol	Calcic Vertisol
13	Tozi	Entic Pellustert	Sodic Epiaquert/Sodic Calciustert	Pellic Vertisol	Calcic Vertisol
14	Damazeen A (depr.)	Typic Chromustert	Typic Haplustert	Chromic Vertisol	Eutric Vertisol
	Damazeen B (mound)	Typic Chromustert	Typic Haplustert	Chromic Vertisol	Calcic Vertisol
15	Bozi	Typic Chromustert	Typic Haplustert	Chromic Vertisol	Calcic Vertisol
16	Ulu	Typic Chromustert	Typic Haplustert	Chromic Vertisol	Calcic Vertisol
19	Renk	Typic Chromustert	Typic Haplustert	Chromic Vertisol	Eutric Vertisol
21	Simsim B27	Typic Chromustert	Chromic Haplustert	Chromic Vertisol	Calcic Vertisol
26	Seinat B50	Typic Chromustert	Chromic Haplustert	Chromic Vertisol	Eutric Vertisol
27	Seinat B55	Entic Pellustert	Chromic Haplustert	Chromic Vertisol	Eutric Vertisol
other sites					
7	Er Rawashda	Typic Pellustert	Typic Calciustert	Pellic Vertisol	Calcic Vertisol
17	Khadiga	Typic Chromustert	Chromic Haplustert	Chromic Vertisol	Eutric Vertisol
18	Boing	Typic Pellustert	Ustic Epiaquert/Typic Haplustert	Pellic Vertisol	Eutric Vertisol
20	El Gelhak	Udic Pellustert	Ustic Epiaquert/ Typic Haplustert	Pellic Vertisol	Eutric Vertisol
22	Seinat B7	Typic Chromustert	Typic Haplustert	Chromic Vertisol	Eutric Vertisol

or to slickensides. Cracks have been more precisely defined, as well as the open and closed condition of cracks, but otherwise the definiton of the order has remained unmodified.

Two suborders have been added: Cryerts, which have a cryic soil temperature regime, and Aquerts, defined in much the same way as aquic suborders in other orders:

'Vertisols which, within 50 cm of the soil surface, have the following combination of characteristics:
1. Are saturated *) with water and reduced **) for part of every year, unless artificially drained; and
2. Have in more than half of each pedon a dominant color (moist) on faces of peds, or in the matrix if peds are absent, as follows:
   a. If there is mottling, a chroma of 2 or less; or
   b. If there is no mottling, a chroma of 1 or less.

---

*) Saturation can be proven with tensiometers or piezometers.
**) Reduction can be proven with platinum electrodes or with dyes such as a,a'-dipyridyl or benzidine.'

The succession of suborders in the key is: Aquerts, Cryerts, Xererts, Torrerts, Uderts and Usterts.

ICOMAQ proposed wetness criteria which centre around the term 'aquic conditions'. In section 9.2.3 we have seen that 'aquic conditions' require all three of: redoximorphic features, saturation and reduction, and we have come to the conclusion that 'aquic conditions' cannot occur in Vertisols because redoximorphic features and reduction are not feasible. Flooding may cause a temporary and non-uniform saturation of the surface soil. When the pH is high (as in the depressional Entic Pellusterts) mobility of ferrous iron is unlikely to occur.

ICOMAQ has also made proposals for a suborder Aquerts, as follows:

'Vertisols that have, both within 50 cm of the mineral soil surface and in some part between a depth of 40 and 50 cm:
1. Aquic conditions or are artificially drained; and *either or both*
2. In more than half of each pedon and within 50 cm of the soil surface, one or more horizons with 50 percent or more color, moist, on faces of peds or in the matrix if peds are absent, as follows:
   a. There are redox concentrations and chroma of 2 or less; *or*
   b. There are no redox concentrations and chroma of 1 or less; *or*
3. Within a depth of 50 cm, sufficient active ferrous iron to give a positive reaction to a,a'-dipyridyl at some time of the year when not being irrigated.'

The definition is basically the same as the one proposed by ICOMERT, but the terminology is different. As 'aquic conditions' imply that the soil has redoximorphic features (one or more of: redox concentrations, redox depletions, reduced matrices), criterion 2 is no more than a quantification of criterion 1. We conclude that Aquerts as defined by ICOMAQ cannot exist.

Colours as specified in both the ICOMAQ and ICOMERT definition for Aquerts refer to either 'faces of peds' or to 'the matrix if peds are absent'. The latter option is futile: Vertisols have, by definition, peds.

In section 9.2.3 we reached the conclusion that the low-chroma soil colour and the paucity of free ferric iron in Pellusterts is related to stability of smectite. Poor drainage is one of the factors promoting smectite stability. This applies to the Pellusterts in closed depressions and level areas in the Blue Nile-Dinder-Rahad clay plain. A suborder of Aquerts could be defined, based on flooding and low-chroma colours, perhaps with the following criteria: flooding for at least three consecutive months, and chromas of less than 2 (conforming to the latest Keys to Soil Taxonomy, of 1990). Aquerts thus defined, could also serve as mapping units; in the Central Clay Plain they would cover closed depressions and level areas, and also represent a category with specific limitations and options for land use. Sodic great groups or subgroups would be relevant.

The term 'epiaquic', although referring to wetness of a soil because of temporary flooding or seasonally heavy rainfall, cannot be used to indicate flooding of Vertisols, as Soil Taxonomy recognizes classes of wetness only if there is a relation with internal soil features such as greyish colours and mottles (Brinkman and Blokhuis 1986). The term 'oxyaquic', which was devised by ICOMAQ to indicate water-saturation without redoximorphic features, could be used in a definition of Aquerts. Aquerts should not include Pellic Vertisols with free external drainage; these should be placed in a separate taxon, perhaps also a suborder. Low-chroma colour (less than 2) and lack of flooding (less than three consecutive months) would probably suffice as criteria on the suborder level, but other common characteristics (formation 'in situ' on basic rock, or in colluvium derived from such rock; high clay content) could be considered for the definition.

If we were to accept the ICOMERT definiton of Aquerts on the colour criteria alone, three representative profiles could be classified in this suborder, in the great group Epiaquerts: Tozi, Boing and El Gelhak. An Epiaquert is wetted from the surface, by flooding. The concept of an Epiaquert applies well to Tozi and El Gelhak, but is at odds with Boing, a residual soil situated on top of a small hill.

Vertisols on the Central Clay Plain that are not Aquerts, are Usterts. Because of our criticism of the Aquert definition, we have, in Table 9.2, also given alternative names for the Tozi, Boing and El Gelhak profiles. The sequence of great groups in the key is: Dystrusterts (low EC in combination with a low pH), Salusterts (with a salic horizon), Gypsiusterts (with a gypsic horizon), Calciusterts (with a calcic horizon) and Haplusterts. The diagnostic horizons mentioned must have an upper boundary within 100 cm of the soil surface. It is surprising that sodicity is not, on the great group level, a diagnostic feature. Sodicity is a more important property of Vertisols than salinity - not only in the Sudan clay plains (section 8.7).

Low pH values, required for Dystrusterts, are not found in Vertisols of the Central Clay Plain. A salic horizon apart from anything else, must have at least 2% of soluble salts. Salt percentages are always lower in our reference profiles. Khashm el Girba 251, GARS 141 and Simsim B27 have a gypsic horizon, but the upper boundary is deeper than 100 cm in these soils. Salusterts and Gypsiusterts do not occur in the Sudan clay plains, except perhaps in parts of the irrigated Gezira/Manaqil scheme.

Er Rawashda and Tozi would qualify as Calciusterts on the basis of high $CaCO_3$ equivalent percentages (Appendix 2), in combination with at least 5% (by volume) of identifiable secondary carbonates.

There are nine subgroups of Calciusterts. Following the key we have classified Er Rawashda as a Typic, and Tozi as a Sodic Calciustert.

All other Vertisols of the Central Clay Plain (22 or 20 of the 24 profiles) are Haplusterts. This implies that most of the differentiation must be on subgroup or lower levels. In this respect, the ICOMERT proposal does not give a better discrimination of the Vertisols of the Central Clay Plain than the present Keys to Soil Taxonomy do. According to Soil Taxonomy there are 20 Chromusterts and 4 Pellusterts. But criteria have changed a great deal: Haplusterts are not Chromusterts!

The key to subgroups of Haplusterts is as follows: Lithic, Halic, Sodic, Petrocalcic, Aridic, Udic, Leptic, Chromic and Typic. Only Sodic, Chromic and Typic Haplusterts occur on the Central Clay Plain. Sodic Haplusterts are:

'other Haplusterts which have, throughout a layer of 15 cm or more thick with an upper boundary within 100 cm of the soil surface, for 6 or more months per year in 6 or more years out of 10, one or both of the following:

1. ESP of 15 or more; or
2. SAR of 13 or more.'

In the Central Clay Plain the Sodic Haplusterts cover the northern, lower-rainfall part (section 8.7.3), and so sodicity appears to be a useful diagnostic property.

Chromic Haplusterts are:

'other Haplusterts which have, in one or more subhorizons within 30 cm of the soil surface, one or more of the following:

1. A color value, moist, of 4 or more; or
2. A chroma of 3 or more, either moist or dry; or
3. A color value, dry, of 6 or more.'

The Chromic Haplusterts listed in Table 9.2 make a group that has no consistency either geographically or pedogenetically. This is not surprising: the diagnostic criteria refer to value, or to chroma, or to both, and these properties have very different pedogenetic implications. Into this subgroup all remaining Haplusterts that are pale or reddish, are dumped in order to create a 'pure' Typic subgroup that conforms to the old idea of 'dark cracking clay soils', in which 'dark' has often been erroneously used for soils with low chroma; this error has now received the ICOMERT blessing. The Typic Haplusterts would also cover the well-drained Pellic Vertisols like Er Rawashda and Boing. We have suggested above that such soils should be in a separate suborder.

In the present classification, high-value Vertisols belong to Entic subgroups. These occur mainly either in the northern part of the clay plain, or in combination with low chromas (Entic Pellusterts). Some of the Chromic Haplusterts in Table 9.2 have, indeed, high chromas (Khashm el Girba 238 and 256, Khadiga), others (Jebel Qeili) have both high value and high chroma. However, to label a soil like Seinat B55, with a chroma of 1.5, as a Chromic Haplustert violates the original concept of Chromic.

In the 1960-precursor to Soil Taxonomy (Soil Survey Staff 1960) a distinction was made between Vertisols with a surface mulch (grumic) and those with a hard surface crust (mazic). We found this distinction most useful in the Simsim/Seinat area: Vertisols with a more sandy surface soil had a crust, but otherwise Vertisols always had a mulch (section 6.5.2).

The distinction mazic/grumic was waived in the 1975-edition of Soil Taxonomy because of the suspected non-permanency of the feature; it was found to be dependent on the length of the period of cultivation and on soil management practices, and it varied between years probably because of the weather. In ICOMERT's Circular Letter nr. 2, some correspondents suggested to re-introduce the mazic vs. grumic distinction because of its agronomic importance. In the discussion that followed (Circulcar Letters nrs. 3 and 4) it appeared that correspondents familiar with less intensive forms of agriculture, or with contrasting parent materials, were in favour of using the mazic/grumic criterion. In Circular Letter nr. 3 mazic subgroups were tentatively proposed for Usterts, Uderts, Torrerts and Xererts (not for Aquerts). Although no conclusion was reached in Circular Letter nr. 4, there was no reference to the mazic/grumic distinction on any level in the proposed key that accompanied that Circular.

The mazic/grumic issue has, in our view, not received the scrutiny which it deserves. In black-red soil catena's in the Southern Gedaref area we found a gradient from grumic to mazic with increasing sand content of the surface soil. The mazic/grumic distinction was part of the catenary differentiation and was accompanied by distinct changes in the vegetation (section 6.5.2); it was also an asset in soil mapping and relevant for land use, both directly - e.g. in relation to soil tillage - and indirectly, because of its relation with other soil properties.

Two other factors may influence surface characteristics in Vertisols. First, there is evidence that mulch development on on-flow sites is weaker than on datum sites (section 7.3.2). Second, the development of a surface mulch is promoted by a weak cohesion of the soil material, for example in soils with much finely-divided lime such as occur in the low-rainfall northern Butana. Sodic Vertisols may develop a crust rather than a mulch because both the shear and the tensile strength of sodium-saturated smectite are greater than those of calcium-saturated smectite.

Soil colour is one of the few clearly expressed and easily measurable differentiating characteristics between Vertisols, and the many attempts by ICOMERT to define certain colours or groups of colours as diagnostic features, are not surprising. However, from reactions to an ICOMERT Circular Letter on the issue, it appeared that the boundary values (Entic/Typic, Chromic/Pellic, Aquic/Chromic/Typic) did not work the same way in different countries, and that the genetic implications of soil colour in Vertisols are far from being solved. It is perhaps wise that in the new version of the FAO/Unesco classification (FAO 1988), the colour criteria have been waived altogether.

9.3.2 The FAO/Unesco classification system of 1974, and the revised edition of 1988

In the first edition of the two-category classification system on which the Legend of the Soil Map of the World 1:5 000 000 is built (FAO/Unesco 1974), Vertisols occurred as a taxon at the highest level; they were differentiated into two Soil Units, Chromic Vertisols and Pellic Vertisols, based on the same colour chroma criteria as were used in Soil Taxonomy.

In Table 9.2 the original FAO/Unesco names are compared with the new names in the revised edition of 1988. The definition of Vertisols has not changed. The key to Soil Units now reads as follows (slightly abbreviated):

- with a gypsic horizon within 125 cm of the surface: Gypsic Vertisols;
- with a calcic horizon or concentrations of soft powdery lime within 125 cm of the surface: Calcic Vertisols;
- with a base saturation (by NH_4OAc) of less than 50 %: Dystric Vertisols;
- other Vertisols: Eutric Vertisols.

In the Central Clay Plain Gypsic and Dystric Vertisols do not occur. The concept of Calcic Vertisols is much wider than that of Calciusterts in the ICOMERT proposals; in fact it covers all soils with a Bwk horizon.

Following the new key, most Vertisols belong to the Calcic soil unit, whereas Eutric Vertisols occur in the higher-rainfall areas. Damazeen A, the depression site, is an Eutric Vertisol, Damazeen B, the mound site, is a Calcic Vertisol. This illustrates the different morphology of gilgai depression and mound profiles - and may well apply to other areas with gilgai in the Central Clay Plain.

The fact that the colour chroma criterion has been abandoned altogether is a loss for characterizing individual soil profiles, but it may be justified in a system that is directed towards 1:5 000 000 soil mapping. On our 1:2 000 000 pedogeomorphic map of the Central Clay Plain, Pellic Vertisols do not occur as a separate unit; only in some areas is there a relatively large proportion of Pellic Vertisols, for example in parts of mapping unit 122. The necessary separation between Pellic Vertisols in areas subject to flooding, and those on well-drained sites, may indeed be impossible on the scale of the World Soil Map.

Comparing the old and the new classifications (Table 9.2) we observe that new diagnostic characteristics have as little differentiating value for the Vertisols of the Central Clay Plain as those of the earlier version of 1974. For our study area, the new diagnostic criteria have limited value for soil mapping. The older divison in Chromic and Pellic Vertisols was perhaps more suitable for producing mappable units than the present one, for example, in having an association of Pellic and Chromic Vertisols (and inclusions of other soils) in addition to a mapping unit of Chromic Vertisols (and inclusions of other soils).

9.4 Soil description, sampling and survey

9.4.1 Soil description and soil sampling

For soils that have mainly diffuse boundaries between horizons which differ in only one or a few characteristics, description or at least sampling at standard depths should be considered as an alternative to description and sampling according to (presumed) pedogenic soil horizons. Horizon definition is bound to be subjective in such soils, and therefore sampling to standard depths is to be preferred. It has the further advantage that data sets suitable for statistical analyses, are more easily compiled and handled.

We have, in most soils of the clay plain area, adhered to a pedogenic horizon definition, description and sampling. Because of the diffuse nature of horizon boundaries in Vertisols, all horizons were measured to the nearest 5 or 10 cm step. In some profiles horizon differentiation was virtually impossible; these soils were described and sampled according to standard depths. In order to evaluate soil horizon versus standard depth sampling we will briefly review the description and sampling procedure of the 19 clay plain Vertisols (Table 6.1).

Five Vertisols (Tozi, Damazeen A, Damazeen B, Renk and Seinat B55) were described and sampled to standard depths, usually 0-15, 15-30, 30-60, 60-90, 90-120, 120-150, 150-180+ cm. Another nine profiles (Khashm el Girba 238, Jebel Qeili, Sennar 49, Jebel Abel, Bozi, Ulu, Simsim B27, Seinat B7 and Seinat B50) were described and sampled approximately to standard depths, or sampling and description were adjusted to standard depths without loosing the pedogenic approach, at least in the upper 90 cm. Below 90 cm there is usually a distinct boundary, marking the beginning of the C horizon (soft powdery lime, change of soil colour). Five profiles appeared to be unfit to a standard depth description and sampling, and all these are in the lower-rainfall areas: Khashm el Girba 213, 215, 251, 256, GARS 141.

The conclusion is that sampling to standard depths is fully justified in the higher-rainfall Vertisols, to a depth of 90 cm. At greater depths the beginning of the Ck horizon is usually distinct, and varies with depth. This one discrete horizon boundary should not get lost in a standard description and sampling procedure. In the lower-rainfall Vertisols there is more differentiation in the surface and the subsurface soil. And related to the morphological variation, there is variation in salinity, sodicity, and contents of gypsum and carbonates. In these soils the pedogenic horizon differentiation would get lost by a standard depth procedure, unless the depth steps are small.

9.4.2 Soil survey methods

In the key areas Khashm el Girba South (section 6.5.1) and Southern Gedaref (section 6.5.2), soil mapping was based as much as possible on a presumed relation between soil properties and terrain features. Photo-terrain units were obtained from aerial photographic interpretation. The units were assumed to represent soil units, and their boundaries soil boundaries.

The survey procedure gave satisfactory results in the Southern Gedaref soil survey. In the areas with some relief, vegetation and landform types were discrete and correlated well with soils or associations of soils, whereas in the clay plains apparently uniform landscapes corresponded well with uniform soil covers: for example the Shuheit series for flat clay plains, the Shuheit-Kafai association for wadi areas (Figures 6.3 and 6.4).

In Khashm el Girba South the method did not work well, for various reasons:

1. Surface soils were the same all over the area. Soil series were defined on characteristics of the subsoil that hardly matched with terrain features.
2. Vegetation types could be mapped from aerial photographs. However, some of the vegetation-type boundaries identified on airphotos, could not be found in the field, whereas some of the vegetation boundaries that were discrete in the field, could not be retrieved on aerial photographs. It became clear that in the grass and herb plains the distribution of last season's rain showers largely defined the vegetation pattern, more so than any more or less permanent edaphic factor. Other vegetation boundaries were constant through the years, but some of these were apparently unrelated to soils.

The extreme uniformity of landform and soils had consequences for drawing up a soil mapping legend. The common problem in devising a mapping legend in a 1:100 000 scale soil survey is, how to group different soils in one mapping unit. In the Khashm el Girba soil survey, however, the difficulty was how to find sufficient differentiating characteristics to create a reasonable amount of mapping units. The mapping units were soil series and complexes of soil series, soil depth phases, variants of soil series, and miscellaneous land types; these soil mapping units are not usually encountered in a 1:100 000 survey (Blokhuis 1963).

In Khashm el Girba South a systematic spatial variation of the soils as a function of, for example, vegetation or hydrology, probably hardly exists. Under these circumstances a soil survey design allowing statistical inventarization, as tested by Van den Broek (1986) is to be preferred. Various sampling schemes can be considered, for example with observations located at random, along parallel point transects, along random point transects, and at intersecting grid lines (Wilding and Drees 1983). Prior knowledge of geology, soils, hydrology and the like must be used in designing the sampling scheme. It will be necessary to first determine the spatial dependence in the field, and so ascertain the optimum observation interval.

At the time of the Khashm el Girba soil survey, 1963, statistical designs were hardly used in soil surveys. One consequence of this was that we were unable to prove that the areas mapped as Asubri series were, indeed, the large areas as they appear on the soil map (Fig. 6.1). Asubri might in reality consist of a multitude of narrow, subparallel or winding bands, separated by bands of the Khashm el Girba series. Van den Broek 1986) found that the soil variation was greater in a direction perpendicular to the River Atbara than parallel to it; this implies that the spatial dependence was largest in the direction parallel to the river.

In other aggradational clay plains the situation is different; soil differences are more closely related to terrain physiography, for example in the Gezira fan, the Singa meander belt and in parts of the Blue Nile-Dinder-Rahad clay plain. In the Northern Kenana and Butana degradational clay plains the great uniformity of terrain physiography, surface features and vegetation over large areas, is presumed to match with a uniform soil cover. There is, however, in these areas scope for a study of spatial variation in soils, in order to prove this soil uniformity.

Summary

Chapter 1: Introduction

Most of the east-central Sudan is covered by vast, flat, apparently featureless clay plains, collectively known as the Central Clay Plain. The parent materals of the fine-textured soils belong to two broad groups: alluvial, deltaic and paludal deposits from rivers of the Nile system, and colluvio-alluvial material weathered from local rocks and transported over relatively short distances. The terms aggradational and degradational clay plains are used to differentiate between the two landscapes.

The climate varies from arid in the northwest to sub-humid in the southeast; over most of the plain it is semi-arid. Annual rainfall is between 150 mm and 1000 mm. There is one rainy season, increasing in length from two months (July and August) in the north to five months (May to September) in the southeast. Temperatures are high throughout the year (mean daily temperatures are from 27 to 30°C.).

The vegetation ranges from semi-desert grassland to savannah woodland. Acacia-species are dominant among the scrubs and trees of the savannahs and savannah woodlands.

The soils have clay percentages of between 60 and 80, and smectite is the dominant clay mineral. The soils are classified as Vertisols on the highest level of abstraction in the classification system of the US Department of Agriculture, Soil Taxonomy (Soil Survey Staff 1975; 1990) and in the French system (CPCS 1967). Vertisols are also a Major Soil Grouping in the classification system of the FAO (FAO/Unesco 1974; FAO 1988) which was devised as a framework for the Legend of the Soil Map of the World, scale 1:5 000 000.

Vertisols have a distinct morphology, showing wide and deep cracks in the dry season, wedge-shaped structural aggregates with polished faces, slickensides, and other features derived from the swelling and shrinking of smectite clays, and the resulting movements in the soil due to shear failure. Within this one genetic type of soil are gradual, but distinct, variations with the amount of rainfall and duration of the rainy season, and this zonality is more evident than the variations related to landscape formation and parent material. The extent of annual flooding is an additional differentiating characteristic.

The clay plains of the Sudan were studied from 1959 to 1963, and in the winter of 1965/66. Detailed information was obtained from soil surveys in parts of the clay plain. In addition a general knowledge of soils and landscape of the entire plain was acquired in many journeys during which observations were made of relief, landform, vegetation, land use and soils. Supplementary information on the geography of soils was taken from soil survey reports covering parts of the clay plain area.

Twenty-seven soil profile pits (Table 6.1), representing various pedogeomorphic landscapes, were studied in detail. Soil samples taken from these profiles were analysed for granulometric composition and for mineralogical and chemical properties. Micromorphological features were studied in thin sections from a selection of these profiles.

In the present study, relationships are drawn between soil morphology, soil parent material, geomorphology, climate and vegetation. Subsequently, the various landscapes that together make up the Central Clay Plain, are defined.

A comparative study of the twenty-seven reference profiles was made to elucidate to what extent the soil characteristics are determined by soil parent material, or by other soil-forming factors, notably climate, relief and time. Attention was focussed on differentiating characteristics rather than on common features, although the latter are far more obvious.

Chapter 2: Geography

The area studied comprises the following geographic regions (Fig. 2.1):

a. The Gezira
b. The Rahad-Dinder-Blue Nile Gezira
c. The Butana, including the Atbara clay plain
d. The Gedaref clay plain
e. The Kenana or Fung.

The Central Clay Plain dips gently from SE to NW. Slopes are less than one per cent. The mesorelief of the aggradational clay plains has the characteristics of a river floodplain (Rahad-Dinder-Blue Nile Gezira), an alluvial fan (Gezira) or a paludal deposit (Atbara clay plain). The mesorelief of the degradational plains is that of a pediplain in its latest stage of planation. The degradational plains are graded towards the aggradational plains that border rivers of the Nile system. The very gently undulating physiography is related to concealed pediments and rocky erosion remnants; the latter, inselbergs or groups of inselbergs, although not numerous, are very conspicuous.

The Central Clay Plain is drained by the Nile river system, consisting, in the clay plain area, of the White Nile, the Blue Nile, the Nile, the semi-perennial tributaries Dinder, Rahad and Atbara, and a number of smaller non-perennial streams. Several small drainage channels originate at the foot of inselbergs or hills; these are often unconnected with any perennial stream and fade out onto the clay flats.

Calculated soil moisture regimes for the area (Van Wambeke 1982, using a mathematical model developed by Newhall; Tavernier and Van Wambeke 1982) are: aridic and ustic, or, following a proposed sub-division of the soil moisture regimes: typic aridic, weak aridic and aridic tropustic. Most soils have an isohyperthermic soil temperature regime, some soils in the northern part of the plain have a hyperthermic regime. A sub-division of the clay plain into four regions, based on precipitation and evaporation, creates units that are of significance for the geography of vegetation and soils.

Four vegetation units in the classification of Harrison and Jackson (1958) cover the Central Clay Plain. Their boundaries are roughly parallel to the 400, 600 and 800 mm isohyets. Edaphic factors, especially the differences between clay soils on one side, and sandy, rocky and stony areas on the other, are particularly important in the lower-rainfall part of the clay plain. Differences in vegetation have been used extensively in soil mapping, on all scales from semi-detailed to exploratory.

Large-scale mechanized rain-fed agriculture, and shifting cultivation are practised in areas with an annual rainfall of 400 mm or above. Livestock husbandry is widespread over the entire clay plain. Irrigated agriculture is practised extensively in areas that are commandable from the Nile waters; these include the well-known Gezira/Manaqil gravity irrigation scheme.

Chapter 3: Geological sequence

The degradational clay plains have formed from Basement Complex rock, or - in parts of the Gedaref clay plain - from Tertiary formations, mainly basalts. Outcrops of Basement Complex rock form hills and inselbergs.

The Mesozoic Nubian and Gedaref formations consist mainly of sandstone. Sandstone outcrops and associated sandy soils occur as islands in the clay plain.

Laterization (formation of ironstone sheets or cappings) has occurred during wet periods in the Mesozoic and Tertiary. In some Vertisols laterite gravel is found on the surface or in the substratum.

Most of the Tertiary was a period of major faulting and warping in East Africa. The upwarping of the Ethiopian massif and the Red Sea hills was accompanied by downwarping in Central Sudan and Egypt along a NNW-SSE axis. It created the plains of Egypt and the Sudan in which the Nile river system developed. Unconsolidated sediments have infilled the Sudan basin. Infilling started Late Tertiary (Pliocene) and has continued until today. The geological differentiation Umm Ruwaba, El Atshan and Gezira Formation is relevant to a pedogeomorphic sub-division of the aggradational clay plains.

Other quaternary formations are the 'qoz' sands west of the White Nile valley - stabilized aeolian deposits derived from Nubian Formation sandstone outcrops - and the White Nile semi-lacustrine sediments. Recent deposits are the sand dunes along the White Nile, and recent river alluvium.

Chapter 4: Pleistocene and recent history of the Nile system in the Sudan basin

The Pleistocene and Recent history of the Nile system in the Sudan is strongly defined by climatic conditions in the catchment areas of the river (Ethiopia and East Africa) and by the climate in the Sudan basin.

The Gezira aggradational clay plain formed as a Blue Nile alluvial fan graded to the White Nile: the Gezira Formation. The Formation consists of two members: the Lower Member, which is heterogeneous, including sandy and gravelly as well as silty and clayey deposits, and the Upper Clay Member (Gezira clay) which consists of a uniform clay sediment, 7 to 45 m thick, locally interrupted by a system of sandy to gravelly palaeochannels.

Two different deposits can be recognized in the upper 250 cm of the Gezira clay: a dark grayish-brown surface clay of 130 to 150 cm thick, and a yellowish-brown clay down to 250 cm or below (locally to at least 20 m). The two sediments have different radiocarbon ages. These differential characteristics, together with the occurrence of specific soil features at the boundary between the two clay deposits, make it seem likely that there were two major periods of deposition, separated by a period of standstill:

- from 27 000 BP or earlier to 20 000/18 000 BP: deposition of yellowish-brown clay;
- from 12 000 to about 4 000 BP: deposition of dark grayish-brown surface clay;
- between 20 000 and 12 000 BP was a period of standstill in deposition with locally marshy conditions and an arid climate on the clay plain.

The Atbara clay plain had a history similar to the Gezira plain: here a paludal dark-grayish brown clay overlies a yellowish-brown clay, which, however, is much thinner than in the Gezira and is often interrupted by coarser-textured strata representing former palaeochannels or silted-up meanders.

The White Nile system developed quite differently. The White Nile valley in the central Sudan acquired the dimensions of a lake during at least two relatively wet periods between 12 000 and 8 000 BP. The lakes developed due to damming or backflooding by Blue Nile floods at the confluence of the two rivers. After 8 000 BP the White Nile shrank, but lacustrine sedimentation continued. Blue Nile deposits have at times spread into the White Nile valley.

Chapter 5: Origin and geomorphology of the degradational clay plains

The degradational clay plains owe their origin to the weathering of Basement Complex rocks and Tertiary lavae, and the subsequent transportation of some of the fine-textured weathering debris to local erosion levels. In total acreage they exceed the aggradational plains; they cover the major parts of the Butana, the Gedaref clay plain and the Kenana. The processes of landscape evolution include parallel slope retreat (back-wearing), pedimentation and rock weathering (Ruxton and Berry 1961). The last stage of degradation is a gently undulating clay plain with few remnants of the older surface as hill groups and inselbergs with fringing pediments. Most of the degradational clay plains are now in this stage.

At first sight the aggradational and the degradational plains look much alike; they are both apparently flat and have similar smectite clay soils. They can, however, be distinguished on contour pattern and relative heights (Figures 2.2 to 2.6).

There are few differences in soil morphology between aggradational and degradational plains, and these are mainly in the substratum: clays of the aggradational plains overlie clayey or coarser-textured substrata, whereas clays of the degradational plains overlie truncated weathering profiles (Berry and Ruxton 1959) at relatively shallow depth. The mineralogy of the sand fractions clearly indicates the different origin of the parent materials.

Chapter 6: The pedogeomorphic map of the Central Clay Plain

In order to illustrate the geographic pattern of soils in the central clay plain area, an exploratory soil map 1:2 000 000 was compiled (Appendix 4). It is coined a pedogeomorphic map, in order to indicate that it is neither a soil map nor a geomorphic map, but contains aspects of both. The legend of the map shows three categories. The highest category differentiates between geomorphic units. The second category contains geomorphic sub-units. Units of the third category are differentiated on both landscape and soil aspects; these are the pedogeomorphic units. Most mapping units are on this third level.

The 1:2 000 000 scale is too small for the definition of mapping units that are mainly or entirely based on soil characteristics. Such units are given on the larger-scale maps of two sample areas (Figures 6.1, 6.3 and 6.4).

The first part of Table 6.1 lists the profiles that are characteristic of the clay plain. The uniformity of the clay cover is clearly shown: nearly all soils belong to a very-fine, montmorillonitic and isohyperthermic family of Typic Chromusterts. Pellusterts occur in level or slightly depressed locations; the differences in colour chroma between the two great groups reflect differences in drainage conditions. On non-clay plain sites Pellusterts developed 'in situ' from basic rock, and they occur on hillslopes and foot slopes. Entic subgroups tend to be more common in the northern, arid parts of the clay plain, and when the soil is a Pellustert. The difference Entic/Typic is, however, less easily related to soil or site characteristics than the difference Chrom-/Pell-.

The uniformity suggested by the soil family names, is to some extent due to the choice of differentiating characteristics in the USDA soil classification system. Another choice would reveal differences between Vertisols of higher and lower rainfall regions and - but less distinctly so - between Vertisols of aggradational and degradational plains. The following characteristics differ between clay-plain Vertisols - in addition to those already mentioned:

- salinity/sodicity;
- presence and depth of occurrence of gypsum;
- presence, size-class and depth of occurrence of soft powdery concentrations of calcium carbonate;
- surface characteristics, notably the presence and degree of development of a mulch, or the presence of a hard crust;
- presence or absence of gilgai microrelief, and type of gilgai;
- colour chroma differences between Chromusterts.

Chapter 7: Morphology of the Vertisols in the Central Clay Plain

The morphology of the Vertisols has been described at three levels:

- macromorphology: field description from profile pits, including site characteristics;
- mesomorphology: stereomicroscopic study of aggregates or soil fragments at low magnification;
- micromorphology: study of thin sections by petrographic microscope.

Macromorphology

We have described the Vertisols as A-Bw-C profiles. The upper few centimetres are formed by a loose surface mulch. Below the mulch, the A horizon has a subangular to angular blocky structure, tending towards a vertic structure. The Bw horizon has a vertic structure: wedge-shaped peds with glossy surfaces. The C horizon has features showing that it is below the zone of pedoturbation. Slickensides, built of adjoining ped surfaces, occur in the Bw and the upper part of the C horizon; slickensides at greater depth are fossil. The appearance of soft powdery lime marks the lower boundary of the zone of pedoturbation. Manganiferous coatings and mottles - with or without ferric iron - occur more frequently in the substratum than in the solum.

Mesomorphology

Two aspects of the stereomicroscopic studies (with magnifications 10x and 50x) merit attention:

1. The forms of carbonate and ferri-manganiferous concentrations that were differentiated in the thin-section studies (see below) and the forms described in the field, could both be recognized under the stereomicroscope. The mesomorphological studies thus provided a link between field observations and thin section studies.
2. All wedge-shaped (bicuneate) ped surfaces, even the finest parallelepiped peds, appear as transparently glazed faces. Larger peds show this feature more distinctly than smaller peds. This observation is specific for the stereomicroscopic studies.

Micromorphology

The thin section observations were concentrated on features that are different between Vertisols or between horizons within a profile. The selected features are: plasmic fabrics, planar voids, carbonate and ferri-manganiferous plasma concentrations, clay illuviation cutans, papules, intercalary crystals of carbonate and gypsum.

The plasmic fabric in Vertisols can be assigned to three categories:

- Surface-related plasma separations: vosepic, skelsepic and glaesepic plasmic fabric;
- Subcutanic plasma separations: masepic plasmic fabric;
- Unrelated plasma separations: asepic and sepic plasmic fabrics; in the Vertisols of our study: argillasepic, insepic, mosepic and omnisepic.

None of the micromorphological features described have the quality of differentiating between geographic regions, but some differentiate clearly between higher and lower rainfall regions. Vertic processes are most clearly shown by the presence of joint planes and an abundance of oriented clay domains, at least part of which forms masepic zones with a striated orientation.

Five forms of carbonate concentrations were distinguished. The differentiating characteristics were chosen in a way that allowed pedogenic interpretations, particularly on the question of whether or not the concentration was formed 'in situ'. A similar approach was followed by the distinction of five forms of ferri-manganiferous concentrations.

The joined results of macro-, meso- and micromorphological observations on clay plain Vertisols show that there is a distinct north-south gradient in characteristics, parallel to an increase in annual rainfall and a lengthening of the rainy season in that same direction. A border zone between the isohyets of 500 mm and 600 mm separates the clay plain into two sub-regions with Vertisols that are different in several morphological properties.

Chapter 8: Mineralogical, chemical and granulometric investigations

Twenty-three of the twenty-seven reference profiles (Table 6.1) were sampled for mineralogical, chemical and granulometric analyses. One objective of the laboratory studies was, to ascertain to which extent the analytical data would support the field and micromorphological observations. Another objective was, to support hypotheses on soil-forming processes. In discussing the data we have differentiated between Vertisols from clay-plain sites, other Vertisols (developed in colluvium or 'in situ'), and non-vertic soils (from other Orders cf. Soil Taxonomy).

The mineralogical composition of the samples was determined by optical mineralogical investigation of the heavy and light minerals of the sand fraction, and by X-ray diffraction of the clay. The following chemical characteristics of the soils were determined: pH-H_20, pH-$CaCl_2$, percentages of carbonate, gypsum $_a$nd organic carbon, cation exchange capacity and exchangeable sodium. Electrical conductivity of a soil/ water extract, and anions and cations in that extract, were determined in some soils of the northern part of the clay plain. The total elemental composition of the soil and of the clay fraction were determined in samples from selected profiles. The methods for chemical and granulometric analysis are described in Appendix 1.

The optical mineralogical investigations of sand fractions revealed major differences between aggradational and degradational clay plains. Differences between the Atbara and the Blue Nile-Dinder-Rahad aggradational clay plains could be related to the catchment areas of the rivers, but post-sedimentary weathering of the deposits must also be considered.

The variation in parent materials, as shown in the mineralogy of the sand (and some silt) fractions was not found in the clay fractions. X-ray diffraction of the clay showed the mineralogy to be strongly smectitic for all clay-plain Vertisols, whereas in most other Vertisols the smectite was poorly crystallized and less dominant. The non-vertic soils have a mixed or kaolinitic clay mineralogy.

Most of the clay-plain Vertisols have a cation exchange capacity of the clay fraction (CEC-clay) around 800 $mmol.kg^{-1}$, with a range from 600 to 1000. Neither X-ray diffraction, nor CEC-clay data could be related to rainfall regime at the site, or nature of the parent material. The CEC-clay of Vertisols from other sites, and of non-vertic soils is more varied.

The smectitic nature of the clay is illustrated by the molar silica/sesquioxide ratios of the clay fraction.

Ferrous iron is present in rock fragments and primary minerals. Most of the ferric iron compounds of the Vertisols are in the clay fraction, and this refers to both free and silicate-bound ferric iron. The clay fractions of the non-vertic soils contain less silicate-bound ferric iron and more free ferric iron than the clay fractions of the Vertisols. Differences in soil colour and drainage conditions between Chromusterts and Pellusterts were not matched by systematic differences in the silicate-ferric-iron/free-ferric-iron ratio of the clay fractions.

Data on the elemental composition of the clay fraction of five samples from fully analyzed clay-plain Vertisols have been used to calculate the approximate chemical composition of smectite. The samples had in common the fact that more than 80% of the fraction <2 μm was smectite. The data were corrected for other minerals present, as shown in the X-ray diffractograms (kaolinite, silica) and for free ferric iron.

The calculated smectites are similar in chemical composition; the main constituents are SiO_2 (50 to 57%), Al_2O_3 (16 to 26%) and Fe_2O_3 (7 to 11%). The smectites have a relatively high percentage of ferric iron, an observation also made in other Vertisols in tropical Africa.

Vertisols in parts of the clay plain with an annual rainfall of 400 mm or less have weakly saline and sodic surface soils, whereas the lower part of the solum is moderately saline and sodic. Entic Pellusterts in closed depressions in the northeastern Kenana (part of the Blue Nile-Dinder-Rahad clay plain) are often sodic and very calcareous, but only weakly saline. The high sodicity is probably inherited from the period of clay deposition, when the area was flooded with Blue Nile water having a residual alkalinity. An alternative hypothesis is presented, considering:

a. a marshy vegetation and anaerobic conditions in these sites for at least part of the year;
b. floodwater with appreciable amounts of sulphate in addition to sodium and calcium.

Sulphate reduction would have had the effect that the original sodium sulphate salinization is changed into a bicarbonate salinization, characterized by a high ESP and a high pH.

Chapter 9: Aspects of soil genesis, classification and survey

In this chapter, soil genesis is discussed under the headings:

- origin and formation of the clays (in aggradational plains, degradational plains and red-black soil catenas);
- soil formation in the Central Clay Plain (on datum sites and in closed depressions, and with special attention for soil colour as an indicator of pedogenic processes in Vertisols).
- pedoturbation, soil structure and gilgai.

This is followed by a discussion of recent proposals on the classification of Vertisols, and the chapter ends with some remarks on soil description, soil sampling and soil survey in an area like the Central Clay Plain.

Origin and formation of the clays

Conditions on the aggradational plains after deposition had come to an end (ca 5 000 BP) were at an optimum for the formation of smectite, and for its conservation. After deposition mineral weathering continued, and silt-size river sediments produced smectite clays.

Clays on the degradational plains have formed from rock weathering on hill slopes and pediments, with transport of solutes and fine-textured colloidal weathering products. The northern boundary of clay formation is set by an annual rainfall that is insufficient for chemical weathering to take place. In the Central Clay Plain this is at about 300 mm annual rainfall.

Most of the parent rock is Basement Complex which consists mainly of gneisses, but more basic rock types also occur. Soils in the vicinity of major hill groups can be mineralogically related to the rock type of the hills, as is evident from locations in the Gedaref clay plain and the southern Kenana.

Clay formation in red-black soil catenas is primarily the formation of smectite, either by mineral transformation of weatherable minerals, or from ions in solution. The first pathway leads to an 'in situ' formation of smectite; it is confined to basic rock types, and residual Vertisols are formed. The second pathway leads to an allochthonous formation of smectite in foot slope or plain positions; it occurs in catenas developed from basic as well as from acid rock, and Vertisols develop in colluvio/alluvial transported material.

The location of Vertisols in the degradational clay plains varies according to parent rock and annual rainfall. In higher-rainfall areas, 'in situ' Vertisols of a dark red (5YR 3/2) colour cover basaltic hills and plateaus, whereas adjoining very dark grayish brown (10YR 3/2), dark gray (10YR4/1) or very dark gray (10YR3/1) Vertisols cover footslopes and clay plains. The picture is quite different in granitic landscapes in the lower-rainfall region (Butana) with smooth hills surrounded by wide, sand-covered pediments, where Vertisols are only found in clay plains below the pediments.

Soil formation in the Central Clay Plain

The main soil-forming process on datum sites - sites that neither receive water from or loose water to adjoining sites - is a physical process that creates a vertic soil structure. Soil formation is not different between aggradational and degradational clay plains; most of the soil variation is related to a north-south rainfall gradient.

Nonsaline-sodic Entic Pellusterts are typical of closed depressions on the Blue Nile westbank. Comparable sites do not occur in lower-rainfall aggradational plains, or if they do, they are flooded for such a short time that the specific soil features of Pellusterts cannot develop. On degradational clay plains level areas and closed depressions are not found.

Values of soil colour in Vertisols of the Central Clay Plain are not correlated with organic-matter contents: Entic and Typic subgroups according to Soil Taxonomy do not have significantly different amounts of organic carbon.

Vertisols with a chroma of less than 2 are classified as Pellic great groups; in the Central Clay Plain: Pellusterts. They occur in level areas or closed depressions, and are subject to flooding during some months every year. The low chroma suggests 'aquic conditions' as defined by ICOMAQ, requiring all three of: redoximorphic features, saturation and reduction. Two possible causes for the origin of the Pellic colour of these Vertisols were considered:

a. The soil shows 'aquic conditions' during part of the year; the Pellic colour is due to a reduced matrix.
b. 'Aquic conditions' as defined by ICOMAQ are not feasible; the Pellic colour is due to lack of free ferric iron as a result of stability of the smectite.

Oxidation/reduction mottles are not found in Pellic Vertisols of the Central Clay Plain; at the same time the low-chroma soil colour cannot indicate permanent reduction, as (1) Vertisols are, by definition, periodically dry, and (2) the soil colour does not change upon exposure to air. As aquic conditions do not exist, the low chroma of Vertisols is ascribed to stability of smectite and a relative paucity of kaolinite and free ferric iron.

Stability of smectite is promoted by a high pH, high levels of basic cations and silica, and impeded drainage. These conditions are fully met on poorly drained sites of the Central Clay Plain. Pellusterts, however, also occur on well-drained hillslope and foot slope positions on basic rock. These soils have high levels of basic cations, a high clay content and poor internal drainage, conditions which equally favour smectite stability.

The hypothesis that low chroma in Vertisols is the consequence of smectite stability and associated lack of free ferric iron was tested by recording the change of colour of some soil samples after successively removing organic matter, soluble minerals (salts, gypsum, carbonates) and free ferric iron. The results clearly showed that Pellic colours in Vertisols are due to the lack of free ferric iron.

Pedoturbation, soil structure and gilgai

The concept of Vertisols as 'turning soils' is based on the presumed process of churning or mechanical pedoturbation. However, observations on Vertisols elsewhere have shown that soil movement - as shown by slickensides - does not necessarily imply a turnover and mixing of the soil. This implies that soil movement without mixing is feasible. The effect of pedoturbation could be a homogenization of an originally heterogeneous parent material. Since the soil parent materials are very uniform in the Central Clay Plain, the homogenizing effect could not be demonstrated in this way. Pedoturbation, however, was shown where soil properties resulting from post-sedimentary soil-forming processes did not change with depth: contents of organic matter that remain at the same general level, radiocarbon ages that did hardly change in the solum but increased sharply below, and the absence of concentrations of soft powdery lime in a soil matrix that was strongly calcareous. The most common example is the presence of soft aggregates of calcium carbonate in the substratum, and their absence in the solum.

A gilgai microrelief is characteristic of the higher-rainfall areas of the Central Clay Plain. Gilgai is a consequence of forces active in subsoil and substratum, but mixing of solum and substratum soil material is not evident. Pedoturbation is not a required condition for gilgai formation.

At this stage of our knowledge, we suggest that in most Vertisols of the clay plain soil movement is accompanied by soil mixing.

Soil classification

The classification according to Soil Taxonomy is compared with recent proposals by the International Committee on Vertisols (ICOMERT) and the International Committee on Aquic Soil Moisture regimes (ICOMAQ). The suborder Aquerts, as proposed by ICOMAQ, requires that Vertisols have 'aquic conditions'. Such conditions, as we have seen, are not feasible. Aquerts could, however, be defined on low-chroma soil colour in combination with length of flooding of the site. Another taxon (on suborder or great group level) should then accomodate the low-chroma Vertisols on well-drained positions. The proposal of ICOMERT to define Chromic subgroups for Vertisols that have either a high colour value or a high colour chroma, or both, does not take into consideration the very different pedogenic processes affecting colour chroma or colour value.

In the revised FAO classification (FAO 1988) nearly all Vertisols of the clay plain belong to the Calcic soil unit. Only the few that lack soft powdery lime in the upper 125 cm are classified as Eutric. In the 1974-version a colour criterion was used: Pellic and Chromic Vertisols, similar to the great group distinction in Soil Taxonomy. This criterion was more useful for characterizing soils in the Central Clay Plain, and more suitable for producing mappable units on the 1:5 000 000 scale of the Soil Map of the World.

Soil description, sampling and survey

The experience gained in soil mapping on different scales on parts of the Central Clay Plain has resulted in a few considerations and recommendations for soil survey, soil description and soil sampling.

For soils that have mainly diffuse boundaries between horizons which differ in only one or a few characteristics, description or at least sampling at standard depths should be considered as an alternative to description and sampling according to (presumed) pedogenic soil horizons. However, any discrete horizon boundary should be adhered to.

In a featureless area with sparse vegetation which, moreover, varies between successive years, such as Khashm el Girba South, a grid survey is to be preferred above any attempt at a physiographic survey. The extreme uniformity of landform and soils has another interesting aspect. Instead of the usual problem in devising a mapping legend in a 1:100 000 scale soil survey - how to group different soils in one mapping unit - the problem in the Khashm el Girba soil survey was: how to find sufficient differentiating characteristics to create a reasonable amount of mapping units.

Samenvatting

Hoofdstuk 1: Inleiding

Het grootste gedeelte van de centraal-oostelijke Soedan wordt ingenomen door uitgestrekte, ogenschijnlijk eenvormige, kleivlakten, gezamenlijk bekend als de centrale kleivlakte (Central Clay Plain). Het moedermateriaal van de kleirijke gronden kan worden onderscheiden in twee grote groepen: - alluviale, delta- en meerbodemafzettingen door rivieren van het Nijlsysteem;

- colluvio-alluviaal verweringsmateriaal, afkomstig van locaal gesteente en verplaatst over relatief korte afstanden.

De termen aggradatiekleivlakten en degradatiekleivlakten worden gebruikt om dit onderscheid aan te geven.

Het klimaat verandert geleidelijk van aried in het noordwesten tot subhumied in het zuidoosten; het grootste deel van de centrale kleivlakte heeft een semi-aried klimaat. De jaarlijkse regenval neemt in dezelfde richting toe van 150 mm tot 1000 mm. Er is één regenseizoen, met een lengte van twee maanden (juli en augustus) in het noorden, en vijf maanden (mei t/m september) in het zuiden. De temperatuur is hoog gedurende het gehele jaar; de gemiddelde dagelijkse temperatuur is tussen 27 en 30°C.

De vegetatie verandert met de regenvalgradiënt van half-woestijn (semi-desert grassland) tot open bos (savannah-woodland). Acacia-soorten zijn dominant in de savannevegetatie.

De bodems hebben een kleipercentage van 60 tot 80, met smectiet als het belangrijkste kleimineraal. In bodemclassificatiesystemen vormen deze gronden een klasse op het hoogste niveau van abstractie; dat geldt voor het systeem van het US Department of Agriculture, Soil Taxonomy (Soil Survey Staff 1975), voor het Franse systeem (CPCS 1967), en voor het systeem van de FAO (FAO/Unesco 1974; FAO 1988) dat ontwikkeld is ten dienste van de legenda van een wereldbodemkaart op een schaal 1:5 000 000. In deze drie systemen wordt de naam Vertisols gebruikt voor deze gronden.

Vertisols hebben een duidelijke morfologie, met wijde en diepe scheuren in de droge tijd, wigvormige structuurelementen met glanzende vlakken, wrijfspiegels (slickensides) en andere kenmerken die het gevolg zijn van het zwellen en krimpen van smectiet-kleien en de daaruit resulterende schuifspanning en breukbewegingen in de grond. Binnen dit ene genetische bodemtype variëren kenmerken en eigenschappen met de hoeveelheid jaarlijkse regenval en de lengte van de regentijd. Deze zonaliteit is duidelijker dan variaties die samenhangen met landschapsvorming en moedermateriaal. De mate van jaarlijkse overstroming is een bijkomende differentiërende factor.

De studie van de kleivlakten in de Soedan werd verricht in de jaren 1959 tot 1963, en in de winter van 1965/66. Bodemkarteringen vormden de basis voor het verkrijgen van gedetailleerde kennis van deelgebieden. De kleivlakte als geheel werd bestudeerd tijdens vele reizen, waarbij waarnemingen werden gedaan van landvormen, vegetatie en bodems. Tenslotte kon voor kennis van de bodemgeografie ook gebruik gemaakt worden van diverse bodemkarteringsrapporten.

Een belangrijke plaats in de studie wordt ingenomen door 27 referentie-profielen, die representatief zijn voor de meeste pedogeomorfologische landschappen. Korrelgrootteverdeling, en chemische en mineralogische eigenschappen van deze gronden werden bestudeerd aan bodemmonsters. Micromorfologische kenmerken werden bestudeerd aan slijpplaatjes.

In dit proefschrift worden de samenhangen tussen bodemmorfologie, moedermateriaal, landvorm, klimaat en vegetatie onderzocht. Vervolgens worden de verschillende landschappen die tezamen de centrale kleivlakte vormen, gedefinieerd, beschreven en in kaart gebracht.

In een vergelijkende studie van de 27 referentieprofielen wordt nagegaan in welke mate de bodemkenmerken en -eigenschappen worden bepaald door moedermateriaal, of door andere bodemvormende factoren, zoals klimaat, relief en tijd. De studie richt zich vooral op de verschillen tussen de gronden en minder op hun gemeenschappelijke kenmerken, al zijn die laatste meer in het oog springend.

Hoofdstuk 2: Geografie

Het studiegebied omvat de volgende geografische provincies:

a. De Gezira
b. De Rahad-Dinder-Blauwe Nijl Gezira
c. De Butana, met de Atbara kleivlakte
d. De Gedaref kleivlakte
e. De Kenana of Fung.

De centrale kleivlakte helt enigszins af van zuidoost naar noordwest, met een gemiddeld hellingspercentage van minder dan één procent. Het mesorelief van de aggradatievlakten is dat van een riviervlakte (Rahad-Dinder Blauwe Nijl Gezira), een alluviale delta (Gezira) of een meerbodemafzetting (Atbara kleivlakte). De degradatievlakten hebben een geringe neerwaartse helling naar de aggradatievlakten langs de rivieren. Het mesorelief van de degradatievlakten is dat van een pediplain in het laatste planatiestadium; de zacht glooiende landvormen zijn gerelateerd aan bedekte pedimenten en rotsachtige erosieresten. De laatste, inselbergs en groepen van inselbergs, hoewel gering in oppervlakte, vormen zeer markante landschapselementen.

De centrale kleivlakte behoort tot het drainagesysteem van de Nijl, dat in het studiegebied de Witte Nijl, de Blauwe Nijl. de Nijl, de in de droge tijd nagenoeg droogvallende zijrivieren Dinder, Rahad en Atbara, en een aantal kleinere, intermitterende rivieren omvat. Aan de voet van heuvels ontspringen vaak kleine regenrivieren; dikwijls hebben deze geen verbinding met een permanente of periodieke rivier en zij verliezen zich op de kleivlakte.

Berekende 'soil moisture regimes' voor het gebied (Van Wambeke 1982; Tavernier en Van Wambeke 1982) zijn 'aridic' en 'ustic', of volgens een voorgestelde onderverdeling van deze bodemvochtregimes: 'typic aridic', 'weak aridic' en 'aridic tropustic'. De meeste bodems hebben verder een 'isohyperthermic soil temperature regime', sommige in het noordelijke deel van de kleivlakte een 'hyperthermic regime'. Een onderverdeling van de kleivlakte naar verschillen in neerslag en verdamping geeft eenheden die van betekenis zijn voor de geografie van vegetatie en bodems.

Vier vegetatie-eenheden volgens de classificatie van Harrison en Jackson (1958) komen in het gebied van de centrale kleivlakte voor. De grenzen van deze eenheden lopen ongeveer evenwijdig met de 400, 600 en 800 mm isohyeten. De verschillen tussen enerzijds kleigronden en anderzijds zandige, stenige en rotsachtige gronden zijn in sterke mate bepalend voor de vegetatie, vooral in het meer ariede deel van de kleivlakte. Bij het in kaart brengen van de bodems, van semi-gedetailleerd tot exploratie-schaal, is veel gebruik gemaakt van de geografie van de vegetatie.

Grootschalige, gemechaniseerde, regenafhankelijke landbouw en zwerflandbouw treft men aan in gebieden met een jaarlijkse regenval van 400 mm en meer. Veehouderij komt op de gehele kleivlakte veel voor. Geïrrigeerde landbouw komt voor langs de rivieren; bekend is het Gezira/Managil irrigatiegebied.

Hoofdstuk 3: Geologische successie

De degradatievlakten zijn ontstaan uit gesteenten van het Basement Complex, of - in delen van de Gedaref kleivlakte - van Tertiaire formaties, in hoofdzaak bazalten. Het Basement Complex dagzoomt in de vorm van heuvels en inselbergs.

De Mesozoïsche Nubische en Gedaref Formaties bestaan in hoofdzaak uit zandsteen. Waar deze formaties aan de oppervlakte liggen ontstaan zandig-stenige eilanden in de kleivlakte.

Laterizatie (vorming van laterietlagen of -koppen) heeft plaats gehad gedurende pluviale perioden in het Mesozoicum en het Tertiair. In sommige Vertisols komt laterietgrint voor aan de oppervlakte of in de ondergrond.

Het Tertiair was in Oost-Afrika vooral een periode van epirogenese. De opwelving van het Ethiopische massief en de Rode-Zeeheuvels hield gelijke tred met een epirogene daling langs een NNW-ZZO-as in de oostelijke Soedan en Egypte. Hierdoor ontstonden laagvlakten waarin zich het stroomgebied van de Nijl ontwikkelde.

Klastische sedimenten hebben het bassin van de centraal-oostelijke Soedan opgevuld. Dit begon in het Laat-Tertiair (Plioceen) en heeft zich tot op heden voortgezet. De geolgische onderscheiding van een Umm Ruwaba, een El Atshan en een Gezira Formatie is terug te vinden in een pedogeomorfologische onderverdeling van de aggradatiekleivlakten (Hoofdstuk 6).

Tot het Kwartair behoren de 'qoz'-zanden ten Westen van de Witte Nijl - gestabiliseerde aeolische sedimenten afkomstig van Nubische zandsteen - en semi-lacustrine Witte-Nijlafzettingen. Jonge rivierafzettingen en rivierduinen langs de Witte Nijl behoren tot het Holoceen.

Hoofdstuk 4: Pleistocene en Holocene geschiedenis van het Nijlsysteem in de Soedan

De Pleistocene en Holocene geschiedenis van het Nijlsysteem in de Soedan is in sterke mate bepaald geweest door de klimaatsomstandigheden in de stroomgebieden van de rivier, Ethiopië, Oost-Afrika en de centraal-oostelijke Soedan.

De Gezira aggradatievlakte is ontstaan als een alluviale delta van de Blauwe Nijl, afhellend naar het dal van de Witte Nijl: de Gezira Formatie. De Formatie bestaat uit twee afzettingen, onderscheiden als 'Lower Member' - heterogeen, variërend van zandig en grintrijk tot lemig en kleiig - en 'Upper Member' of 'Gezira clay' - een uniform kleisediment, 7 tot 45 m dik, plaatselijk onderbroken door zandige tot grintrijke verlaten kreekbeddingen (palaeochannels).

In de bovenste 250 cm van het kleiprofiel in de Gezira kunnen twee lagen worden onderscheiden: een bovenste kleipakket van 130 tot 150 cm dik, met een Munsell kleur van 10YR 3/2 tot 4/2, en een daaronder gelegen klei-afzetting tot tenminste 250 cm (plaatselijk tot 20 m of meer) met een Munsell kleur van 10YR 5/4. De twee sedimenten verschillen in radiometrische ouderdom (radiocarbon age). De aanwezigheid van twee verschillende kleipakketten, en van specifieke bodembestanddelen op de grens tussen deze pakketten, maakt het waarschijnlijk dat er voor de Gezira klei twee perioden van sedimentatie zijn geweest, gescheiden door een periode van stilstand, als volgt:

- van 27 000 BP of eerder tot 20 000/18 000 BP: afzetting van 10YR 5/4-klei (BP = before present);
- van 12 000 BP tot ongeveer 4 000 BP: afzetting van 10YR 3-4/2-klei;
- tussen 20 000 BP en 12 000 BP was er een periode van stilstand in de sedimentatie; de kleivlakte was plaatselijk moerassig, en het klimaat aried.

De geschiedenis van de Atbara kleivlakte is vergelijkbaar met die van de Gezira, zij het dat het bovenste kleipakket meer het karakter heeft van een lacustrine afzetting dan van een alluviale delta. Het bovenste kleipakket is ook minder dik en wordt op veel plaatsen onderbroken door zandiger lagen, vermoedelijk vroegere stroombeddingen of dichtgeslibde meanders.

Het stroomgebied van de Witte Nijl heeft in tenminste twee relatief regenrijke perioden tussen 12 000 en 8 000 BP de omvang gehad van een meer. Deze meren konden ontstaan doordat sediment van de Blauwe Nijl ter plaatse van de samenvloeiing van beide rivieren tot bezinking kwam en de uitstroom van de Witte Nijl blokkeerde of, doordat ten tijde van hoog water in de Blauwe Nijl, de afvoer van water uit de Witte Nijl werd belemmerd. Sedimentatie in de vallei van de Witte Nijl gebeurde in hoofdzaak onder lacustrine omstandigheden. Sediment van de Blauwe Nijl is in bepaalde perioden in het stroomgebied van de Witte Nijl afgezet.

Hoofdstuk 5: Ontstaan en geomorfologie van de degradatiekleivlakten

De degradatiekleivlakten zijn ontstaan door verwering van gesteenten van het Basement Complex en Tertiaire lavas, gevolgd door transport van een deel van het fijne verweringsmateriaal naar locale erosiebases. In oppervlakte overtreffen zij de aggradatiekleivlakten; het grootste deel van de Butana, de Gedaref kleivlakte en de Kenana zijn degradatievlakten. De landschapsvormende processen zijn parallelle terugwijking van hellingen (parallel slope retreat; back-wearing), pediment-vorming en gesteenteverwering (Ruxton en Berry 1961). Het laatste stadium van planatie is een zwak golvende kleivlakte met enkele restanten van het oude landoppervlak in de vorm van heuvels en inselbergs met pedimenten. De meeste degradatiekleivlakten zijn thans in dit stadium.

Op het eerste gezicht zijn er nauwelijks verschillen tussen aggradatie- en degradatiekleivlakten: in beide gevallen een vlak terrein en smectitische kleigronden. De twee landschappen kunnen echter worden onderscheiden door een verschillend patroon van hoogtelijnen en een verschillende absolute hoogteligging (Figuren 2.2 t/m 2.6).

Er is eveneens weinig verschil in de bodemprofielen tussen de twee soorten kleivlakte, behalve in het onderliggende substraat (C-horizont): de kleigronden van de aggradatievlakten liggen doorgaans op een kleipakket van andere aard en soms op sedimenten van een grovere textuur, terwijl de kleigronden van de degradatievlakten op betrekkelijk geringe diepte liggen op onthoofde verweringsprofielen (Berry en Ruxton 1959). De mineralogie van de zandfracties wijst duidelijk op een verschillende herkomst van de moedermaterialen.

Hoofdstuk 6: De pedogeomorfologische kaart van de centrale kleivlakte

Een overzichtskaart op een schaal 1:2 000 000 (Appendix 4) werd samengesteld om de geografie van de verschillende gronden te illustreren. Wij hebben deze kaart een pedogeomorfologische kaart genoemd om daarmee aan te geven dat het noch om een bodemkaart, noch om een geomorfologische kaart gaat, maar om een kaart die elementen van beide bevat. De legenda van de kaart heeft drie niveaus. Op het hoogste niveau worden geomorfologische eenheden onderscheiden. Op het tweede niveau vindt men geomorfologische sub-eenheden. Op het laagste niveau worden eenheden onderscheiden naar zowel landschappelijke als bodemkundige aspecten; dit zijn de pedogeomorfologische eenheden. De meeste kaarteenheden behoren tot deze laatste categorie.

De 1:2 000 000 kaartschaal is te klein voor het onderscheiden van kaarteenheen die geheel gebaseerd zijn op bodemkenmerken. Bodemkundige kaarteenheden komen voor in de legenda's van de op een grotere schaal gekarteerde voorbeeldgebieden (Figuren 6.1, 6.3 en 6.4).

In het eerste deel van Tabel 6.1 worden de referentieprofielen van de centrale kleivlakte opgesomd. In de tabel is de uniformiteit van de bodems duidelijk zichtbaar in de naamgeving volgens Soil Taxonomy: bijna alle gronden behoren tot de 'very-fine, montmorillonitic, isohyperthermic family' van de subgroep Typic Chromusterts. Pellusterts komen voor in laagten; het verschil in 'chroma' van de bodemkleur gaat samen met een verschil in drainagetoestand. Pellusterts komen echter ook voor als residuaire gronden op basisch gesteente, op hellingen en aan de hellingvoet.

De meeste Pellusterts behoren tot de Entic subgroep. Entic Chromusterts komen voor in het noordelijke, droogste deel van de centrale kleivlakte. Het onderscheid Entic/Typic is minder sterk gecorreleerd aan kenmerken van bodem en standplaats dan het onderscheid Chrom-/Pell-.

De uniformiteit, die wordt gesuggereerd door de classificatie volgens Soil Taxonomy op het niveau van de 'soil family', is tot op zekere hoogte het gevolg van de keuze van differentiërende kenmerken. Een andere keuze zou de verschillen onderstrepen die er bestaan tussen Vertisols met een verschillend neerslagregime en - maar minder duidelijk - tussen Vertisols van aggradatie- en van degradatiekleivlakten. Aan de reeds genoemde verschillen tussen Vertisols van de centrale kleivlakte (aard van het substraat, kleur) kunnen nog de volgende worden toegevoegd:

- mate van verzouting en van sodium-verzouting;
- aanwezigheid en diepte van voorkomen van gips;
- aanwezigheid, grootte en diepte van voorkomen van zachte, poederachtige concentraties van calcium carbonaat;
- kenmerken van de terreinoppervlakte, vooral de aanwezigheid en mate van ontwikkeling van een 'mulch', dan wel van een harde korst;
- het al of niet aanwezig zijn van een 'gilgai' microrelief;
- verschillen in chroma van de kleur tussen Chromusterts.

Hoofdstuk 7: Morfologie van de Vertisols in de centrale kleivlakte

De morfologie van de Vertisols werd beschreven op drie niveaus:

- de macromorfologie: beschrijvingen van profielen in het veld, en van kenmerken van de locatie;
- de mesomorfologie: stereomicroscopische studies bij geringe vergroting van structuurelementen of grondbrokken;
- de micromorfologie: studie van slijpplaatjes van ongestoorde bodemmonsters, met behulp van een petrografische microscoop.

Macromorfologie

Wij hebben de Vertisols beschreven als A-Bw-C-profielen. De bovenste 1 tot 5 cm bestaan uit een 'mulch' van losliggende aggregaatjes. Onder de mulch heeft de A-horizont een afgerond-blokkige tot scherp-blokkige structuur. De Bw-horizont heeft een vertische structuur, gekenmerkt door wigvormige structuurelementen met glanzende vlakken. De C-horizont (substratum) heeft kenmerken die erop wijzen, dat de horizont beneden de pedoturbatie-zone ligt. 'Slickensides', bestaande uit aaneensluitende glanzende structuurvlakken, komen voor in de Bw-horizont en het bovenste deel van de C-horizont; 'slickensides' op grotere diepte zijn fossiel. De diepte waarop zachte carbonaataccumulaties verschijnen, markeert de ondergrens van de zone van pedoturbatie. Huidjes en vlekken van mangaanoxide - al of niet tezamen voorkomend met ferri-oxiden - komen vaker voor in het substraat dan in het solum.

Mesomorfologie

Twee aspecten van de stereomicroscopische studie (met vergrotingen van 10x en 50x) verdienen aandacht:

1. De vormen van concentraties van carbonaat en mangaan/ferri-ijzer die in de slijpplaatjes werden onderscheiden (zie onder), en de vormen die in het veld werden beschreven, konden beide worden herkend onder de stereomicroscoop.De mesomorfologie vormde daarmee een schakel tussen veldwaarnemingen en waarnemingen aan slijpplaatjes.
2. Alle wigvormige structuurelementen, zelfs de kleinste, blijken een transparante, glazuurachtige oppervlakte te bezitten. Bij grotere structuurvlakken is dit het duidelijkst te zien. Dit kenmerk is specifiek voor de stereomicroscopische waarnemingen.

Micromorfologie

De waarnemingen aan slijpplaatjes werden vooral gericht op kenmerken waarin Vertisols van elkaar verschillen en op kenmerken waarin horizonten binnen een profiel van elkaar verschillen. Het betreft hier de volgende: plasma-rangschikkingen (plasma separations), spleetvormige holten (planar voids), plasma-concentraties van carbonaat, mangaan en ferri-ijzer, klei-illuviatiehuidjes (argillans), 'papules' en losliggende kristallen of groepjes van kristallen (intercalary crystals) van carbonaat en gips.

De plasma-rangschikkingen kunnen in drie groepen worden onderscheiden :

- Surface-related plasma separations: vosepic, skelsepic and glaesepic plasmic fabric;
- Subcutanic plasma separations: masepic plasmic fabric;
- Unrelated plasma separations: asepic and sepic plasmic fabrics (in de bestudeerde Vertisols: argillasepic, insepic, mosepic and omnisepic).

Geen van de beschreven micromorfologische kenmerken heeft betekenis voor het ondersteunen van een differentiatie van geografische gebieden, maar sommige hebben dat wèl voor het onderscheid tussen gebieden met lage en relatief hoge regenval. Vertische processen manifesteren zich het duidelijkst in de aanwezigheid van 'joint planes' en het veelvuldig voorkomen van 'domains' (klei-pakketjes) van georiënteerde klei die, althans voor een deel, voorkomen als 'masepic zones' met een 'striated orientation.

Vijf vormen van carbonaat-concentraties werden onderscheiden. De differentiërende kenmerken zijn zodanig gekozen, dat een pedologische interpretatie mogelijk werd, b.v. over de vraag of de concentratie al of niet 'in situ' zou zijn ontstaan. Eenzelfde benadering werd gevolgd bij het onderscheiden van vijf vormen van ijzer-mangaanconcentraties.

Wanneer wij de resultaten van de macro-, meso- en micromorfologische waarnemingen van Vertisols van de centrale kleivlakte combineren, blijkt een duidelijke noord-zuidgradiënt aanwezig, in overeenstemming met een regenvalgradiënt in dezelfde richting. Een overgangszone tussen de 500 mm en 600 mm isohyeten verdeelt de kleivlakte in twee delen waarin de Vertisols in veel opzichten een verschillende morfologie hebben.

Hoofdstuk 8: Mineralogisch, chemisch en granulometrisch onderzoek

Van de 27 referentieprofielen (Tabel 6.1) werden er 23 bemonsterd voor mineralogische, chemische en granulometrische analyse. Het doel van dit laboratoriumonderzoek was tweeledig:

1. om na te gaan in hoeverre de analytische gegevens de veldwaarnemingen zouden ondersteunen;
2. om hypothesen betreffende bodemvorming te ondersteunen.

De mineralogische samenstelling van de grondmonsters werd bepaald door microscopisch-petrografische inventarisatie van de zware en lichte zandfractie en door röntgendiffractie van de klei. De volgende chemische eigenschappen werden bepaald: pH-H_2O, pH-$CaCl_2$, percentages carbonaat, gips en organische koolstof, kationenuitwisselingscapaciteit (CEC) en uitwisselbaar Na^+. Het electrisch geleidingsvermogen in een bodem/water-extract (ECe) en de anionen en kationen in dat extract werden bepaald van een aantal gronden in het noordelijke deel van de kleivlakte. De elementaire samenstelling van de grond en van de kleifractie werden bepaald in een aantal profielen. De methoden van chemische analyse en textuurbepaling zijn beschreven in Appendix 1.

Het optisch-mineralogische onderzoek van de zandfracties gaf duidelijke verschillen te zien tussen aggradatie- en degradatiekleivlakten. Verschillen tussen de Atbara kleivlakte en de Rahad-Dinder-Blauwe Nijl Gezira konden worden gerelateerd aan de geologie van de stroomgebieden van de rivieren. Voortgaande verwering van de sedimenten na afzetting heeft ook invloed gehad op de huidige mineralogische samenstelling van de zandfracties.

De verschillen in moedermateriaal zoals aangetoond in de mineralogie van de zandfracties (en van enkele siltfracties) werden in de kleifractie niet teruggevonden. Röntgendiffractie toonde het smectitisch karakter en de sterke kristalliniteit van de klei, vooral in Vertisols van de vlakten. In andere Vertisols (residuaire en semi-residuaire) was het smectitisch karakter minder uitgesproken of de kristalliniteit geringer. De niet-vertische gronden hadden een gemengde of kaolinitische kleimineralogie.

De meeste Vertisols van de kleivlakte hebben een CEC van de kleifractie van ongeveer 800 $mmol.kg^{-1}$, met een bereik van 600 tot 1000. Noch de resultaten van de röntgendiffractie, noch die van de CEC-klei, konden worden gerelateerd aan het regenvalregime van de locatie of aan het moedermateriaal. De CEC-klei van de andere Vertisols en van de niet-vertische gronden vertoont een grotere variatie dan die van de Vertisols van de kleivlakte.

Het smectitisch karakter van de klei werd nader geïllustreerd door de molaire silica/ sesquioxide-verhoudingen van de kleifractie.

Ferro-ijzer is aanwezig in primaire mineralen, en werd aangetoond in saprolietmonsters van residaire Vertisols. Het meeste ferri-ijzer in Vertisols bevindt zich in de kleifractie, en dat geldt zowel voor vrij ijzer als voor silicaat-gebonden ijzer. De kleifracties van de niet-vertische gronden bevatten minder silicaat-gebonden ferri-ijzer en meer vrij ferri-ijzer dan de kleifracties van de Vertisols. Verschillen in bodemkleur en drainagetoestand tussen Chromusterts en Pellusterts gingen niet parallel met systematische verschillen in de silicaat-ferri-ijzer/vrij ferri-ijzer- ratio van de kleifractie.

De gegevens van de volledige chemische analyse van monsters uit vijf referentieprofielen zijn bewerkt voor het berekenen van een benaderde chemische samenstelling van de aanwezige smectiet. In de gekozen monsters was aangetoond, dat tenminste 80 % van de kleifractie uit smectiet bestond. De cijfers van de chemische analyse werden gecorrigeerd voor de aanwezigheid van andere mineralen, zoals die door röntgendiffractie waren aangetoond (kaoliniet, quartz) en voor vrij ferri-ijzer.

De berekende smectieten vertonen onderling weinig verschil in chemische samenstelling: de belangrijkste componenten zijn SiO_2 (50 tot 57%), Al_2O_3 (16 tot 26%) en Fe_2O_3 (7 tot 11%). De smectieten zijn relatief rijk aan ferri-ijzer, een waarneming die ook gedaan is aan andere Vertisols in tropisch Afrika.

Vertisols in delen van de kleivlakte met een jaarlijkse regenval van 600 mm of minder, zijn zwak zout en sodisch in de bovengrond, en matig zout en sodisch in de ondergrond. Pellusterts in afvoerloze laagten in het noordoosten van de Kenana zijn vaak sodisch en zeer kalkrijk, maar nauwelijks zout. De hoge sodiciteit is waarschijnlijk een relict uit de tijd dat de klei werd afgezet door water van de Blauwe Nijl met een overmaat aan alkaliniteit (residual alkalinity). Voor een alternatieve hypothese werd uitgegaan van:

a. een moerassige vegetatie en een anaeroob milieu gedurende tenminste een deel van het jaar;
b. overstromingswater met een aanzienlijke hoeveelheid sulfaat naast natrium en calcium.

Sulfaatreductie zou onder deze omstandigheden zijn opgetreden, waardoor de oorspronkelijke natriumsulfaatverzouting werd omgezet in een bicarbonaatverzouting met een hoog percentage uitwisselbaar natrium en een hoge pH.

Hoofdstuk 9: Aspecten van bodemgenese, classificatie en kartering

In dit hoofdstuk wordt allereerst aan een drietal aspecten van de bodemgenese aandacht besteed:

- ontstaan van de klei (in aggradatie- en degradatievlakten en in bodemcatena's);
- bodemvorming in de centrale kleivlakte (op vlakten en in laagten; bodemkleur als indicator van bodemvormende processen);
- pedoturbatie, bodemstructuur en gilgai.

Hierna volgen een bespreking van recente voorstellen voor de classificatie van Vertisols en enkele opmerkingen over bodembeschrijving, -bemonstering en -kartering.

Oorsprong en vorming van de klei

De omstandigheden op de aggradatievlakten nadat de depositie was geëindigd (ca 5 000 BP) waren optimaal voor de vorming van smectiet en voor zijn conservering. Door verwering van sedimentdeeltjes van silt-grootte nam de hoeveelheid klei op de vlakten geleidelijk toe.

De kleien op de degradatievlakten zijn ontstaan door gesteenteverwering op heuvels en pedimenten, gevolgd door verplaatsing van fijn colloïdaal en opgelost materiaal. De noordgrens van kleivorming wordt bepaald door een jaarlijkse regenval die te gering is voor chemische verwering. In de centrale kleivlakte ligt deze grens bij 300 mm. Het uitgangsgesteente is doorgaans Basement Complex; dit bestaat voor een belangrijk deel uit gneiss, maar meer basische gesteenten komen ook voor. Bodems in de nabijheid van grotere heuvels kunnen mineralogisch worden gerelateerd aan het gesteente van die heuvels. Dit is vooral het geval in sommige gedeelten van de Gedaref kleivlakte, en in de zuidelijke Kenana.

In catena's die zowel 'rode' (ferrallitische) als 'zwarte' (vertische) gronden omvatten (red-black soil catenas) is kleivorming allereerst vorming van smectiet, door transformatie van mineralen of door synthese van ionen in oplossing. De eerste weg leidt tot een 'in situ' vorming van smectiet en is beperkt tot basische gesteenten. Op deze wijze worden residuaire Vertisols gevormd. De tweede weg leidt tot een allochtone vorming van smectiet op hellingvoeten en in vlakten. Deze vormingswijze komt voor in catena's op zure en op basische gesteenten. Vertisols ontwikkelen zich hier op verplaatst materiaal.

De ligging van Vertisols in de degradatie-kleivlakten varieert met het uitgangsgesteente en met de regenval. In gebieden met basalt en relatief hoge regenval bedekken 'in situ' gevormde donkerrode (5YR 3/2) Vertisols de hellingen, terwijl donkergrijze tot grijsbruine (10YR 3/2, 3/1, 4/1) Vertisols voorkomen op de aansluitende hellingvoeten en kleivlakten. In pediplains, ontwikkeld in een granitisch landschap en een semi-aried klimaat (noordelijke Butana), komen Vertisols alleen voor in de kleivlakten. Restanten van het oude landoppervlak zijn aanwezig als vlakke heuvels, omgeven door wijde, met zand en gesteentefragmenten bedekte pedimenten.

Bodemvorming in de centrale kleivlakte

Het belangrijkste bodemvormende proces op vlakke locaties - die geen regenwater ontvangen van, of afgeven aan, aangrenzende locaties (Eng.: datum sites) - is een physisch proces dat resulteert in een vertische bodemstructuur. Dit proces is niet verschillend tussen aggradatie- en degradatiekleivlakten. De variatie in bodems is gerelateerd aan een noord-zuid gerichte regenvalgradiënt.

Sodische, zwak verzoute Entic Pellusterts zijn typisch voor afvoerloze laagten in de aggradatievlakte ten westen van de Blauwe Nijl. Vergelijkbare locaties worden niet aangetroffen in het ariede deel van de vlakte, ofwel de laagtes staan daar korter onder water. In de degradatievlakten komen afvoerloze laagten niet voor.

De 'values' van de bodemkleur in Vertisols van de centrale kleivlakte blijken niet gecorreleerd te zijn aan het percentage organische stof: er zijn geen systematische verschillen in organische-stofgehalte tussen Typic en Entic subgroups.

Vertisols met een chroma van minder dan 2 behoren, in het systeem van Soil Taxonomy, tot een 'Pellic great group'; in de centrale kleivlakte van de Soedan zijn dat Pellusterts. De meeste Pellusterts staan enkele maanden per jaar onder water. Het lage chroma lijkt te wijzen op 'aquic conditions', zoals gedefinieerd door ICOMAQ, met als kenmerken: oxidatie/reductievlekken of grijze kleur (redoximorphic features), verzadiging en reductie. Twee oorzaken voor de grijze kleur van de Pellusterts zijn denkbaar:

a. De locatie heeft, gedurende een deel van het jaar, 'aquic conditions'; de Pellic kleur is een gevolg van reductie.
b. 'Aquic conditions' kunnen niet voorkomen; de Pellic kleur wordt veroorzaakt door het ontbreken van vrij ferri-ijzer in de grond, en dat is weer een gevolg van de stabiliteit van smectiet.

Oxidatie/reductievlekken komen in de Pellusterts van de centrale kleivlakte niet voor, een uniforme grijze kleur daarentegen wel. Deze kan niet het gevolg zijn van een permanent-reductief milieu, omdat (1) Vertisols per definitie periodiek droog zijn, en (2) de grijze kleur niet verandert bij blootstellen van de grond aan de lucht. Wij zijn van mening dat de grijze kleur een gevolg is van de stabiliteit van smectiet: ferri-ijzer blijft 'opgesloten' in het kristalrooster.

De stabiliteit van smectiet wordt bevorderd door een hoge pH, hoge niveaus aan basen en silica en door een beperkte drainage. Aan deze voorwaarden wordt op de slecht-gedraineerde gedeelten van de centrale kleivlakte ruimschoots voldaan. Pellusterts komen echter ook voor op goed gedraineerde hellingen op basisch gesteente. Deze gronden hebben een hoog niveau aan basen, een hoog kleigehalte en slechte interne drainage, en onder deze omstandigheden kan smectiet eveneens stabiel zijn.

De hypothese dat een laag chroma van de bodemkleur in Vertisols het gevolg is van stabiliteit van smectiet en het daarmee gepaard gaande gebrek aan ferri-ijzer, is getest door de kleurveranderingen te noteren na het successievelijk verwijderen van organische stof, oplosbare mineralen (zouten, gips, carbonaat) en vrij ferri-ijzer. De resultaten toonden duidelijk aan dat Pellic kleuren in Vertisols veroorzaakt worden door het ontbreken van vrij ferri-ijzer.

Pedoturbatie, bodemstructuur en gilgai

Het concept van Vertisols als 'ronddraaiende gronden' is gebaseerd op het verondersteIde proces van mechanische pedoturbatie. Er zijn echter ook gevallen bekend, waaruit blijkt dat beweging in de bodem - aangetoond door de aanwezigheid van slickensides - niet noodzakelijkerwijs een omkering en vermenging van de grond ten gevolge heeft; bodembeweging zonder menging zou dus mogelijk zijn. Pedoturbatie zou o.a. kunnen worden aangetoond wanneer een oorspronkelijk heterogeen moedermateriaal thans gehomogeniseerd is. Omdat in de centrale kleivlakte het uitgangsmateriaal zeer homogeen is, kan pedoturbatie hier niet op deze wijze worden aangetoond.

Pedoturbatie zou in de centrale kleivlakte wel kunnen worden aangetoond door de uniformiteit in het profiel van die bodemeigenschappen en -kenmerken, die het gevolg zijn van post-sedimentaire bodemvormende processen: gehaltes aan organische stof die niet met de diepte afnemen, ^{14}C-dateringen die gelijk blijven in het solum en abrupt toenemen in het onderliggende substraat, en de afwezigheid van zachte carbonaat-concentraties in een kalkrijk bodemmateriaal. De duidelijkste indicatie van pedoturbatie is wellicht de aanwezigheid van zachte carbonaatconcentraties in het substraat, en het ontbreken daarvan in het solum.

Gilgai microrelief is kenmerkend voor het zuidelijke deel van de kleivlakte, met relatief hoge regenval. Gilgai is het resultaat van schuifspanning in ondergrond en substraat, maar er is geen menging van substraat en solum. Pedoturbatie is blijkbaar niet een vereiste voor het ontstaan van gilgai.

Voor zover wij weten, gaat in de meeste Vertisols van de centrale kleivlakte bodembeweging samen met bodemmenging.

Bodemclassificatie

De classificatie volgens Soil Taxonomy werd vergeleken met recente voorstellen van de International Committee on Vertisols (ICOMERT) en de International Committee on Aquic Soil Moisture Regimes (ICOMAQ). De 'suborder' Aquerts zou in het voorstel van ICOMAQ moeten voldoen aan de eis van 'aquic conditions'. We hebben eerder gezien, dat op deze wijze gedefinieerde hydromorfe omstandigheden in Vertisols niet aanwezig kunnen zijn. Aquerts zouden echter wel kunnen worden gedefiniëerd naar laag chroma van de bodemkleur in combinatie met een bepaalde periode dat het land onder water staat. In een ander taxon (op het niveau van 'suborder' of 'great group') zouden dan de Vertisols met laag chroma op goed gedraineerde locaties, moeten worden ondergebracht. Het voorstel van ICOMERT, alle Vertisols met een hoge value en/of een hoog chroma, onder te brengen in Chromic 'subgroups', houdt geen rekening met de zeer verschillende processen die van invloed zijn op value en op chroma van de kleur.

Volgens de herziene FAO-classificatie (FAO 1988) behoren nagenoeg alle Vertisols van de centrale kleivlakte tot de 'soil unit' Calcic Vertisols. De weinige die geen zachte kalkconcentraties hebben in de bovenste 125 cm, worden gerekend tot de Eutric Vertisols. In de oorspronkelijke classificatie, van 1974, werd een kleurcriterium gehanteerd (Pellic en Chromic Vertisols), vergelijkbaar met het onderscheid op 'great group' niveau in Soil Taxonomy. Dit onderscheid op kleur blijkt meer functioneel te zijn voor het karakteriseren van de gronden van de centrale kleivlakte dan het latere kalkcriterium, en het is ook meer geschikt voor het creëren van karteringseenheden voor de FAO wereldbodemkaart op een schaal 1:5 000 000.

Bodembeschrijving, bemonstering en kartering

De ervaringen opgedaan bij bodemkarteringen op diverse locaties in de centrale kleivlakte en op verschillende kaartschaal, geven aanleiding tot enkele overwegingen ten aanzien van beschrijving, kartering en bemonstering.

In bodemprofielen met doorgaans geleidelijke overgangen tussen horizonten die slechts in enkele kenmerken van elkaar verschillen, zou beschrijving en bemonstering volgens standaarddiepten moeten worden overwogen als alternatief voor beschrijving en bemonstering van (veronderstelde) pedogenetische horizonten. Een eventuele duidelijke horizontgrens in een dergelijk profiel moet echter niet worden veronachtzaamd.

In een schijnbaar gelijkvormig gebied met een spaarzame vegetatie, die bovendien - ten gevolge van een regenval die per locatie en per jaar verschilt - niet strikt plaatsgebonden is, zoals in het Khashm el Girba gebied, is een kartering volgens een raaiensysteem betrouwbaarder dan enige vorm van physiografische kartering. De grote eenvormigheid van terrein en bodems in dit gebied had nog een merkwaardige consequentie. Terwijl bij het opstellen van een legenda voor een 1:100 000 bodemkartering het probleem meestal is: hoe groepeer ik een veelheid van bodems in een beperkt aantal kaarteenheden, was het probleem in de Khashm el Girba kartering: hoe vind ik voldoende differentiërende kenmerken om een redelijke hoeveelheid kaarteenheden te creëren.

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Glossary of Arabic words[1]

badob	cracking clay soil.
dukhn	the food grain *Pennisetum typhoideum.*
dura	the great millet, *Sorghum vulgare.*
gerf	the sloping land of a river-bank or small pockets of silt land cultivated as the waters subside after the annual flood.
hafir	a pit, locally a pool usually made by man.
hariq	a type of cultivation based on firing the old stand of grasses just prior to sowing.
jebel	hill or mountain.
kerrib	strongly eroded and dissected river banks.
khor	a small seasonal stream.
lubia	the bean *Dolichos lablab.*
mahal	meaning unfertile, as distinct from 'hariq': land on which weed growth is poor because of a seed failure due to poor rains in the previous year.
maiya	basin left by the receding river, particularly in Blue Nile Province.
qoz	sand-dune.
simsim	the oil-seed crop *Sesamum orientale.*
sudd	permanent swamps of the White Nile in southern Sudan.
teras	plural: terus, a small earth bund built with hand tools for impounding rain-water for growing 'dura'.
toich	annually flooded grazing lands along the watercourses draining into the 'sudd'.

[1]Largely based on Glossary of Arabic and vernacular words in Tothill (1948b, p.941-955).

Curriculum Vitae

Wouterus Andries Blokhuis werd geboren op 13 november 1926 in Assen. Na het behalen van het einddiploma HBS-B aan de RHBS te Ter Apel in 1944, begon hij in 1945 zijn studie aan de Landbouwhogeschool met als studierichting Nederlandse bosbouw en als ingenieurs-bijvakken agrogeologie en landschapsarchitectuur. Van 1947 tot 1949 was hij in militaire dienst.

Na zijn afstuderen in 1956 werd hij docent aan het International Training Centre for Aerial Survey (ITC) in Delft. Van 1959 tot 1963 werkte hij in de Soedan als 'soil surveyor' bij het Ministry of Agriculture, Sudan Government. Van 1963 tot zijn pensionering in 1991 was hij, met een onderbreking van drie jaar, als wetenschappelijk medewerker/universitair docent verbonden aan de vakgroep Bodemkunde en Geologie van de Landbouwhogeschool/Landbouwuniversiteit, waar hij o.a. meewerkte aan een regionale planningstudie in Sarawak, aan het ontwikkelen van de studierichting Tropisch Landgebruik en aan een multidisciplinair onderzoekprogramma in Côte d'Ivoire.

Van 1975 tot 1978 was hij als Professor of Agronomy (Soils) verbonden aan Njala University College, University of Sierra Leone. Gedurende korte perioden werkte hij voor ingenieursbureaus: in Iran voor Sir Alexander Gibb & partners, en in de Soedan voor Ilaco/Nedeco.

APPENDIX 1

Laboratory methods for chemical and granulometric analyses

Soil samples

Bulk samples were taken from each described section of the profile, whether a genetic horizon, a geological layer or merely a depth section. The samples were analyzed in the laboratories of the Department of Soil Science and Geology, Agricultural University, Wageningen. Some specific determinations (radiocarbon age, identification of shells) were done elsewhere; such cases have been mentioned in the text. In a few profiles, samples of adjoining horizons (layers, depth sections) were mixed into one composite sample, for example Sennar 49, Tozi and Damazeen. Some of the samples from deeper layers were taken by soil auger; see the profile descriptions of, for example Gelhak and Seinat B50.

All samples were air-dried. Large clods were desintegrated into smaller pieces by breaking and crumbling. The samples were then sieved through a 2mm sieve. The dried, well-mixed and ground samples of fine earth (fraction < 2mm) formed the sample material for most of the chemical and mineralogical determinations. Many samples contain hard nodules of carbonate. Most of these resist breaking and crumbling and become part of the coarse fraction. Only ca-granules < 2mm and soft forms of carbonate are part of the fine earth.

For a number of analyses pre-treatment of the samples was required in order to remove soil compounds such as organic matter, carbonates, gypsum, salts and 'free' ferric iron; pre-treatments are indicated when relevant.

Analytical procedures are according to Begheijn and Van Schuylenborgh (1971), unless otherwise stated.

Particle-size distribution

The samples were pre-treated with peroxide and hydrochloric acid to remove cementing material (organic matter and carbonates). Salts were removed by suction and washing. The sand fractions (50-100, 100-250, 250-500, 500-1000 and 1000-2000 μm) were obtained by dry sieving. The fraction <50 μm was peptized in sodium pyrophosphate. The fractions <2 μm and <50 μm were determined by the pipette method.

Separation of the clay fraction for elemental analysis and X-ray diffraction

The fraction < 50μm, obtained as described above under particle-size determination, was peptized with sodium hydroxide. The fraction <2 μm was pipetted from the filtrate, coagulated with hydrochloric acid, and saturated with lithium by adding a lithium chloride solution. Excess salts were removed by dialyzing for several days, and the clay was recovered by freeze-drying.

Pre-treatment of soil samples for the determination of the mineralogical composition of the sand fractions

The samples were treated with peroxide and hydrochloric acid to remove organic matter and carbonates, and by sodium dithionite to remove free ferric iron. The fraction <50 μm was removed by wet-sieving. With the aid of bromoform (specific weight 2.89) sand fractions were separated into a heavy and a light fraction.

Elemental analysis of the fine earth

- After removal of organic matter by heating at 800 °C. for one hour, a sample of fine earth was decomposed by fusion with sodium carbonate. In the solution obtained, total Si was determined colorimetrically.
- For determination of the other elements, a sample of fine earth was digested by HF, whilst the liberated water was bound by concentrated sulphuric acid. In the solution obtained, Fe, Al, Ca, Mg, Ti, Mn and P were determined colorimetrically, Na, K and Li by flame photometer.
- For the determination of Fe(II) and Fe(III), a fine-earth sample was decomposed in a HF-H_2SO_4-mixture. After transferring the reaction mixture into a saturated boric acid solution, Fe(II) was measured colorimetrically with orthophenanthroline, and total iron was measured afterwards in the same solution upon adding a reductant ($NH_2OH.HCl$).
- Loss on ignition was determined by heating the sample to 900°C. The mass loss upon heating is accounted for by chemically-bound water, and CO_2 from organic matter and from carbonates. In Appendix 1 the loss on ignition has been indicated as %H_2O+.

Remark: The elemental analysis of fine earth and clay fractions of the four samples of profile Ulu (nr. 16) was obtained from X-ray fluorescence spectrometry (Van Reeuwijk 1992).

Elemental analysis of the clay fraction

Clay fractions, obtained following the methods described above, were analyzed in the same way as the fine earth.

'Free' Fe_2O_3, 'free' Al_2O_3 and 'amorphous' Fe_2O_3

Free Fe_2O_3 was measured in the fine earth fraction of part of the samples of which the elemental analysis was determined. In some profiles free Al_2O_3 and amorphous Fe_2O_3 were analyzed in addition. In fewer profiles these soil compounds were also determined in the clay fraction.

Free iron and aluminium compounds in the soil were extracted by a dithionite-citrate solution (Mehra and Jackson 1960). According to Stucki et al. (1988), the iron compounds dissolved by dithionite 'are primarily iron oxides of varying crystallinity', although the dithionite-extract would also contain 'the comparatively small fractions of water-soluble, exchangeable, and organically-bound Fe'.

Active (amorphous) iron was extracted by Tamm's oxalate buffer solution, containing oxalic acid and ammonium oxalate. Oxalate dissolves the amorphous and organically-bound iron (Stucki et al., 1988). Iron was determined in the extract colorimetrically with o-phenanthroline.

Four samples were tested on the possible presence of non-crystalline clay minerals, notably allophane (section 8.3.2).

Samples were treated in the same way (Van Reeuwijk 1992). The dissolved 'active' or short-range order compounds of Fe, Al and Si were determined in the extract by atomic adsorbtion spectrometry.

Cation-exchange capacity (CEC) and exchangeable sodium

A sample of fine earth was treated with Li-EDTA (0.1 M, buffered at pH 8.0). Extraction by Li-EDTA removes all adsorbed Ca and Mg from the soil solution by EDTA chelation. Na and K in non-saline soils are removed by excess Li. In saline/sodic soils replacement of Na is incomplete, but it was found (Begheijn 1978; 1980) that the Na/Li molar ratio in the extract equals that of the adsorbtion site. This permits correction for both CEC (+) and for exchangeable Na (+). In the Li-EDTA extract Cl-, CO_3^{2-} (including HCO_{3-}) and SO_4^{2-} were measured in order to correct for NaCl, $CaCO_3$, $CaSO_4$ and Na_2CO_3 dissolved during the extraction; for the calculation of exchangeable ions, it was assumed that all CO_3^{2-}, HCO_{3-} and SO_4^{2-} found were derived from $CaCO_3$ and $CaSO_4.2H_2O$, and Cl- from NaCl. The CEC was determined by flame photometric determination of Li in both the extracting solution and the extract. Extracted Na was determined by atomic emission spectrometry.

pH

The pH of the soil is measured in a 1:2.5 soil:liquid mixture by use of electrode and pH-meter. The liquid is either water (pH-H_2O) or 0.1 M $CaCl_2$ (pH-$CaCl_2$).

Organic carbon

The soil was oxidized by $K_2Cr_2O_7$ (potassium dichromate) in concentrated sulphuric acid under steady heating in 90 seconds to 175°C. Organic carbon was determined colorimetrically by measuring the colour-intensity of the green chromous ions formed during oxidation.

Carbonates according to Scheibler (Houba et al. 1985)

Hydrochloric acid is added to a soil sample to dissolve the carbonates present. The volume of CO_2 developed, is measured and compared with the volume of CO_2 developed from pure $CaCO_3$.

Gypsum (Begheijn 1980)

The sample was extracted with Na_{3-}EDTA solution (0.1 M), whereby gypsum dissolves by chelation to EDTA. $CaSO_4$ was determined turbidimetrically.

Electrical conductivity (Richards 1954, p. 89)

The electrical conductivity of a soil:water extract was measured by means of a conductivity cell and conductivity meter, in soil:water extracts in the ratio 1:1, 1:1.5 or 1:2 (cf. section 8.7.2.1).

Watersoluble anions and cations (Richards 1954, pp. 94-100)

In three profiles (Sennar 49, Jebel Abel and Tozi) the anions and cations were determined in the soil:water extract that was prepared for measuring the electrical conductivity (cf. section 8.7.2.2).

APPENDIX 2:

Soil profile descriptions, and laboratory data of soil samples

Terms for describing soils and sites

Soil profile and site descriptions are according to the FAO Guidelines for soil profile descriptions (FAO 1977). In addition we have introduced some new terms, or given existing terms a more specific meaning, in order to arrive at a more adequate description of the soils of the Central Clay Plain, notably the Vertisols.

We have added **surface** to the site characteristics. Surface characteristics in Vertisols are important to soil genesis and to land use. The features described include width of cracks, diameter of the polygons enclosed by cracks, presence of surface mulch or crust, occurrence of carbonate and other nodules, and of stones and gravel.

Next to landform, **microrelief** is given a separate caption ; a gilgai microrelief and other forms of unevenness of the soil are very common, and differ characteristically between Vertisols. A distinction has been made between **uneven** or **irregular** surfaces, that are directly related to the cracking pattern and are of the same scale, and **gilgai**, that is superimposed over the cracking pattern and is of a larger scale: the diameter of polygons enclosed by cracks is in the order of 25 to 50 cm, whereas successive mounds of a gilgai microrelief are at least 2 to 3 m, and usually 5 to 8 m, apart. The terms **wavelength** and **amplitudo** have been used to describe the horizontal and vertical dimensions, respectively, of a gilgai microrelief. The elevated parts are (gilgai) **mounds**, the lowest parts (gilgai) **depressions**. For wavy or lattice gilgai (types according to Hallsworth et al. 1955) the terms are **microridges** and **microvalleys**, respectively.

The horizon designations are those of a draft Chapter 4: Estimation and description of soils in the field, of a new edition of the Soil Survey Manual; this Manual appeared originally in 1951 (Soil Survey Staff 1951). Changes from the original edition in the coding of master horizons relevant to our study are: A now includes A and A1, but not A2 ; E has replaced A2. Transitional horizons in which the properties of one horizon merge with another, are indicated AB, BC, etc. Mixed horizons that consist of identifiable parts of two master horizons are indicated A/B, B/C, etc.

Specific kinds of master horizons are indicated by lower case letters. Relevant for descriptions of soil profiles in the Central Clay Plain are:

k : accumulation of carbonates. We have restricted the use of the suffix k to powdery forms of carbonate of which an 'in situ' formation is certain; k is not used for hard nodules as these may have been transported.
r : weathered or soft bedrock

t : accumulation of silicate clay
u : unspecified; used with A and B when these horizons are not qualified by another suffix, but need to be sub-divided, e.g. Au1, Au2.
w : development of colour or structure (only with B horizons)
y : accumulation of gypsum.
Lithologic discontinuities are indicated by Arabic numerals, preceding the master horizon designations.

In two cases we have not followed the conventions proposed in the draft Chapter:
a. It is suggested that the suffix w should not be used in addition to suffixes k and/or y. We think that all B horizons in Vertisols should carry the suffix w because structure development is their most characteristic feature. We have indicated soft lime or gypsum, if present, with an additional k and y.
b. Lower case letter suffixes should not be used with transitional horizons (draft Chapter 4). We have maintained the suffixes in transitional horizons because these horizons form an important, and sometimes even a major part of the soil profile in Vertisols, for example in Khashm el Girba 251 (nr.3): A, A/Bwk, B/Awky, B/Cwky, C/Bwky, Ck. We have refrained, however, from adding the suffixes in non-continuous transitional horizons to the code of the master horizon part in which they occur: the B/Awky horizon in the above example is, strictly speaking, a Bwky/A horizon, whereas the B/2Cwky should be written as Bwky/2Cky. Such details can, if required, be taken from the profile descriptions.

For different depth zones in the profile the terms **surface soil, subsoil** and **substratum** have been used. The surface soil is the A horizon, in which the vertic structure is usually weakly developed; the subsoil is the Bw horizon with strongest development of the vertic structure; the substratum is the C horizon, below the depth of cracking or below the depth of pedoturbation. In the northern, lower-rainfall region of the clay plain, the Bw horizon (or subsoil) may in fact be the substratum, being below the zone of present-day pedoturbation.

In the description of **soil structure** the following terms are used in addition to those suggested in the FAO Guidelines:
- the typical flattened angular blocky peds of Vertisols are described as **wedge-shaped peds, tilted wedges** or **parallelepipeds.** Only the latter term denotes a size class: parallelepipeds are the finest wedge-shaped peds, usually with dimensions not exceeding 10 mm.
- **lamination** of a profile wall: the appearance of the wall of a soil pit when wedge-shaped peds protrude obliquely from the face of the profile. Often this lamination is distinct even when the soil structure is so weakly developed that individual peds cannot be dislodged from the soil. Lamination indicates a predisposition for a structure that is expected to develop upon further drying, or upon repeated wetting and drying.

- the type of structure is indicated in the most general way as **vertic**, and as **bicuneate** or **parallelepiped** when reference is made to the specific shape (and size) of peds.
- **shiny ped faces** or **ped surfaces** refer to glossy surfaces of fine wedge-shaped peds; **slickensided ped surfaces** to larger peds (2 to 5 cm) that have polished and striated surfaces. **Slickensides** are polished and grooved surfaces larger than about 5 cm, and - more specifically - surfaces that are continuous over adjoining peds.

The above terms are somewhat loosely applied. As they were used during successive periods of field work, they have not always been given precisely the same meaning. We have adhered to the original field descriptions as much as possible.

The large prism-like blocks between cracks are not described as prismatic soil aggregates. There are two reasons for this : firstly, this feature is so obvious in any cracked soil, that description seems superfluous when crack width, diameter of crack-enclosed polygons, and depth of cracking are recorded; secondly, soil blocks between cracks are not considered as structural elements in the draft of the new Soil Survey Manual, because cracks would normally not reappear at the same spot every year.

Carbonate concentrations have been described using the following terms:
- **ca-granules** are hard, discrete and usually rounded, and 1 to 3 mm in diameter.
- **ca-nodules** have the same shape as granules, but are up to 2 cm in diameter, and occasionally larger.
- **ca-specks** are tiny accumulations of soft powdery lime, with a few mm's diameter; they may form vertical streaks that are related to biopores.
- **aggregates of soft powdery lime** are much larger than ca-specks; white ca-nodules and -granules may be contained inside the aggregates.

The occurrence of ca-specks or of aggregates of soft powdery lime is shown by the suffix k to the master horizon symbol. The colours of ca-granules and -nodules are described as white, yellowish, dark-grey, reddish,etc., without strictly adhering to the Munsell codes. The term concretion has not been used: a concentric fabric can be observed in a cross-section under the microscope, not in the field.

Red mottles, and coatings on ped surfaces are considered to be **ferric** (or **ferruginous**); blue-black mottles and coatings are described as **manganiferous, (iron-)manganese** or **iron-manganese** mottles and coatings. In many cases these concentrations contain ferric iron in addition to manganese; this is not shown in the field, but sometimes both components can be identified in thin sections. Manganese oxides have a strong pigmenting effect and tend to obscure any ferric oxides present.

There are some inconsistencies in the profile descriptions:

- The surface mulch is usually described under 'surface', but in a few profiles the mulch is described (and sampled) as the first soil horizon.
- Cracks are sometimes described in the horizons in which they occur, but more often the depth of cracking (and some indication on the width of cracks) is given under 'remarks'. The width on the soil surface and the dimensions of the cracking pattern are described under 'surface'.

Soil classification is according to the latest amendment, dated 1990, of Soil Taxonomy (Soil Survey Staff 1990) and to both versions of the FAO/Unesco system, of 1974 and 1988, respectively.

KHASHM EL GIRBA 213 (1)

date of description :	13 and 23/10/1961
USDA Soil Taxonomy :	Typic Chromustert, very-fine, montmorillonitic, isohyperthermic
FAO/UNESCO :	Chromic Vertisol (1974); Calcic Vertisol (1988)
location :	Khashm el Girba Irrigation Scheme; topo map 1:250,000, sheet 55-D; 15°06'N - 35°43'E.
elevation :	464 m
landform :	alluvial plain of the river Atbara
soil sope class :	flat
microrelief :	none, but surface is uneven
surface :	A thin, brittle surface crust overlies a 3 cm thick, well-developed, fine and medium granular mulch. Wide cracks are developing, but otherwise the cracking pattern is obscured by the thick mulch.
parent material :	fine-textured alluvium of the Atbara
vegetation or land use :	open grass plain with dense and tall *Cymbopogon nervatus*, with scattered, relatively tall bushes of *Acacia mellifera*; many of the *Acacia* are dying.

Profile description :

0-40 cm A	clay; dry; 10YR 3/4; 4/3,d; hard; moderate subangular blocky, peds are 1-2 cm in diameter with horizontal dimensions slightly larger than the vertical; there is a substrucuture, showing a generally faint, sometimes distinct, very fine subhorizontal lamination, defining 2-5 mm thick parallelepiped peds, that can not be removed from the profile wall; many grey ca-nodules; shell fragments; many fine roots; gradual, smooth boundary.
40-70 cm A/Bwkl	clay; almost dry; 10YR 3/4; 4/3,d, with few intrusions of darker-coloured soil; hard; structure as in surface horizon; soil more compact than surface horizon as cracks are narrower and fine roots fewer; many grey ca-nodules; ca-specks in the intrusions of darker-coloured soil; shell fragments; gradual, smooth boundary.
70-90 cm A/Bwk2	clay; almost dry; 10YR 3/4; 4/3,d, with many intrusions of darker-coloured soil; hard; weak subangular blocky, with peds 1-3 cm in diameter; shape of peds and nature of substructure as in overlying horizons; many grey ca-nodules; white ca-specks, 1-2 mm high, 1 mm diameter; few fine and medium roots; clear, smooth boundary.
90-130 cm B/Awk	clay; slightly moist; equal amounts of 10YR 3/4 surface soil and 10YR 3/2 subsoil, forming a network of tongues and intrusions; a pocket of reddish soil; hard to firm; weak subangular blocky with peds 1-3 cm in diameter, with sometimes horizontal dimensions slightly larger than the vertical one; horizontal lamination generally faint, not causing a parallelepiped substructure; grey ca-nodules; few clusters of fine gypsum crystals; shell fragments; few medium roots; gradual, smooth boundary.
130-155 cm B/2Cwky	clay; slightly moist; 10YR 3/2, moist and dry, with few tongues of 10 YR 3/4 surface soil, and vertical streaks and pockets of reddish soil; hard to firm; very weak subangular blocky, with peds 2-5 cm in diameter; peds have shiny faces; horizontal lamination faint; grey ca-nodules; soft powdery lime in aggregates 3 cm horizontally and 1 cm vertically, containing hard, white ca-granules; common clusters of fine and medium gypsum crystals; few fine roots; diffuse, smooth boundary.

155-175 cm 2C/Bwky	clay; moist; equal amounts of 10YR 3/2 subsoil and 5YR 3/3 substratum, with some pockets of more reddish soil; friable when moist, very hard when dry; weak structure, with slickensided ped surfaces; a weakly developed parallelepiped substructure appears as a weak lamination; soft powdery lime in aggregates 1 cm horizontally and 2 cm high; common coarse lense-shaped, yellowish-white gypsum crystals; abrupt, smooth boundary.
175-200 cm 2Cky1	clay; slightly moist; 5YR 3/3 with few pockets of 10YR 3/2 subsoil; hard to firm; weak structure as in 155-175 cm; common grey ca-granules; aggregates of soft powdery lime; large clusters of coarse lense-shaped gypsum crystals, abruptly abundant at 175 cm, with depth decreasing to common, medium clusters of small crystals; many dark metallic bluish manganese coatings; a remnant of a root; gradual, smooth boundary.
200-240 cm 2Cky2	clay; slightly moist; 5YR 3/3; firm when moist, very hard when dry; moderate angular blocky with shiny, slickensided ped surfaces and a parallelepiped substructure, with peds 5 to 10 mm or finer; many grey ca-granules, leaving a metallic bluish coating when removed from the soil; soft powdery lime as aggregates 1 cm horizontally, and 2-3 cm high, containing fine, white ca-nodules; small clusters of medium and small, lense-shaped gypsum crystals; few fine roots; termite activity; clear, smooth boundary.
240-300 cm+ 2Ck	clay; moist; 7.5YR 4/4; firm when moist, very hard when dry; compound moderate columnar (peds 5-10 cm high) and moderate angular blocky (peds 0.5-1 cm in diameter); abundant more or less horizontal slickensides, and slickensided ped surfaces; many grey ca-granules, leaving a metallic bluish coating when removed from the soil (as in overlying horizon, but coatings more distinct); aggregates of soft powdery lime containing white and grey ca-granules; few large (1 cm diameter, 2-3 cm long), irregularly shaped, extremely hard ca-nodules; some pockets of fine sand with ca-pseudomycelium and many fine pores; distinct termite activity.

Remarks :

1. Open cracks are distinct from 0 to 70 cm, and they can be traced till 200 cm depth.
2. Pockets of reddish soil in 90-175 cm may be burnt surface soil (from grass fire) fallen into a crack, or an intrusion from the substratum.
3. Grey nodules in 130-155 cm are not distinct as they have approximately the same colour as the soil matrix.
4. In 90-130 cm there is no description of ca-specks or soft powdery lime. This is probably an omission in the field notes. Ca-specks are most likely to be present, and therefore the suffix k has been added to the horizon symbol.
5. Shell fragments are found till 130 cm depth.
6. Roots are found till 240 cm depth.
7. Termite activity is present throughout the profile till 3 m depth. Termite nests are only found below 175 cm and these are either loosely filled with organic debris, or they appear as clay balls, 5-10 cm in diameter. The latter are built from fine soil crumbs, cemented together.

Summary profile description :

A deep clay profile (description till 300 cm) consisting of a 10YR 3/4 surface soil, tonguing (between 70 and 130 cm) into a 10YR 3/2 subsoil, that forms a transitional horizon (between 130 and 175 cm) to a 5YR 3/3 substratum - below 240 cm 7.5YR 4/4 substratum - that merges into a fine sandy soil at about 300 cm. Hard grey ca-granules and -nodules occur throughout. Fine ca-specks appear at 40 cm depth, below 130 cm they give way to aggregates of soft powdery lime with hard ca-nodules. Clusters of gypsum crystals are found between 130 and 240 cm depth. Fine metallic-bluish coatings of manganese are found below 175 cm, especially surrounding ca-granules. Termite activity occurs throughout, but notably below 175 and 300 cm, or deeper.

Laboratory data of profile 1, Khashm el Girba 213

horizon nr., depth (cm)	particle size distribution, µm; % of fine earth								pH		$CaCO_3$ %	org. carbon %
	sand						silt	clay				
	2000-1000	1000-500	500-250	250-100	100-50	total	50-2	<2	H_2O	0.01M $CaCl_2$		
1 0-40	2.9	0.5	0.2	3.7	3.5	10.8	27.7	61.5	7.8	7.1	7.8	0.4
2 40-70	3.1	0.9	0.2	3.6	2.8	10.6	27.3	62.1	7.8	7.4	7.9	0.4
3 70-90	6.1	0.1	0.2	2.6	2.8	12.8	24.7	62.5	8.0	7.6	8.6	0.4
4 90-130	2.2	0.3	0.1	2.0	2.6	7.2	24.8	68.0	7.7	7.4	8.7	0.5
5 130-155	1.0	0.1	0.1	1.7	3.0	5.9	27.4	66.8	7.8	7.5	6.0	0.3
6 155-175	1.0	0.3	0.1	1.7	2.9	6.0	29.9	61.1	8.0	7.6	9.3	0.3
7 175-200						5.4	30.8	63.8	7.8	7.5	8.8	0.2
8 200-240						6.1	40.5	53.4	8.2	7.6	13.7	0.1
9 240-300	1.2	0.5	0.1	0.7	4.3	6.8	37.0	56.3	8.1	7.7	8.9	0.1

horizon nr., depth (cm)	exchangeable Na		CEC % mmol/kg	$CaSO_4$ %	water-soluble Na mmol/kg	EC mS/cm	extract for EC determination g/ml
	mmol/kg	%					
1 0-40	76	18.2	417		8	0.7	1:1
2 40-70	99	21.6	459		12	1.0	1:1
3 70-90	106	22.9	462		18	1.6	1:1
4 90-130	117	23.7	494	0.5	42	2.6	1:1.5
5 130-155	122	24.8	492				
6 155-175	106	24.2	438				
7 175-200	115	34.0	338	0.8	57	3.8	1:1.5
8 200-240	94	32.8	287	0.9			
9 240-300	90	27.5	327		27	1.6	1:1.5

horizon nr., depth (cm)	elemental composition of the fine earth (% by weight)												
	SiO_2	Fe_2O_3	Al_2O_3	TiO_2	MnO	CaO	MgO	Na_2O	K_2O	FeO	P_2O_5	SO_3	H_2O+
1 0-40	51.1	10.5	14.3	1.5	0.1	6.9	4.1	1.3	0.8	0.2	0.2		9.8
2 40-70	50.4	10.5	14.8	1.5	0.1	5.5	4.2	1.4	0.9	0.3	0.2		10.1
3 70-90	50.7	10.3	14.3	1.5	0.1	6.9	4.1	1.3	0.9	0.2	0.2		9.9
4 90-130	49.9	9.9	14.6	1.4	0.1	6.2	4.1	1.3	1.1	0.4	0.2		9.8
5 130-155	51.1	10.3	15.0	1.5	0.1	4.4	4.0	1.5	1.0	0.4	0.2		8.8
6 155-175	50.4	9.7	14.2	1.4	0.1	6.0	4.0	1.4	1.0	0.3	0.2		9.5
7 175-200	47.5	9.8	14.4	1.3	0.1	7.7	3.4	1.5	1.0	0.2	0.2		9.8
8 200-240	46.2	9.2	13.8	1.3	0.2	10.2	3.3	1.5	1.0	0.2	0.2		11.9
9 240-300	50.6	7.7	15.2	1.4	0.2	5.9	0.9	1.5	1.2	0.6	0.2		9.6

horizon nr., depth (cm)				molar ratios			
	free Fe_2O_3	free Al_2O_3	amorphous Fe_2O_3	SiO_2/R_2O_3	SiO_2/Al_2O_3	SiO_2/Fe_2O_3	Al_2O_3/Fe_2O_3
1 0-40	3.7	1.7		4.2	6.1	13.2	2.2
2 40-70	3.6	1.7		4.0	5.8	12.8	2.2
3 70-90	3.6	1.7		4.1	6.0	13.3	2.2
4 90-130	3.8	1.8		4.0	5.8	12.9	2.2
5 130-155	3.5	1.4		4.0	5.8	12.8	2.2
6 155-175	3.5	1.4		4.1	6.0	13.2	2.2
7 175-200	5.0	2.7		3.9	5.6	13.1	2.3
8 200-240	4.8	2.7		4.0	5.7	13.6	2.4
9 240-300		2.3		4.0	5.7	14.1	2.5

horizon nr., depth (cm)	elemental composition of the clay fraction (% by weight)												
	SiO_2	Fe_2O_3	Al_2O_3	TiO_2	MnO	CaO	MgO	Na_2O	K_2O	FeO	P_2O_5	SO_3	H_2O+
7 175-200	50.6	12.8	17.6	1.1	0.1	0.9	3.0	2.8	1.1	0.5			11.5
8 200-240	52.1	13.0	17.1	1.1	0.1	0.4	3.1	1.2	tr	0.5			9.3

horizon nr., depth (cm)				molar ratios			
	free Fe_2O_3	free Al_2O_3	amorphous Fe_2O_3	SiO_2/R_2O_3	SiO_2/Al_2O_3	SiO_2/Fe_2O_3	Al_2O_3/Fe_2O_3
7 175-200				3.3	4.9	10.5	2.2
8 200-240				3.5	4.9	10.7	2.1

KHASHM EL GIRBA 215 (2)

date of description :	22/10/1961
USDA Soil Taxonomy :	Typic Chromustert, very-fine, montmorillonitic, isohyperthermic
FAO/UNESCO :	Chromic Vertisol (1974); Calcic Vertisol (1988)
location :	Khashm el Girba Irrigation Scheme; topo map 1:250,000, sheet 55-D; 15°08'N - 35°42'E.
elevation :	462 m
landform :	alluvial plain of the river Atbara
soil slope class :	flat
microrelief :	none, but surface is uneven
surface :	A thin, brittle surface crust overlies a 2 cm thick, well-developed fine and medium granular mulch. Cracks are developing; widest cracks are 3 cm wide at the surface, and there are many fine surface cracks. Polygons between large cracks are 30-50 cm across. Mulch sloughing down into cracks, partly obscuring these at the surface. Many grey ca-nodules. Slightly uneven topography.
parent material :	fine-textured alluvium of the Atbara
vegetation or land use :	open treeless grass plain, with mainly *Cymbopogon nervatus*, 150 cm high.

Profile description :

0-35 cm Au1	clay; dry; 10YR 3/4; 3.5/3,d; moderate fine and medium subangular blocky, with a faint horizontal lamination, indicating a predisposition for a parallelepiped substructure; many grey ca-nodules; wide cracks with dead grass fragments and seeds; many fine roots; gradual, smooth boundary.
35-55 cm Au2	clay; slightly moist; 10YR 3/4; 3.5/3,d; slightly hard to firm; structure as above but slightly weaker; many grey ca-nodules; cracks as in overlying horizon, but narrower; many fine roots; gradual, smooth boundary.
55-85 cm A/Bwk	clay; moist; heterogeneous soil with 10YR 3/4 surface soil and 10YR 2/2 subsoil, forming a network of tongues and intrusions; friable; moderate very fine and fine subangular blocky; peds are sub-horizontally arranged parallelepipeds with shiny faces; 10YR 2/2 soil contains white ca-specks; many grey ca-nodules; many fine roots; termite activity; gradual, smooth boundary.
85-120 cm B/Awk	clay; moist; heterogeneous soil as in overlying horizon; firm.
120-140 cm B/2Cwk	clay; moist; heterogeneous soil due to admixture of underlying fine sandy clay; firm.
85-140 cm	heterogeneous and ill-defined horizons; the upper part contains 10YR 3/4 surface and 10YR 2/2 subsoil, the lower part 10YR 2/2 subsoil and underlying fine sandy clay; soil structure and parallelepipeds as in 55-85 cm, but weaker; ca-granules; grey ca-nodules fewer and smaller than in 55-85 cm; fine roots and rootrests; termite activity; gradual, smooth boundary.

140-170 cm	fine sandy clay; slightly moist; very hard.
170-190 cm	clay loam; slightly moist; very hard.
190-220 cm	loamy fine sand; slightly moist; very hard.
220-245 cm	heterogeneous, varying from loamy fine sand (slightly hard) to clay (very hard).
140-245 cm 2Ck1	stratified alluvium with abrupt changes in texture; sandy strata show the original fine bedding, clayey strata show an angular blocky structure; sandwiched between clay strata are very thin bands of greyish sand (Munsell N5), appearing as a sandy coating on the clay; clayey parts have colours in hue 7.5YR, the average colour of the soil is 10YR 4/3; 5.5/3,d; ca-pseudomycelium cements parts of the soil; grey ca-granules, single or in nests, leaving a metallic-bluish manganese coating (Munsell N5) when removed from the soil; these coatings occur especially on the clayey parts of the soil; many fine pores; termite nests containing massive clay balls, 10 to 15 cm across; crickets found at 200 cm; gradual, smooth boundary.
245-265 cm 2Ck2	clay, with some admixture of loamy sand: heterogeneous soil, with inclusions both from above and below; dry; 10YR 3/3; 4/3,d; hard; strong fine angular blocky; more reddish hue than overlying soil (140-245 cm) and more compact.
265-300 cm+ 2Ck3	as 140-245 cm; consistence varies from soft (sand) to very hard (clay).

Remarks:
1. Cracks can be traced till 180 cm, and are connected with fissures that reach to at least 300 cm.
2. There is no gypsum in this profile.

Summary profile description:
A deep clay profile overlying a stratified sediment with textural variations from fine sand to clay as from 140 cm; the textural variations have been described till 300 cm. The clay profile shows a 10YR 3/4 surface soil, tonguing into a 10YR 2/2 subsoil, that, in turn, merges with a 7.5YR clayey substratum at 120 cm. Vertic structure moderately developed in the clay profile. Grey ca-nodules occur throughout in 0-120 cm, whereas ca-specks are restricted to the 10YR 2/2 subsoil; ca-pseudomycelium and manganese coatings on clay surfaces, especially at the sites of ca-granules and fine nodules; termite activity is found till 245 cm depth.

Laboratory data of profile 2, Khashm el Girba 215

horizon nr., depth (cm)	particle size distribution, µm; % of fine earth								pH		$CaCO_3$ %	org. carbon %
	sand						silt	clay				
	2000-1000	1000-500	500-250	250-100	100-50	total	50-2	<2	H_2O	0.01M $CaCl_2$		
1 0-35						6.3	35.2	58.5	8.2	7.3	3.5	0.4
2 35-55						5.2	31.4	63.4	8.2	7.4	4.4	0.4
3 55-85						4.4	30.8	64.8	8.0	7.4	6.9	0.5
6 140-170						6.6	47.6	45.8	8.1	7.5	17.0	0.2

horizon nr., depth (cm)	exchangeable Na		CEC % mmol/kg	$CaSO_4$ %	water-soluble Na mmol/kg	EC mS/cm	extract for EC determination g/ml
	mmol/kg	%					
1 0-35	59	12.1	489		6	0.5	1:1
2 35-55	83	16.5	503		8	0.7	1:1
3 55-85	110	21.4	513		26	2.4	1:1
6 140-170	80	28.9	288		18	1.7	1:1

horizon nr., depth (cm)	elemental composition of the fine earth (% by weight)												
	SiO_2	Fe_2O_3	Al_2O_3	TiO_2	MnO	CaO	MgO	Na_2O	K_2O	FeO	P_2O_5	SO_3	H_2O+
1 0-35	52.3	10.2	14.9	1.5	0.1	5.0	3.8	1.5	1.1	0.6	0.2		9.0
2 35-55	53.2	10.3	15.1	1.6	0.1	5.1	4.0	1.5	1.1	0.7	0.2		9.3
3 55-85	50.7	10.2	14.5	1.6	0.1	6.5	4.0	1.6	1.1	0.6	0.2		10.1
6 140-170	44.6	9.0	13.5	1.5	0.1	11.1	3.7	1.8	1.0	0.6	0.2		13.2

horizon nr., depth (cm)				molar ratios			
	free Fe_2O_3	free Al_2O_3	amorphous Fe_2O_3	SiO_2/R_2O_3	SiO_2/Al_2O_3	SiO_2/Fe_2O_3	Al_2O_3/Fe_2O_3
1 0-35	5.0	2.8	0.2	4.1	6.0	13.8	2.2
2 35-55	4.8	2.7	0.2	4.2	6.0	13.9	2.3
3 55-85	4.8	3.0	0.2	4.1	6.0	13.4	2.2
6 140-170	4.7	1.7	0.1	3.9	5.6	13.4	2.3

horizon nr., depth (cm)	elemental composition of the clay fraction (% by weight)												
	SiO_2	Fe_2O_3	Al_2O_3	TiO_2	MnO	CaO	MgO	Na_2O	K_2O	FeO	P_2O_5	SO_3	H_2O+
2 35-55	52.8	12.0	18.5	1.4	0.1		3.4	0.4	1.0	tr	0.2		11.1
6 140-170	50.6	13.3	17.8	1.5	0.1		2.6	0.3	1.0	tr	0.3		10.2

horizon nr., depth (cm)				molar ratios			
	free Fe_2O_3	free Al_2O_3	amorphous Fe_2O_3	SiO_2/R_2O_3	SiO_2/Al_2O_3	SiO_2/Fe_2O_3	Al_2O_3/Fe_2O_3
2 35-55				3.4	4.9	12	2.4
6 140-170				3.3	4.8	10	2.1

KHASHM EL GIRBA 251 (3)

date of description :	21/10/1961
USDA Soil Taxonomy :	Typic Chromustert, very-fine, montmorillonitic, isohyperthermic
FAO/UNESCO :	Chromic Vertisol (1974); Calcic Vertisol (1988)
location :	some km's west of the Khashm el Girba Irrigation Scheme; topo map 1:250,000, sheet 55-D; 15°15'N - 15°30'E
elevation :	460 m
landform :	very gently undulating pediplain of the Butana
soil slope class :	flat
microrelief :	none, but there is a gilgai-like patchiness (see below)
surface :	patches with fine surface cracks only, and not exceeding one square meter, alternate with patches of the same size that have moderately wide cracks. The surface is a brittle flaky crust, overlying a fine granular mulch of 2 cm thick, that easily sloughs into the wider cracks.
parent material :	colluvio/alluvial clay, derived from weathering of local Basement Complex rock (the upper sediment may consist of, or has an admixture of, alluvial clay from the Atbara)
vegetation or land use :	open treeless grass plain with the short grass *Setaria* spec. dominant; the grass tussocks are concentrated on the patches where cracking is most distinct.

Profile description :

0-30 cm A	clay; dry; 10YR 3.5/2, moist and dry; hard; moderate medium subangular blocky with a weak parallelepiped substructure with 1-2 mm thick peds; many grey ca-nodules; few shell fragments; few fine roots; gradual, smooth boundary.
30-65 cm A/Bwk1	clay; dry; 10YR 3.5/2, moist and dry, with some intrusions of 10YR 2/1 subsoil; hard; soil structure as above; ca-specks, vertically arranged in the 10YR 2/1 soil; many grey ca-nodules; few shell fragments; few fine roots; gradual, smooth boundary.
65-115 cm B/Awky1	clay; moist; equal amounts of 10YR 3.5/2 (moist and dry) surface soil and 10YR 2/1 subsoil, forming a network of tongues and intrusions; friable; structure as above, but weaker, with less interpedal pore space; ca-specks and aggregates of soft powdery lime in 10YR 2/1 soil; many grey ca-nodules, smaller than in overlying horizons; few shell fragments; few fine living and decaying roots; clear, smooth boundary.
115-140 cm B/Awky2	clay; moist; 10YR 2/1 with some tonguing of 10YR 23.5/2 (moist and dry) surface soil; friable; structure as above, but weak, and the parallelepiped substructure has not sufficiently developed to allow parting of the finest peds; subangular blocky peds have shiny faces; few fine aggregates of soft powdery lime; many fine grey ca-nodules; few nests of fine gypsum crystals; few medium roots; clear, smooth boundary.
140-175 cm B/Cwky	clay; moist; transitional horizon with upper part 10YR 2/1, and lower part 10YR-2.5Y 4/2, with a tonguing transition between the two; firm; angular blocky, with slickensided ped surfaces; a fine lamination, often parallel to the slickensides, indicates a predisposition for a parallelepiped substructure; common aggregates of soft powdery lime; common white ca-granules; grey ca-nodules; abundant coarse crystals of gypsum, decreasing with depth to common; weak coatings of manganese; gradual, smooth boundary.

175-205 cm C/Bwky	clay; moist; 10YR-2.5Y 4/2 dominant, with some tonguing of 10YR 2/1; friable; very weak medium subangular blocky, and a very weakly developed lamination; slickensided ped surfaces and larger slickensides; some of the voids between adjacent large slickensides are filled with finely stratified soil; common aggregates of soft powdery lime; grey ca-nodules and non-cemented fine clayey nodules with a similar appearance; distinct manganese coatings; common coarse lens-shaped gypsum crystals; pockets of reddish soil; clear, smooth boundary.
205-235 cm Ck1	clay; moist; 10YR-2.5Y 4/2; friable; moderate fine subangular blocky; slickensides; finely stratified soil infills the void between opposite slickensides; common aggregates of soft powdery lime and white ca-granules, increasing with depth to abundant; grey ca-granules; compact fine clayey nodules as in overlying horizon; distinct manganese coatings and ferric mottles; pockets of reddish soil; few fine roots; clear, smooth boundary.
235-310 cm Ck2	clay; moist; colour heterogeneous due to the abundance of various forms of ca-concentrations, manganese coatings and ferric mottles; friable; structureless, but because of the abundant ca-aggregates, -nodules and -granules, the soil falls apart easily into fragments; aggregates of soft powdery lime and white ca-granules occupy about 50% of the soil mass; some of the ca-aggregates contain fine grey ca-granules; grey ca-nodules; compact fine clayey nodules; gradual, smooth boundary.
310-350 cm+ Ck3	clay; moist; 10YR 4/3, but heterogeneous in colour due to the presence of many 5YR 4/4 ferric mottles, ca-concentrations and manganese coatings; firm; structureless but well-fragmented soil as in 235-310 cm; slickensides and shiny ped faces; ca-concentrations as in overlying horizon; compact fine clayey nodules.

Remarks :

1. Cracks are distinct till a depth of about 65 cm.
2. Termite activity found throughout the 350 cm profile.
3. The compact fine clayey nodules that are present below 175 cm, appear in the 310-350 cm horizon as impregnated throughout by Fe and Mn. This morphology suggests that the ubiquitous grey ca-nodules are fine clayey nodules hardened by impregnation of carbonate, iron and manganese.
4. The pockets of reddish soil in 175-235 cm are distinct from ferric mottles in colour.

Summary profile description :

A deep clay profile with a 10YR 3.5/2 surface soil (A), tonguing into a 10YR 2/1 subsoil (A/B and B/A), that in turn is tonguing into a 10YR - 2.5Y 4/2 substratum (C), that is reached at a depth of 205 cm. The lower part of the B-horizon (B/A) has fine gypsum, the transition to the substratum (B/C and C/B) has abundant coarse lens-shaped gypsum. Grey ca-nodules are present throughout the profile. The substratum has abundant ca-concentrations in both hard and soft forms, and impregnations with iron and manganese are frequent, also in soft fine clayey nodules; in addition there are iron and manganese mottles and coatings which give the soil a hydromorphic appearance.

Laboratory data of profile 3, Khashm el Girba 251

horizon nr., depth (cm)	particle size distribution, µm; % of fine earth								pH		$CaCO_3$ %	org. carbon %
	sand						silt	clay				
	2000-1000	1000-500	500-250	250-100	100-50	total	50-2	<2	H_2O	0.01M $CaCl_2$		
1 0-30						6.4	26.4	67.2	8.3	7.7	6.4	0.4
2 30-65						5.7	26.4	67.9	8.3	7.8	7.4	0.5
3 65-115						5.4	25.4	69.2	8.1	7.7	5.6	0.5
4 115-140						4.5	23.5	71.9	8.0	7.7	6.3	0.5
5 140-175						4.8	23.7	71.5	7.5	7.4	6.7	0.3
6 175-205						5.3	23.0	71.7	7.8	7.6	6.4	0.3
7 205-235						4.7	20.7	74.6	8.2	7.6	13.8	0.1
9 310-350						3.7	23.7	72.6	8.0	7.5		tr

horizon nr., depth (cm)	exchangeable Na		CEC % mmol/kg	$CaSO_4$ %	water-soluble Na mmol/kg	EC mS/cm	extract for EC determination g/ml
	mmol/kg	%					
1 0-30	81	15.2	532		8	0.7	1:1
2 30-65	106	19.4	545		13	1.3	1:1
3 65-115	142	24.9	570		21	1.9	1:1
4 115-140	153	26.3	581		39	2.4	1:1.5
5 140-175	158	28.4	557		79	4.9	1:1.5
6 175-205	155	26.9	576	10.6			
7 205-235	154	39.2	393	0.6			
9 310-350	174	28.5	610		41	2.4	1:1.5

horizon nr., depth (cm)	elemental composition of the fine earth (% by weight)												
	SiO_2	Fe_2O_3	Al_2O_3	TiO_2	MnO	CaO	MgO	Na_2O	K_2O	FeO	P_2O_5	SO_3	H_2O+
1 0-30	52.3	8.8	15.7	1.5	0.2	5.3	3.7	1.2	0.8	0.4	0.1		9.6
2 30-65	50.1	8.8	15.5	1.5	0.2	6.0	3.8	1.3	0.7	0.4	0.2		10.0
3 65-115	51.1	8.8	15.7	1.5	0.1	4.7	3.8	1.3	0.7	0.4	0.2		9.4
4 115-140	50.8	9.1	16.2	1.5	0.1	4.9	3.8	1.3	0.7	0.4	0.2	tr	9.6
5 140-175	45.1	8.1	14.3	1.3	0.1	9.6	3.3	1.2	0.6	0.3	0.1	4.9	8.9
6 175-205	52.0	9.1	16.1	1.5	0.1	5.3	3.6	1.3	0.7	0.4	0.1	0.5	9.3
7 205-235	48.1	8.8	14.6	1.3	0.1	8.0	3.0	1.0	0.6	0.2	0.1		11.8
9 310-350	54.7	10.0	16.3	1.5	0.2	1.6	3.3	1.1	0.7	0.1	0.1		7.0

horizon nr., depth (cm)				molar ratios			
	free Fe_2O_3	free Al_2O_3	amorphous Fe_2O_3	SiO_2/ R_2O_3	SiO_2/ Al_2O_3	SiO_2/ Fe_2O_3	Al_2O_3/ Fe_2O_3
1 0-30	4.8			4.1	5.7	15.1	2.7
2 30-65	4.6			4.0	5.5	14.5	2.7
3 65-115	4.9			4.0	5.5	14.9	2.7
4 115-140	4.7			3.9	5.3	14.2	2.7
5 140-175	4.2			3.9	5.4	14.2	2.6
6 175-205	4.6			4.0	5.5	14.6	2.7
7 205-235	3.4			4.0	5.6	14.3	2.6
9 310-350	4.1			4.1	5.7	14.4	2.5

horizon nr., depth (cm)	elemental composition of the clay fraction (% by weight)												
	SiO_2	Fe_2O_3	Al_2O_3	TiO_2	MnO	CaO	MgO	Na_2O	K_2O	FeO	P_2O_5	SO_3	H_2O+
2 30-65	50.5	12.5	18.5	1.3	0.1		3.0	0.3	0.7	0.4	0.2		11.1
4 115-140	48.5	12.6	18.7	1.3	0.1		2.9	0.3	0.7	0.3	0.2		11.1
9 310-350	51.0	10.8	19.4	1.2	0.1	tr	3.0	0.3	0.7	0.5	0.2		9.8

horizon nr., depth (cm)				molar ratios			
	free Fe_2O_3	free Al_2O_3	amorphous Fe_2O_3	SiO_2/ R_2O_3	SiO_2/ Al_2O_3	SiO_2/ Fe_2O_3	Al_2O_3/ Fe_2O_3
2 30-65				3.2	4.6	10.5	2.3
4 115-140				3.1	4.4	10.1	2.3
9 310-350	5.3			3.3	4.5	12.8	2.8

KHASHM EL GIRBA 238 (4)

date of description :	18 and 22/10/1961
USDA Soil Taxonomy :	Typic Chromustert, very-fine, montmorillonitic, isohyperthermic
FAO/UNESCO :	Chromic Vertisol (1974); Calcic Vertisol (1988)
location :	Khashm el Girba Irrigation Scheme; topo map 1:250,000, sheet 55-D; 15°09'N - 35°40'E.
elevation :	461 m
landform :	alluvial plain of the river Atbara. The profile is situated in a relatively low-lying strip of land with numerous small, intermittent drainage gullies ('khors').
soil slope class :	flat
microrelief and surface :	gilgai-like: mounds with moderately wide cracks and tufts of 'ankoog' grass, and an interconnected network of depressions, sometimes acting as, or connected with, small drainage gullies; the depressions are devoid of vegetation and have wide cracks, up to 5 cm across. Wavelength around 150 cm, amplitudo 10 cm. In the beds of the 'khors' the soil has a hard surface crust,tied to the underlying soil; cracks are sharp-edged, and there is no surface mulch.
parent material :	fine-textured alluvium of river Atbara
vegetation or land use :	tall grass 'ankoog' dominant; other grasses include *Setaria* ssp. and *Cymbopogon nervatus.*

Profile description (soil structure is described separately below) :

0-30 cm Au1	clay; 0-5 cm moist, very friable; 5-30 cm wet, very sticky and very plastic; 10YR 3/4; 4/2,d; grey ca-nodules; many shell fragments; fine roots; clear,smooth boundary.
30-60 cm Au2	clay; wet; 10YR 3/4; very sticky and very plastic; Au2differs from in the grade of structure; grey ca-nodules; many shell fragments; fine roots; gradual, smooth boundary.
60-100 cm Ak	clay; moist; 10YR 3/4; firm; very few ca-specks; many shell fragments; fine roots; gradual, smooth boundary.
100-130 cm B/Ak	clay; moist; 10YR 3/4 surface soil tonguing into 10YR 2/2 subsoil, the latter increasing with depth (10YR 2/2 soil occupies over 50% of the entire horizon); firm; ca-specks; many shell fragments; fine roots; gradual, smooth boundary.
130-160 cm Bwk	clay with some coarser-textured pockets; moist; 10YR 2/2; firm; frequent ca-granules; few shell fragments; fine roots; gradual, smooth boundary.
160-200 cm B/2Cwk	clay with some coarser-textured pockets; moist; 10YR 3/1-2/2, and lighter-coloured pockets; many clusters of ca-granules; white ca-nodules; faint manganese coatings; fine roots; diffuse, smooth boundary.
200-230 cm 2C/Bw(k)	clay; slightly moist; 10YR 3/3, with admixture of darker soil (2C/B is continuous with B/2C); firm; weak lamination, slickensides, shiny ped faces; distinct manganese coatings, sometimes covering small peds entirely, giving them the appaearance of grey nodules; diffuse, smooth boundary.
230-255 cm 2Ck1	clay with inclusions of sandy and silty clay, the latter showing stratification and many fine pores; 10YR 3/3 (colour of the clay matrix); distinct lamination; slickensides and shiny ped faces; very firm; many white ca-nodules; fine roots; gradual, smooth boundary.

255-300 cm+ 2Ck2	clay with inclusions of silt loam; 10YR 4/3;5/4,d (clay matrix); clay has very firm consistence, silt loam pockets are friable; structureless, massive; silt loam pockets have many fine pores, ca-pseudomycelium and ca-granules; irregularly shaped 1-2 cm diameter white and rounded ca-nodules; few and faint manganese coatings; the heterogeneity of the horizon is not changing with depth.

General description of soil structure 0 to 200 cm :
Medium subangular blocky 0 to 200 cm; grade of development moderate in 0 to 100 cm, moderate to weak in 100 to 130 cm, and weak in 130 to 200 cm. There is a faint lamination, that indicates the predisposition for a parallelepiped substructure with peds 1-3 mm thick, that is moderate to strong in 0 to 130 cm, and weak in 130 to 200 cm. Slickensides are present in 160 to 200 cm. The grade of structure development is decreasing with depth. No difference in structure was found between mound and depression profiles.

Remarks :
1. Carbonate concentrations have not been described in 200 230 cm. This is probably an omission. The suffix 'k' has been added to the horizon symbol in parentheses.
2. No grey ca-nodules are found below 160 cm depth.
3. The clusters of ca-granules, described for 160-200 cm - and probably occurring in 200-300 cm as well - have the appearance of being developed from a single, large ca- nodule, by weathering.
4. Some of the small peds in the lower horizons are continuously coated by manganese (or manganese and iron); they appear as grey ca-nodules. Perhaps ca-nodules originate from this horizon, or they are merely receiving ferric and manganese coatings and impregnations.

Summary profile description :
A deep clay profile (description till 300 cm) consisting of a 10YR 3/4 surface soil (A;0-100 cm), tonguing (between 100 and 130 cm) into a 10YR 2/2 subsoil (B;130-160 cm), that, through a transitional horizon, overlies a heterogeneous substratum (2C;230-300cm+), consisting of clay with silty,loamy and sandy pockets that sometimes show a distinct stratification.
Soil structure is medium angular blocky (0-200cm), with a parallelepiped substructure showing as a fine lamination; the lamination continues into the substratum, whereas slickensides and shiny ped faces occur only in the substratum.
Grey ca-nodules, ca-specks and white ca-nodules occur; the grey nodules mainly in the surface soil, the ca-specks in 100 to 130 cm, the white nodules in 130 to 300cm+. Coatings of manganese (or manganese with ferric iron) occur below 160 cm. There is no gypsum.

KHASHM EL GIRBA 256 (NR. 5)

date of description :	13/10/1962
USDA Soil Taxonomy :	Typic Chromustert, very-fine, montmorillonitic, isohyperthermic
FAO/UNESCO :	Chromic Vertisol (1974); Calcic Vertisol (1988)
location :	Khashm el Girba Irrigation Scheme; topo map 1:250,000, sheet 55-D; 1524'N - 35N - 35E.
elevation :	470 m
landform :	very gently undulating pediplain of the Butana
soil slope class :	flat
microrelief :	none
surface :	many fine surface cracks; wide cracks are developing; rounded quartz pebbles and grey ca-nodules and -granules
parent material :	colluvio/alluvial clay derived from weathering of local Basement Complex rock
vegetation or land use :	open treeless grass plain with a thin cover of *Setaria* ssp., partly green, partly dry; few bunches of *Cymbopogon nervatus.*

Profile description :

0-25 cm Au1	clay; dry, with depth moist; 10YR 3/3; very hard when dry, very friable when moist; fine angular blocky with wedge-shaped peds that show on the profile wall as a distinct lamination; many grey ca-nodules and -granules; fine gravel; diffuse, smooth boundary.
25-45 cm Au2	clay; slightly moist; 10YR 3/3; slightly hard when dry, friable when moist; fine angular blocky; finest peds are parallelepipeds, 1-2 mm thick that appear as a lamination on the profile wall; many grey ca-nodules and -granules; fine gravel; gradual, smooth boundary.
45-80 cm A/Bwk	clay; slightly moist; surface soil (10YR 3/3) tonguing into subsoil (10YR 3/1); hard when dry; moderate medium subangular blocky, with wedge-shaped peds that appear as a moderately distinct lamination on the profile wall; the 10YR 3/1 peds have shiny faces; grey ca-nodules and -granules; ca-specks in 10YR 3/1 soil; fine gravel; clear, smooth boundary.
80-110 cm B/Awky	clay; slightly moist; surface soil (10YR 3/3) tonguing into a matrix of 10YR 3/1 soil; slightly hard when dry, firm when moist; strong angular blocky, with wedge-shaped peds: lamination of the profile wall distinct: grey ca-nodules and -granules; ca-specks in 10YR 3/1 soil; fine gypsum crystals, increasing in coarseness with depth to medium; gradual, smooth boundary.
110-125 cm Bwky	clay; slightly moist; 10YR 3/1; slightly hard when dry, firm when moist; structure as in 80-110 cm, but grade weaker; ped surfaces shiny; grey ca-nodules and -granules; medium aggregates of soft powdery lime; medium and coarse gypsum crystals; fine gravel; gradual, smooth boundary.
125-155 cm B/Cwky	clay; moist; soil heterogeneous, the dominant colour is 10YR 3/2; very firm; fine and very fine angular blocky, with peds that have shiny surfaces; distinct slickensides with rootprints; abundant coarse gypsum crystals; white ca-nodules and -granules, partly coated with iron and manganese; gradual, smooth boundary.
155-180 cm C/Bwky	gravelly clay; moist; 10YR-2.5Y 3/2; very firm; structure as in 125-155 cm; distinct slickensides; white and apparently weathering, partly fragmented ca-nodules and -granules, in part coated with iron and manganese; coarse gypsum crystals; clear, smooth boundary.

180-220 cm+ Ckr	weathering rock; slightly moist; 10YR 4/2, 10YR 8/1 when dry; next to fragments of weathering rock, there are ca-nodules with a similar appearance, these are white, but partly coated and impregnated with iron and manganese; the material of this horizon has a hydromorphic appearance due to ferric and manganese (metallic-bluish) mottles.

Remarks :
1. Fine roots occur in 0-80 cm, decreasing in abundance with depth.
2. The fine class of structure in 125-155 cm is probably due to the abundance of coarse gypsum crystals throughout the soil mass.

Summary profile description :
Moderately deep Vertisol profile, developed 'in situ' or on locally colluviated material. A 10YR 3/3 surface soil (A: 0-45 cm), is tonguing (between 45 and 110 cm) into a 10YR 3/1 subsoil (B: 110-125 cm). Through two transitional horizons (B/C, C/B, 125-180 cm) a Ckr horizon of weathering rock with partly iron- and manganese-coated ca-nodules is reached. Fresh rock is found below 220 cm.
Vertic structure throughout the solum; slickensides occur in the B/C and C/B horizons, 125-180 cm.
Grey ca-nodules and -granules occur throughout the solum and in the transition to the substratum; white ca-specks, with depth increasing in size to aggregates of soft powdery lime, occur only in the 10YR 3/1 subsurface soil material.
Gypsum is found in 80-180 cm; it increases with depth in both abundance and crystal size, and ends abruptly at 180 cm depth, where the weathering rock begins.

JEBEL QEILI (NR. 6)

date of description :	11/10/1962
USDA Soil Taxonomy :	Entic Chromustert, fine, montmorillonitic, hyperthermic
FAO/UNESCO :	Chromic Vertisol (1974); Calcic Vertisol (1988)
location :	12 km east of Jebel Qeili (Butana), along Khartoum- Asubri road; topo map 1:250,000, sheet 55-C; 15°31'N - 33°53'E.
elevation :	approximately 450 m
landform :	flat to gently undulating pediplain with scattered inselbergs. Jebel Qeili forms part of a range of inselbergs marking the Blue Nile-Atbara divide.
soil slope class :	flat
microrelief :	none
surface :	slightly uneven; thick, loose, moist surface mulch; fine surface cracks; colour 10YR 4/3;5/3,d; much subrounded quartz gravel and hard, grey ca-nodules
parent material :	colluvio/alluvial clay, derived from the weathering of Basement Complex rock
vegetation or land use :	open grass plain with dominant *Schoenefeldia gracilis* and *Cymbopogon nervatus*; other grasses present include *Aristida* ssp.

Profile description :

0-25 cm A	clay; moist/wet; 10YR 4/3; very friable; fine crumb; grey ca-nodules and white ca-granules; fine and medium subangular quartz gravel; many fine roots; gradual, smooth boundary.
25-50 cm Ak	clay; moist; 10YR 4/3; friable; very weak parallelepiped structure, showing as a distinct lamination on the profile wall; grey ca-nodules and white ca-granules; few fine, white ca-specks; fine and medium subangular quartz gravel; many grass roots; diffuse, smooth boundary.
50-75 cm A/Bwk	clay; dry; 10YR 4/3, with tongues of 10YR 3.5/1; very hard; structure as in Ak horizon; fine grey ca-nodules throughout; many fine, white ca-specks in the tongues of 10YR 3.5/1-colour; gravel as in overlying horizon; fine roots till 60 cm depth; diffuse, smooth boundary.
75-100 cm B/Awk	clay; dry; 10YR 3.5/1, with tongues of 10YR 4/3; very hard; moderately developed parallelepiped structure, showing as a distinct lamination on the profile wall; fine, medium and large ca-nodules throughout; white, soft ca-granules in 10YR 3.5/1 soil; fine quartz gravel; clear, smooth boundary.
100-140 cm Bwky	clay; very slightly moist; 10YR 3.5/1, and some patches of soil with a greenish/ greyish colour; very hard; structure as in overlying horizon; many fine, medium and large ca-nodules; white, soft ca-granules; fine, white specks consisting of clusters of gypsum crystals; fine quartz gravel; diffuse, smooth boundary.
140-180 cm BCwky	clay; very slightly moist; 10YR 3/1.5; 4.5/1,d; some patches of soil with a greenish-greyish colour; extremely hard; structure as in 75-140 cm; grey ca-nodules; fine, medium and large aggregates of soft, powdery lime; fine gypsum crystals; iron-manganese coatings on peds; fine quartz gravel; diffuse, smooth boundary.
180-200 cm+ Cky	clay; very slightly moist; 10YR-2.5Y 4/2; 5/2,d; extremely hard; moderate fine angular blocky, peds are horizontally aligned tilted wedges; many fine, medium and large ca-nodules; medium aggregates of soft, powdery lime and white soft ca-granules; fine gypsum crystals; iron-manganese coatings on peds; reddish streaks; fine quartz gravel.

Remarks :

1. Fine quartz gravel and pebbles occur throughout the profile.
2. Few shell fragments occur throughout the profile.
3. Cracks can be traced till 150 cm depth.
4. The soil is very compact between 100 and 200 cm depth.
5. Slickensides are present, but not distinct.
6. The greenish/greyish patches of soil below 100 cm depth, and the reddish streaks in the C-horizon give the subsoil and especially the substratum a hydromorphic appearance, but this colour mottling may also reflect 'in situ' weathering of minerals.

Summary profile description :

A deep clay profile with a 10YR 4/3 surface soil, overlying a very dark-coloured (10YR 3.5/1) subsoil, merging into a 10YR-2.5Y 4/2 substratum. There are very gradual transitions in the solum where tongues of 10YR 4/3-soil penetrate into 10YR 3.5/1 subsoil. Fine ca-specks begin at 25 cm depth, and are distinct between 50 and 140 cm. Large aggregates of soft powdery lime occur below 140 cm; they are accompanied by clusters of fine gypsum crystals. The lower subsoil and especially the substratum have fine reddish and greenish/greyish mottles.

Laboratory data of profile 6, Jebel Qeili

horizon nr., depth (cm)	particle size distribution, µm; % of fine earth								pH		$CaCO_3$ %	org. carbon %
	sand						silt	clay				
	2000-1000	1000-500	500-250	250-100	100-50	total	50-2	<2	H_2O	0.01M $CaCl_2$		
1 0-25						5.2	29.4	65.4	8.5	7.8	3.0	0.4
2 25-50						9.6	25.5	57.9	8.7	7.9	5.7	0.8
3 50-75	1.2	2.3	3.2	3.8	8.0	18.5	30.4	51.1	7.5	7.1	3.0	0.4
4 75-100	0.8	1.8	2.7	3.4	6.9	15.6	23.2	61.2	8.6	8.1	2.7	0.6
5 100-140	0.6	1.7	2.3	2.8	6.8	14.2	24.7	61.1	9.5	7.9	4.6	0.4
6 140-180						11.2	24.0	64.8	7.4	7.2	6.4	0.5
7 180-200						11.9	22.9	65.2	7.5	7.2	5.6	0.3

horizon nr., depth (cm)	exchangeable Na		CEC % mmol/kg	$CaSO_4$ %	water-soluble Na mmol/kg	EC mS/cm	extract for EC determination g/ml
	mmol/kg	%					
1 0-25	26	4.9	535		5	0.6	1:1
2 25-50	60	11.2	536		6	0.6	1:1
3 50-75	84	15.2	554		15	1.7	1:1
4 75-100	97	16.6	586		22	2.3	1:1
5 100-140	107	18.4	580		36	3.6	1:1
6 140-180	115	19.0	607	0.5			
7 180-200	120	23.7	507	2.9	64	4.1	1:2

horizon nr., depth (cm)	elemental composition of the fine earth (% by weight)												
	SiO_2	Fe_2O_3	Al_2O_3	TiO_2	MnO	CaO	MgO	Na_2O	K_2O	FeO	P_2O_5	SO_3	H_2O+
1 0-25	58.8	7.7	13.2	1.3	0.1	4.0	2.9	1.1	0.7	0.3	0.1		8.0
2 25-50	55.3	7.6	13.1	1.1	0.2	5.6	2.4	0.7	0.7	0.2	0.1		9.8
3 50-75	56.8	7.6	13.1	1.2	0.2	5.5	2.3	0.8	0.6	0.2	0.1		9.4
4 75-100	56.2	7.4	13.0	1.2	0.1	5.2	2.4	0.8	0.6	0.3	0.1		9.3
5 100-140	57.9	7.6	13.3	1.2	0.1	4.7	2.4	0.8	0.6	0.2	0.1		9.0
6 140-180	55.8	8.2	14.3	1.3	0.1	4.4	2.5	0.8	0.5	0.1	0.1		8.9
7 180-200	55.0	7.9	13.9	1.2	0.1	4.8	2.3	0.7	0.4	0.1	0.1		8.0

horizon nr., depth (cm)				molar ratios			
	free Fe_2O_3	free Al_2O_3	amorphous Fe_2O_3	SiO_2/R_2O_3	SiO_2/Al_2O_3	SiO_2/Fe_2O_3	Al_2O_3/Fe_2O_3
1 0-25	3.2			5.5	7.6	20.6	2.7
2 25-50	2.8			5.2	7.2	19.6	2.7
3 50-75	2.6			5.4	7.4	20.2	2.7
4 75-100	2.5			5.4	7.3	20.5	2.8
5 100-140	2.7			5.4	7.4	20.5	2.7
6 140-180	3.8			4.9	6.6	18.4	2.7
7 180-200	3.3			5.0	6.7	18.8	2.8

horizon nr., depth (cm)	elemental composition of the clay fraction (% by weight)												
	SiO_2	Fe_2O_3	Al_2O_3	TiO_2	MnO	CaO	MgO	Na_2O	K_2O	FeO	P_2O_5	SO_3	H_2O+
2 25-50	49.6	10.3	19.5	1.2	0.1	0.3	1.7	0.1	0.5	0.2	0.1		15.9
4 75-100	49.9	9.8	19.7	1.2	0.1	0.3	1.7	0.2	0.5	0.1	0.1		16.0
7 180-200	52.1	105	20.0	1.3	0.1	tr	2.4	0.2	0.3	0.3	0.2		10.2

horizon nr., depth (cm)				molar ratios			
	free Fe_2O_3	free Al_2O_3	amorphous Fe_2O_3	SiO_2/R_2O_3	SiO_2/Al_2O_3	SiO_2/Fe_2O_3	Al_2O_3/Fe_2O_3
2 25-50				3.2	4.3	12.9	3.0
4 75-100				3.3	4.3	13.6	3.2
7 180-200				3.3	4.4	13.2	3.0

ER RAWASHDA (NR. 7)

date of description :	11/3/1966
USDA Soil Taxonomy :	Typic Pellustert, very-fine, montmorillonitic, isohyperthermic
FAO/UNESCO :	Pellic Vertisol (1974); Calcic Vertisol (1988)
location :	6 km south-west of Er Rawashda village, on road to Gedaref; near Er Rawashda Mechanised Crop Production Scheme; topo map 1:250,000, sheet 55-H; 14°09'N - 35°33'E.
elevation :	approximately 600 m
landform :	very gently undulating pediplain
soil slope class :	flat
microrelief :	uneven surface to weakly developed gilgai, normal type, wavelength 2 to 3 m, amplitudo 15 cm
surface :	cracks are 5 to 10, sometimes 15 cm wide at the surface, they sometimes approach sinkholes; cracks partly obscured by surface mulch; very brittle surface crust, breaking into a mulch, 2-3 cm thick, consisting of hard, granular peds, 2 to 5 mm across; many light-grey ca-nodules; stones, up to 50 cm diameter, occur mainly concentrated on spots of about 15 m wide, that have less surface cracks.
parent material :	locally colluviated material derived from weathering of basaltic rock
vegetation or land use :	grass plain with a few bushes; area has been burnt.

Profile description :

0-35 cm A	clay; 10YR 3/1.2; 3.5/1,d; very wide cracks; subangular blocky, with depth to angular blocky; abundant ca-nodules and -granules, varying from white to light blue-grey, and in size from smaller than 1 to 5 mm; the 1-2 mm white ca-granules are sometimes concentrated in horizontal strata of a few mm's thick; diffuse, smooth boundary.
35-75 cm Bw1	clay; 10YR 3/1.2; 3/0.5,d; cracks up to 5 cm wide; weak fine angular blocky with wedge-shaped peds that have shiny surfaces; soil rather compact, without void space between peds; ca-nodules and -granules as in 0-35 cm; fibrous roots; diffuse, smooth boundary.
75-120 cm Bw2	clay; 10YR 3/1.8; 3/1,d; moderate medium to coarse angular blocky with wedge-shaped peds that have shiny faces; slickensides; ca-nodules and -granules as in 0-75 cm; many fibrous roots; diffuse, smooth boundary.
120-140/160 cm Bw3	clay; 10YR 3/1.4; 3/1,d; strong angular blocky with wedge-shaped peds that have shiny, slickensided ped faces with roots and rootprints; ca-nodules and -ca-granules as in overlying horizons, but less abundant; abrupt, wavy boundary.
140/160 cm+ CR	rock boulders, almost unweathered.

Remarks :

1. Very wide cracks till 100 cm (but pit old and very much desiccated).
2. Moisture not determined (old pit)
3. From 35 to 150 cm there is a gradually increasing number of slickensides, and there are coarser and more distinct tilted wedges and an overall stronger grade of structure.
4. Rock boulders below 140/160 cm depth are basalt.
5. The abrupt change from soil to rock boulders indicates that the profile is not strictly residual but has developed on locally colluviated fine-textured material.
6. Soft powdery lime may be present in the Bw3 horizon.

Summary profile description :
A very uniform Pellustert developed in locally colluviated material weathered from basalt. Cracks are very wide at the surface and in the profile wall till 100 cm (note: profile pit was opened a few months ago, and this may have induced strong soil shrinkage).
Vertic structure well-developed throughout; wedge-shaped peds in 35-75 cm are fine, otherwise they are medium to coarse; ped surfaces are shiny below 35 cm; slickensides occur below 75 cm. Colour (moist) varies from 10YR 3/1.2 to 3/1.8. White and blue-grey ca-nodules and -granules are abundant throughout the solum. At about 150 cm there is an abrupt change to boulders of slightly weathered basaltic rock.

Laboratory data of profile 7, Er Rawashda

horizon nr., depth (cm)	particle size distribution, µm; % of fine earth								pH		$CaCO_3$ %	org. carbon %
	sand						silt	clay				
	2000-1000	1000-500	500-250	250-100	100-50	total	50-2	<2	H_2O	0.01M $CaCl_2$		
1 0-35						1.1	19.5	79.3	7.5	6.9	16.0	0.2
2 35-75						1.0	21.1	77.9	7.5	6.5	16.1	0.9
3 75-120						0.9	20.4	78.7	7.1	6.8	15.3	0.6
4 120-140/160						1.0	20.0	79.0	7.3	7.0	9.3	0.5

horizon nr., depth (cm)	exchangeable Na		CEC % mmol/kg	$CaSO_4$ %	water-soluble Na mmol/kg	EC mS/cm	extract for EC determination g/ml
	mmol/kg	%					
1 0-35	19	3.4	559				
2 35-75	51	8.9	573				
3 75-120	64	11.7	546				
4 120-140/160	72	11.8	611				

horizon nr., depth (cm)	elemental composition of the fine earth (% by weight)												
	SiO_2	Fe_2O_3	Al_2O_3	TiO_2	MnO	CaO	MgO	Na_2O	K_2O	FeO	P_2O_5	SO_3	H_2O+
1 0-35	40.8	8.4	15.9	1.2	0.2	9.2	5.1	3.0	1.6	0.5	0.2		13.2
2 35-75	43.5	8.6	14.0	1.2	0.2	9.1	4.3	1.6	0.6	0.5	0.2		15.0
3 75-120	38.0	8.9	14.5	1.1	0.2	8.4	4.3	1.5	0.6	0.3	0.2		14.9
4 120-140/160	42.5	9.4	15.4	1.1	0.2	5.7	4.5	1.3	0.5	0.5	0.1		12.1
5 >140/160 (rock)	39.4	6.5	14.6	0.9	0.2	8.9	11.7	3.3	0.5	4.4	0.1		3.2

horizon nr., depth (cm)				molar ratios			
	free Fe_2O_3	free Al_2O_3	amorphous Fe_2O_3	SiO_2/R_2O_3	SiO_2/Al_2O_3	SiO_2/Fe_2O_3	Al_2O_3/Fe_2O_3
1 0-35	4.0	3.2		3.2	4.5	11.6	2.6
2 35-75	3.5	2.3		3.7	5.3	12.8	2.4
3 75-120	3.2	2.2		3.2	4.5	10.9	2.5
4 120-140/160	3.3	2.2		3.4	4.7	11.9	2.5
5 >140/160 (rock)	3.9	1.1		3.1	4.6	9.7	2.1

horizon nr., depth (cm)	elemental composition of the clay fraction (% by weight)												
	SiO_2	Fe_2O_3	Al_2O_3	TiO_2	MnO	CaO	MgO	Na_2O	K_2O	FeO	P_2O_5	SO_3	H_2O+
1 0-35	50.7	11.2	18.6	0.9	0.1								
2 35-75	49.2	11.4	18.1	0.9	0.1								
3 75-120	52.3	11.1	17.4	0.9	0.1								
4 120-140/160	49.3	11.4	17.2	0.9	0.1								

horizon nr., depth (cm)				molar ratios			
	free Fe_2O_3	free Al_2O_3	amorphous Fe_2O_3	SiO_2/R_2O_3	SiO_2/Al_2O_3	SiO_2/Fe_2O_3	Al_2O_3/Fe_2O_3
1 0-35				3.4	4.6	12.1	2.6
2 35-75				3.3	4.6	11.6	2.5
3 75-120				3.6	5.1	12.5	2.5
4 120-140/160				3.4	4.9	11.5	2.4

HADELIYA (NR.8)

date of description : 26/10/1961
USDA Soil Taxonomy : Typic Ustifluvent, fine, montmorillonitic, hyperthermic
FAO/UNESCO : Calcaric Fluvisol (1974); Calcaric Fluvisol (1988)
location : Gash delta, station Hadeliya, 'misqa' 12, 'hod' 184, 'muraba' 24, 'gitta' 13; topo map 1:250,000, sheet 46-M; 16°07'N - 36°08'E.
elevation : approximately 480 m
landform : inland alluvial delta (alluvial fan) of the river Gash; the profile is situated at the lower end of the delta
soil slope class : flat
microrelief : uneven, due to annual flooding; there are also conspicuous sinkholes, up to 2 m diameter and 1 m deep, and many windblown hummocks
surface : see 'microrelief' and 'remarks'
parent material : fine-textured alluvium of Gash river
vegetation or land use : the site is flooded and cultivated in one year out of three, as an average (this depends on the magnitude of the annual flood of the Gash river). In the present year the site has not been flooded. There is a dense grass cover, and some bushes of *Capparis decidua* and scattered *Calotropis procera.*

Profile description :
The profile shows no horizons, and a fine sedimentary stratification is only present in the upper 3 cm. There are slight and very gradual changes with depth, mainly in moisture condition and soil colour. Colour changes from 10YR 5/2.5,dry, at 3 cm depth, through 10YR 4/3,moist, at 60 cm, to 10YR 4/2.5,moist, at 150 cm depth. The consistence when dry is very hard, when moist friable. The soil is apparently structureless, massive, but if taken from the profile wall it parts along inclined surfaces of weakness, like incipient slickensides. These surfaces are darker-coloured (approximately 10YR 3/2) than the soil matrix, and have slight manganese (or iron-manganese) coatings that give the soil a heterogeneous colour. Fine white ca-specks and aggregates of soft powdery lime are common throughout the soil. Fine roots are frequent to 30 cm depth . Cracks can normally be traced till 40 cm depth. One of the walls of the pit cuts through a sinkhole. Below the sinkhole cracks are distinct till the bottom of the pit, at 180 cm. Flanking the sinkhole are some wide cracks that reach to 1 m depth. Under the sinkhole is a wedge-shaped body with very compact soil, bordered by the cracks that flank the sinkhole; this body reaches till the bottom of the pit. It can be detached easily from the profile wall, and it contains pockets of almost pure silt, yellowish in colour. In the sinkhole there is an accumulation of grass seeds.

Laboratory data of profile 8, Hadeliya

horizon nr., depth (cm)	particle size distribution, µm; % of fine earth								pH		$CaCO_3$ %	org. carbon %
	sand						silt	clay				
	2000-1000	1000-500	500-250	250-100	100-50	total	50-2	<2	H_2O	0.01M $CaCl_2$		
1 0-15		0.1	0.2	2.9	8.7	11.9	38.7	49.4	6.9	6.9		0.7
2 15-30		0.2	0.3	4.2	8.5	13.2	38.5	48.3	7.1	6.7		0.5
3 30-60		0.1	0.2	4.1	8.5	12.9	38.8	48.3	7.0	6.8		0.5
4 60-90		0.1	0.3	4.1	7.5	12.0	39.4	48.7	7.3	7.0		0.4
5 90-120		0.1	0.2	3.6	7.1	11.0	40.0	49.0	6.9	6.8		0.5
6 120-150		0.1	0.1	2.3	5.1	7.6	40.7	51.7	6.7	6.7		0.6
7 150-180		0.1	0.2	2.5	4.8	7.6	37.9	54.5	6.5	6.4	0.7	0.5

horizon nr., depth (cm)	exchangeable Na		CEC % mmol/kg	$CaSO_4$ %	water-soluble Na mmol/kg	EC mS/cm	extract for EC determination g/ml
	mmol/kg	%					
1 0-15	3	1.1	264	0.2			
2 15-30	2	0.8	251	0.4			
3 30-60		0	328	0.4			
4 60-90	1	0.3	341	0.4			
5 90-120	3	0.9	334				
6 120-150	6	1.7	363				
7 150-180	9	2.3	389				

horizon nr., depth (cm)	elemental composition of the fine earth (% by weight)												
	SiO_2	Fe_2O_3	Al_2O_3	TiO_2	MnO	CaO	MgO	Na_2O	K_2O	FeO	P_2O_5	SO_3	H_2O+
1 0-15	54.5	9.0	18.0	1.1	0.2	2.2	3.0	1.6	1.8	0.4	0.2		7.4
2 15-30	57.0	8.8	17.6	1.1	0.2	2.5	2.9	1.7	1.8	0.3	0.2		6.6
3 30-60	54.6	8.8	17.7	1.1	0.2	2.7	2.9	1.7	1.8	0.3	0.2		6.9
4 60-90	54.0	8.9	17.9	1.1	0.2	2.5	3.0	1.8	1.9	0.3	0.2		7.0
5 90-120	54.8	8.9	18.2	1.1	0.2	2.7	3.1	1.8	1.9	0.4	0.2		7.1
6 120-150	53.6	9.4	18.5	1.1	0.2	2.6	3.1	1.7	1.9	0.2	0.2		7.7
7 150-180	52.7	9.7	17.8	1.0	0.2	2.8	2.9	1.4	2.1		0.2		8.0

horizon nr., depth (cm)				molar ratios			
	free Fe_2O_3	free Al_2O_3	amorphous Fe_2O_3	SiO_2/R_2O_3	SiO_2/Al_2O_3	SiO_2/Fe_2O_3	Al_2O_3/Fe_2O_3
1 0-15	3.7	1.2	0.4	3.9	5.2	16.2	3.1
2 15-30	3.5	1.3	0.3	4.2	5.5	17.3	3.1
3 30-60	3.5	1.5	0.3	4.0	5.2	16.5	3.2
4 60-90	3.5	1.3	0.2	3.9	5.1	16.1	3.1
5 90-120	3.5	1.3	0.2	3.9	5.1	16.3	3.2
6 120-150	3.3	1.5	0.4	3.7	4.9	15.1	3.1
7 150-180	3.6	1.6	0.3	3.7	5.0	14.4	2.9

horizon nr., depth (cm)	elemental composition of the clay fraction (% by weight)												
	SiO_2	Fe_2O_3	Al_2O_3	TiO_2	MnO	CaO	MgO	Na_2O	K_2O	FeO	P_2O_5	SO_3	H_2O+
2 15-30	51.2	12.8	19.7	1.1	0.1		2.7	0.5	2.0	0.3	0.2		10.2
7 150-180	47.9	11.3	20.4	1.0	0.1	0.4	1.5	0.4	1.7	0.2	0.2		13.6

horizon nr., depth (cm)				molar ratios			
	free Fe_2O_3	free Al_2O_3	amorphous Fe_2O_3	SiO_2/R_2O_3	SiO_2/Al_2O_3	SiO_2/Fe_2O_3	Al_2O_3/Fe_2O_3
2 15-30				3.1	4.4	10.7	2.4
7 150-180				2.9	4.0	11.2	2.8

GARS 141 (NR. 9)

described by W.A.Blokhuis and L.H.J.Ochtman [1]

date of description :	February 1960
USDA Soil Taxonomy :	Typic Chromustert, very-fine, montmorillonitic, isohyperthermic
FAO/UNESCO :	Chromic Vertisol (1974); Calcic Vertisol (1988)
location :	Gezira Agricultural Research Station, Wad Medani; plot 141 (permanently uncultivated and non-irrigated plot); topo map 1:250 000, sheet 55-G; 14°24'N - 33°30'E.
elevation :	405 m
landform :	alluvial plain of the Blue Nile (Gezira fan)
soil slope class :	flat
microrelief :	uneven, but no gilgai
surface :	there is an irregular pattern of cracks, enclosing polygons of 40 to 200 cm diameter; width of cracks at the surface is 5 to 14 cm; there is a thin, brittle and finely stratified crust (10YR 4/5; 3.5,d), parting into a surface mulch, that at the time of description was well-developed and sloughing into the cracks; dark-grey ca-nodules (3 to 10 mm diameter) and white ca-granules (1 to 3 mm diameter) are common on the surface.
parent material :	fine-textured alluvium of the Blue Nile
vegetation or land use :	tall grass savannah, with *Cymbopogon nervatus* (dominant), *Sorghum ssp.*, *Sporobolus helveolus,* and various herbs. Grasses and herbs are dry. Few scrub, 1-2 m high, of *Acacia nubica* and *A.seyal.*

Profile description :

0-2 cm Au1	clay; dry; 10YR 3/4, moist and dry; slightly hard; thin brittle surface crust, overlying a fine and medium granular surface mulch; grey ca-nodules and white ca-granules as described under 'surface'; abrupt, smooth boundary.
2-15 cm Au2	clay; dry; 10YR 3/3.5; 3/3,d; wide cracks from the surface; compound medium, fine and very fine angular blocky; the finest peds are wedge-shaped with their long axis tilted 15° to 45° from the horizontal, and these give the profile wall a finely laminated appearance; ca-nodules and ca-granules as described above; gradual, smooth boundary.
15-40 cm Ak1	clay; dry; 10YR 3/3.5; 3/3,d; very hard; structure as in 2 to 15 cm; common dark-grey ca-nodules and white ca-granules; few very fine white ca-specks in vertical streaks; cracks narrowing; gradual, smooth boundary.
40-60 cm Ak2	clay; dry; 7.5YR 3/2; 10YR 3/3,d; very hard; compound moderate fine and very fine angular blocky, the finest peds are parallelepipeds; few dark-grey ca-nodules; few very fine white ca-specks in vertical streaks; narrow cracks; gradual, smooth boundary.
60-90 cm A/Bwk	clay; very slightly moist; 7.5YR 3.5/2; 4/2,d, tonguing into 10YR 4/1.5, moist and dry; very hard; compound moderate fine and very fine angular blocky, the finest peds are parallelepipeds; few dark-grey ca-nodules; common fine white ca-specks in vertical streaks in the 10YR 4/1.5 soil; narrow cracks; clear, smooth boundary.

[1] adapted from Blokhuis, W.A. and L.H.J.Ochtman, 1960. Profile Gezira Clay Soil. Misc.Paper no. 1, Soil Survey Division, Gezira Research Station, Wad Medani, Sudan.

90-130 cm B/Awky	clay; very slightly moist; 10YR 4/1.5, moist and dry, with intrusions of soil with a colour of 7.5YR 3.5/2; 4/2,d; compound weak angular blocky and fine and very fine bicuneate structure; the finest peds have shiny faces; few dark-grey ca-nodules; aggregates of soft powdery lime and fine gypsum crystals in clusters of 3 to 5 mm diameter in the 10YR 4/1.5 soil (gypsum mainly in the upper part of the horizon, soft powdery lime mainly in the lower part); gradual, smooth boundary.
130-165 cm 2Cky1	clay; slightly moist; 10YR 5/3; 4.5/3,d; extremely firm; weak medium and fine angular blocky without the peds being distinctly wedge-shaped; slickensides; common, 1-3 cm diameter, dark-grey and white ca-nodules; common aggregates of soft powdery lime; common, coarse lense-shaped gypsum crystals, 2 to 5 mm long, in clusters or single; metallic-bluish coatings (manganese or iron-manganese) on spots on slickensides; gradual, smooth boundary.
165-185 cm 2Cky2	clay; slightly moist; 10YR 5/3.5; 5/3,d; as 130-165 cm, but gypsum crystals, single or in clusters, are abundant; many metallic-bluish (iron-)manganese coatings and reddish ferric coatings give the soil a heterogeneous colour; gradual, smooth boundary.
185-220 cm 2Cky3	clay; slightly moist; 10YR 5/4; 5/3,d; as 165 -185 cm, but the amount of gypsum decreases with depth; clear, smooth boundary.
220-250 cm+	as 185-220 cm, but there is no gypsum.

Remarks:

1. Few shell fragments occur throughout the profile.
2. Fine roots occur till a depth of 50 cm.
3. Termite tunnels are common between 60 and 250 cm depth.

Description on 5/9/1959, at the end of the rainy season :
Cracks are closed; the moist surface soil is covered by a 4 mm thick surface crust. The surface is uneven due to last season's cracks, that are still traceable, they now form an irregular pattern of microgullies. There is a green herb vegetation with, a.o. *Ipomoea cordofana, Momordica tuberosa* and *Ocimum basilicum.*

The profile morphology differs from the one described in the dry season in moisture conditions and soil structure, as follows:

0-2 cm	very slightly moist; weak very fine subangular blocky
2-40 cm	moist to wet; structureless, massive
40-60 cm	moist to wet; no interpedal voids, but the tilted wedges are distinct in the profile wall
60-130 cm	moist; no interpedal voids; tilted wedges faint in the 7.5YR 3.5/2 soil, distinct in the 10YR 4/1.5 soil.
130-250 cm	as in the dry season.

Summary profile description :
A deep clay profile (described till 250 cm depth), consisting of a 10YR 3/3.5 (0-40 cm) and 7.5YR 3/2 (40-60 cm) surface soil, tonguing (between 60 and 130 cm) into a 10YR 4/1.5 subsoil that overlies a 10YR 5/3 substratum.
The type of soil structure is the same throughout the solum (0-130 cm): compound angular blocky, whereby the smallest peds are tilted parallelepipeds. From below the mulch till about 60 cm the structure is distinctly compound: the largest peds are medium angular blocky, the finest are wedge-shaped peds of a few mm's. Between 60 and 130 cm the structure is less distinctly compound, the largest peds becoming smaller, the finest peds larger; the latter have shiny, slickensided ped surfaces. The soil between 130 and

250 cm, although considered to be a C horizon, has a weak angular blocky structure, with somewhat wedge-shaped peds.
Dark-grey ca-nodules and fine white ca-granules are common throughout the profile. Fine ca-specks are rare in the Ak horizon (15-60 cm), common and arranged in vertical streaks in the 10YR 4/1.5 soil of the A/B and B/A horizons (60-130 cm), whereas larger accumulations of soft powdery lime are common below 130 cm.
Fine gypsum crystals occur single or in clusters in the 10YR 4/1.5 soil of the B/A horizon (90-130 cm); they increase in size and abundance in the upper part of the 2C horizon (130-185 cm), after which they decrease rapidly in abundance. They are not found below 220 cm.
Fine coatings of manganese or manganese and ferric iron are restricted to the 2C horizon below 130 cm; they are most distinct, and accompanied by ferric mottles, between 165 and 250 cm.

Laboratory data of profile 9, GARS 141

horizon nr., depth (cm)	particle size distribution, µm; % of fine earth								pH		$CaCO_3$ %	org. carbon %
	sand						silt	clay				
	2000-1000	1000-500	500-250	250-100	100-50	total	50-2	<2	H_2O	0.01M $CaCl_2$		
1 0-2			2.4	6.1	6.4	14.9	23.3	61.8	8.2	8.0[1)]	2.2	0.3
2 2-40			2.5	6.0	5.6	14.1	22.2	63.7	8.6	8.0	2.5	0.1
3 40-60			2.1	4.4	5.5	12.0	22.8	65.3	8.7	8.0	2.1	0.1
4 60-90		0.2	1.4	3.4	4.4	9.4	23.1	67.5	8.7	8.0	1.8	0.2
5 90-110		0.3	1.4	3.6	4.4	9.7	22.6	67.8	7.8	7.9	2.2	0.2
6 110-130		0.2	1.0	2.8	4.3	8.3	22.9	68.9	7.8	7.8		0.2
7 130-165			0.6	1.9	4.2	6.7	24.6	68.7	7.8	7.8	3.9	0.2
8 165-185		0.1	0.5	1.9	3.7	6.2	22.4	71.5	7.8	7.8	4.9	0.1
9 185-220		0.1	0.5	1.5	3.1	5.2	23.2	71.6	7.8	7.8	4.5	tr

horizon nr., depth (cm)	exchangeable Na		CEC % mmol/kg	$CaSO_4$ %	water-soluble Na mmol/kg	EC mS/cm	extract for EC determination g/ml
	mmol/kg	%					
1 0-2	34	8.0	425		8	0.9	1:1
2 2-40	80	17.0	470		6	0.5	1:1
3 40-60	96	20.8	462		8	0.7	1:1
4 60-90	120	24.0	500		11	1.1	1:1
5 90-110	140	27.9	501	1.8	61	4.1	1:1.5
6 110-130	142	28.0	506	0.8			
7 130-165	142	32.3	439	9.7			
8 165-185	133	30.7	433	6.5			
9 185-220	136	27.7	491	5.3	68	4.5	1:1.5

horizon nr., depth (cm)	elemental composition of the fine earth (% by weight)												
	SiO_2	Fe_2O_3	Al_2O_3	TiO_2	MnO	CaO	MgO	Na_2O	K_2O	FeO	P_2O_5	SO_3	H_2O+
1 0-2	53.7	10.3	15.8										
2 2-40	52.9	10.3	16.1										
3 40-60	52.8	10.7	17.0										
4 60-90	52.6	10.9	17.0										
5 90-110	51.8	11.1	17.1										
6 110-130	51.3	11.0	16.3										
7 130-165	45.6	9.9	15.2										
8 165-185	48.3	10.5	16.0										
9 185-220	48.4	11.4	16.2										

horizon nr., depth (cm)				molar ratios			
	free Fe_2O_3	free Al_2O_3	amorphous Fe_2O_3	SiO_2/R_2O_3	SiO_2/Al_2O_3	SiO_2/Fe_2O_3	Al_2O_3/Fe_2O_3
1 0-2				4.1	5.8	13.9	2.4
2 2-40				4.0	5.6	13.7	2.5
3 40-60				3.8	5.3	13.2	2.5
4 60-90				3.7	5.3	12.9	2.4
5 90-110				3.6	5.1	12.4	2.4
6 110-130				3.7	5.4	12.4	2.3
7 130-165				3.6	5.1	12.2	2.4
8 165-185				3.6	5.2	12.3	2.4
9 185-220				3.5	5.1	11.3	2.3

horizon nr., depth (cm)	elemental composition of the clay fraction (% by weight)												
	SiO_2	Fe_2O_3	Al_2O_3	TiO_2	MnO	CaO	MgO	Na_2O	K_2O	FeO	P_2O_5	SO_3	H_2O+
1 0-2	43.1	12.3	16.9	1.3	0.1								
2 2-40	42.7	12.1	17.6	1.3	0.1								
3 40-60	41.3	11.9	17.1	1.2	0.1								
4 60-90	40.7	12.0	16.9	1.2	0.1								
5 90-110	39.9	11.8	16.8	1.2	0.1								
6 110-130	42.3	12.1	17.0	1.2	0.1								
7 130-165	41.8	11.8	16.8	1.2	0.1								
8 165-185	43.7	12.4	17.2	1.2	0.1								

horizon nr., depth (cm)				molar ratios			
	free Fe_2O_3	free Al_2O_3	amorphous Fe_2O_3	SiO_2/ R_2O_3	SiO_2/ Al_2O_3	SiO_2/ Fe_2O_3	Al_2O_3/ Fe_2O_3
1 0-2				3.1	4.6	9.4	2.0
2 2-40				2.9	4.1	9.4	2.3
3 40-60				2.9	4.1	9.3	2.3
4 60-90				2.8	4.1	9.1	2.2
5 90-110				2.8	4.1	9.0	2.2
6 110-130				2.9	4.2	9.3	2.2
7 130-165				2.9	4.2	9.3	2.2
8 165-185				3.0	4.3	9.4	2.2
9 185-220				2.9	4.2	9.3	2.2

SENNAR 49 (NR. 10)

date of description :	17 and 23/1/1963
USDA Soil Taxonomy :	Typic Chromustert, very-fine, montmorillonitic, isohyperthermic
FAO/UNESCO :	Chromic Vertisol (1974); Calcic Vertisol (1988)
location :	proposed site for Sennar Agricultural Research Station, north-west of Sennar Junction, topo map 1:250,000, sheet 55-K; 13°43'N - 33°32'E.
elevation :	416 m
landform :	alluvial plain of the Blue Nile
soil slope class :	flat
microrelief :	none
surface :	weak brittle surface crust, 10YR 4/2; 5/2,d, overlying a 3 mm thick mulch (see profile description); grey and white ca-nodules and few yellowish ca-granules; cracking pattern distinct
parent material :	fine-textured alluvium of the Blue Nile
vegetation or land use :	fallow after a crop of *Pennisetum typhoideum* (bullrush millet or 'dukhn') one or two seasons ago, with tall grasses *Sporobolus helveolus, Sorghum ssp., Aristida ssp, Cymbopogon nervatus* and others.

Profile description :

0-3 cm Au1	clay; dry; 10YR-2.5Y 3/2; 4/2,d; loose; fine and medium crumb structure; few grey and white ca-nodules and yellowish ca-granules; abrupt, smooth boundary.
3-55 cm Au2	clay; dry to slightly moist; 10YR-2.5Y 3/2; 4/2,d; very hard when dry; moderate fine and very fine subangular blocky, finest peds (2-10 mm) are tilted wedges that appear in the profile wall as a distinct lamination; grey ca-nodules and yellowish ca-granules; common fine and few medium roots; gradual, smooth boundary.
55-85 cm A/Bwk	clay; moist; 10YR 3/2, with pockets of 10YR 3.5/2 and 10YR 4/3 (colour of the substratum); firm; structure as in 3-55 cm, but weaker: the finest wedge-shaped peds cannot be separated from adjoining peds; ca-nodules and -granules as in 3-55 cm; distinct ca-specks in vertical streaks; gradual, smooth boundary.
85-130 cm B/Awky	clay; moist; heterogeneous, with equal quantities of 10YR 3/2-soil and 10YR 3.5/2-soil; firm; structure similar to that in 55-85 cm: the largest peds are tilted wedges up to 3 cm, with shiny faces, whereas the finest parallelepipeds, of 2 mm high, appear as a fine lamination on the profile wall, and they adhere together; ca-nodules and -granules as above; some aggregates of soft powdery lime; common fine gypsum crystals in clusters or forming fine threads; common salt efflorescence as prominent, white pseudomycelium; gradual, smooth boundary.
130-160 cm Bwky	clay; moist; 10YR 3/1; firm; structure as in 85-130 cm, but tilted wedges slightly larger, with slickensided ped surfaces; few large aggregates of yellowish-white soft powdery lime; common medium gypsum crystals, lense-shaped to angular; salt efflorescence as pseudomycelium on shiny ped faces and slickensides; gradual, smooth boundary.
160-190 cm B/2Cwky	clay; moist; transitional horizon with equal quantities of 10YR 3/1-subsoil and 10YR 4/2-substratum; firm; weak to moderate coarse angular blocky: peds are tilted wedges with grooved, slickensided surfaces (the grooves occur in patterns of two wavelengths); the profile wall shows a fine lamination similar to that in 85-160 cm; common large distinct aggregates of soft powdery lime; grey and white ca-granules; gypsum accumulation as in overlying horizon; salt efflorescence on ped faces; diffuse, smooth boundary.

190-260 cm+ 2Cky — clay; moist; 10YR 4/2 and 10YR 4/3, with pockets of 7.5YR 4/4; firm; moderate coarse, medium and fine angular blocky: peds are tilted wedges with shiny surfaces and the lamination of the profile wall is weak; slickensides are less distinct as compared to overlying horizon; common dark-grey ca-granules leaving a slight imprint (manganese or manganese with iron) when removed from the soil; few white ca-granules; weak fine (iron)-manganese coatings on ped surfaces; common large, distinct aggregates of soft powdery lime forming vertical streaks up to 20 cm long; some large clusters with medium yellowish gypsum crystals; salt efflorescence on slickensides.

Remarks:

1. Cracks are wide till 70 cm depth, and can be traced till about 150 cm.
2. In 3-55 cm some fine and medium roots, in 55-85 cm common fine roots, in 85-260 cm fine roots adhered to slickensides.
3. One distinct slickenside observed in 130-160 cm; slickensides are distinct in 160-190 cm, less distinct in 190-260 cm.
4. Termite nests occur throughout the profile below 85 cm.

Summary profile description:

A very deep clay profile (described till 260 cm) with a 10YR-2.5Y 3/2 surface soil (90-55 cm), overlying a heterogeneous soil with pockets of 10YR 3/2, 10YR 3.5/2 and 10YR 4/3 (55-130 cm), that in turn overlies a 10YR 3/1-subsoil. Through a heterogeneous horizon (B/2C, 160-190 cm), a substratum (2C horizon) is reached at 190 cm. It has colours of 10YR 4/2, 10YR 4/3 and 7.5YR 4/4. There is a vertic structure with tilted wedges and a lamination caused by fine parallelepipeds, protruding obliquely from the profile wall. The finest tilted wedges (parallelepipeds) occur as discrete peds in the A horizon only.
Grey ca-nodules and -granules occur throughout the profile. Fine ca-specks occur in the A/Bk horizon (55-85 cm); deeper in the profile there are larger aggregates of soft powdery lime.
Gypsum appears first in the A/B horizon (55-85 cm) as fine crystals; with depth crystals are getting larger and more numerous; gypsum occurs till 260 cm depth.
Salt efflorescences and pseudomycelium occur below 85 cm; these may be gypsum or more soluble salts, or both.
Few fine coatings of manganese, or manganese with iron, occur in the C horizon, on slickensides, and embedding dark-grey ca-granules.

Laboratory data of profile 10, Sennar 49

horizon nr., depth (cm)	particle size distribution, µm; % of fine earth								pH		$CaCO_3$ %	org. carbon %
	sand						silt	clay				
	2000-1000	1000-500	500-250	250-100	100-50	total	50-2	<2	H_2O	0.01M $CaCl_2$		
1 0-3	0.3	1.3	2.8	4.3	3.6	12.3	20.5	67.2	8.1	7.4[1)]	10.2	0.5
2 3-25 } 3 25-55 }	0.1	1.1	2.2	3.6	2.8	9.8	19.3	70.9	8.5	7.7	6.6	0.4
5 85-130		0.7	1.5	2.3	2.1	6.6	22.9	70.4	7.9	7.7	10.8	0.3
6 130-160		0.5	1.4	2.1	2.5	6.5	19.5	73.9	8.0	7.7	6.3	0.4
8 190-260	0.1	0.5	1.1	1.9	2.1	5.7	22.2	72.7	8.3	7.9	8.3	0.2

horizon nr., depth (cm)	exchangeable Na		CEC % mmol/kg	$CaSO_4$ %	water-soluble Na mmol/kg	EC mS/cm	extract for EC determination g/ml
	mmol/kg	%					
1 0-3	19	4.1	458		4	0.7	1:1
2 3-25	47	11.4	411		5	0.5	1:1
3 25-55	67	15.1	444		9	0.4	1:1.5
5 85-130	110	24.1	456		18	1.2	1:1.5
6 130-160	156	30.1	519	0.4	76	3.6	1:2
8 190-260	153	36.1	424		57	2.7	1:2

horizon nr., depth (cm)	elemental composition of the fine earth (% by weight)												
	SiO_2	Fe_2O_3	Al_2O_3	TiO_2	MnO	CaO	MgO	Na_2O	K_2O	FeO	P_2O_5	SO_3	H_2O+
1 0-3	50.2	7.3	14.2	1.1	0.2	7.4	3.1						
2/3 3-55	52.1	7.8	15.1	1.1	0.1	5.2	2.8						
5 85-130	48.0	7.6	14.6	1.1	0.1	7.6	3.1						
6 130-160	51.7	8.0	15.6	1.1	0.1	4.6	3.5						
8 190-260	50.1	8.0	15.4	1.1	0.1	6.1	3.3						

horizon nr., depth (cm)				molar ratios			
	free Fe_2O_3	free Al_2O_3	amorphous Fe_2O_3	SiO_2/R_2O_3	SiO_2/Al_2O_3	SiO_2/Fe_2O_3	Al_2O_3/Fe_2O_3
1 0-3				4.3	6.0	18.2	2.0
2/3 3-55				4.4	5.1	17.9	2.1
5 85-130				4.2	5.6	16.8	3.0
6 130-160				4.2	5.6	17.1	3.0
8 190-260				4.2	5.5	16.8	2.0

horizon nr., depth (cm)	elemental composition of the clay fraction (% by weight)												
	SiO_2	Fe_2O_3	Al_2O_3	TiO_2	MnO	CaO	MgO	Na_2O	K_2O	FeO	P_2O_5	SO_3	H_2O+

horizon nr., depth (cm)				molar ratios			
	free Fe_2O_3	free Al_2O_3	amorphous Fe_2O_3	SiO_2/R_2O_3	SiO_2/Al_2O_3	SiO_2/Fe_2O_3	Al_2O_3/Fe_2O_3

[1] pH in saturated CaSO4 instead of 0.01 M CaCl2

SENNAR 71 (NR. 11)

date of description :	24/1/1963
USDA Soil Taxonomy :	Entic Chromustert, very-fine, montmorillonitic, isohyperthermic
FAO/UNESCO :	Chromic Vertisol (1974); Calcic Vertisol (1988)
location :	proposed site for Sennar Agricultural Research Station, north-west of Sennar Junction; topo map 1:250,000, sheet 55-K; 13°37'N - 33°32'E.
elevation :	420 m
landform :	alluvial plain of the Blue Nile
soil slope class :	flat
microrelief :	none; the profile site is in a ponded area without surface runoff.
surface :	cracks, at the surface 10 cm wide, at 5 cm depth 5 cm wide, enclose polygons of about 50 cm across; surface mulch is weakly developed and thin.
parent material :	fine-textured alluvium of the Blue Nile
vegetation or land use :	tall grass *Sporobolus helveolus* in tufts; between the tufts the soil is bare; few bushes of *Acacia seyal* and *Acacia nubica.*

Profile description (soil structure and some other characteristics are described separately below) :

0-1 cm Au1	clay; dry; fine granular surface mulch; abrupt, smooth boundary.
1-25 cm Au2	clay; dry; 2.5Y-10YR 4/2; 10YR 4.5/2,d; slightly hard; grey ca-nodules and white ca-granules; much coarse sand and fine gravel; shell fragments; gradual, smooth boundary.
25-50 cm Au3	clay; slightly moist; hard when dry, firm when moist; colour, ca-nodules and ca-granules, and shell fragments as above horizon; gradual, smooth boundary.
50-105 cm Ak	clay; moist; 10YR 3.5/2; firm; many white ca-granules; few fine ca-specks; gradual, smooth boundary.
105-165 cm A/Bwk	clay; moist; heterogeneous horizon: surface soil tonguing into 10YR 3/2 subsoil; the surface soil fragments have a friable consistence, those of the subsoil are firm; common ca-specks in vertical streaks; abundant fine 'ca-gravel': granules, nodules, soft and hard concretions; gradual, smooth boundary.
165-215 cm B/2Cwk	clay; moist; heterogeneous horizon, transitional between 10YR 3/2 subsoil and 10YR 4/3 substratum; firm; strong accumulation of carbonates in various forms: grey nodules and granules, white granules, some large white aggregates of soft powdery lime containing hard white nodules (concretions); some of the grey nodules leave a manganese coating when taken from the soil mass; gradual, smooth boundary.
215-280 cm+ 2Ck	clay; moist; 10YR 4/3 (in lowest part of horizon tending towards 2.5Y 4/3), with pockets of 7.5YR 4/4; firm; carbonatic accumulations as in overlying horizon; grey nodules leave a metallic-bluish imprint when removed from the soil.

General descriptions :

A. Soil structure

The type of structure is subangular (0-50 cm) to angular (50-280 cm) blocky with wedge-shaped peds that are protruding obliquely from the profile wall, showing as a subhorizontal lamination. In the surface soil till 50 cm these wedge-shaped peds, with dimensions of 1 to 2 cm, are subdivided into finer wedges, and these may consist of even finer ones of the same shape. The finest peds are about 10 mm wide, 2 mm high and 4 mm deep parallelepipeds.

From 50 to 105 cm the structure remains the same, but the finest peds of the compound structure become slightly coarser.

From 105 to 280 cm the structure is not distinctly compound and peds vary in size between 5 and 20 mm. There are two major differences with the surface soil : firstly, the finest wedge-shaped peds appear as a 'visible' structure only, a predisposition for a fine bicuneate structure; and, secondly, the ped faces are shiny and have the characteristics of small slickensides. This feature is at a maximum between 105 and 215 cm, but shiny faces are also found in 50-105 cm and 215-280 cm.

B. Cracks are distinct till 60 cm, and can be traced till 110 cm.

C. Roots are frequent in 0-50 cm, frequent to few in 50-100 cm, and very few in 100-280 cm.

D. There is some termite activity throughout the profile, till 280 cm depth at least.

Summary profile description :

A Vertisol profile with relatively high value of the surface soil colour (Entic subgroup cf. USDA Soil Taxonomy). The 10YR 4/2 surface soil (A horizon, 0-105 cm) overlies a 10YR 3/2 subsurface soil (A/B horizon, 105-165 cm), that - through another transitional horizon (B/2C, 165-215 cm) - overlies a substratum (2C horizon) with colour 10YR 4/3.

Structural aggregates are tilted wedge-shaped peds throughout; in the surface 50 cm coarser peds can be parted into increasingly finer ones of the same shape, whereas below 105 cm the structure is not compound and peds have average dimensions between 5 and 20 mm. Ped faces are slickensided below 50 cm, strongest between 105 and 215 cm.

Grey ca-nodules and white ca-granules occur throughout the profile. Fine ca-specks occur between 50 and 160 cm, and aggregates of soft powdery lime, containing hard white ca-nodules, occur below 105 cm, and are most distinct between 165 and 215 cm. Below 105 cm there is a strong accumulation of carbonates in all forms that have been described in any of the overlying horizons.

Mottles of manganese, or manganese with ferric iron, occur below 165 cm, but most clearly below 215 cm, generally as a double coating of soil matrix and enclosed grey ca-nodule.

JEBEL ABEL (NR. 12)

date of description :	12/5/1963
USDA Soil Taxonomy :	Entic Chromustert, very-fine, montmorillonitic, isohyperthermic
FAO/UNESCO :	Chromic Vertisol (1974); Calcic Vertisol (1988)
location :	3 km west of Abu Na'ama village, on road to Jebel Abel; topo map 1:250,000, sheet 55-O; 12°43'N - 34°06'E.
elevation :	440 m
landform :	alluvial plain of the Blue Nile
soil slope class :	flat
microrelief :	uneven surface, but no gilgai
surface :	cracks, 5 to 10 cm wide, enclose polygons of approximately 50 cm diameter; a well-developed surface mulch (granular peds, 2 to 10 mm) obscures the cracks to a large extent, and there is also slumping due to recent rains; fine surface cracks have developed in a brittle crust that has formed upon drying after recent rains; some white ca-nodules, 2-3 cm diameter; colour of surface crust: 2.5Y 4/2,wet, 2.5Y 4/2 and 5/2, dry.
parent material :	fine-textured alluvium of the Blue Nile
vegetation or land use :	woodland savannah with dominantly *Balanites aegyptiaca* and *Acacia seyal* (both red-bark and green-bark varieties), and some *Acacia fistula, A.mellifera* and *A.nubica.* Some dry stalks of *Sorghum ssp.*

Profile description :

0-15 cm Au1	clay; dry below a few mm's wet surface soil; 2.5Y 4/2;(10YR)-2.5Y 4/2,d; very hard (mulch: hard); moderate medium angular blocky with wedge-shaped peds protruding obliquely from the profile wall; wide cracks largely filled with loose mulch; few white ca-granules; many medium and fine roots; diffuse, smooth boundary.
15-30 cm Au2	as overlying horizon, but grade of structure is very weak; however, the lamination on the profile wall of obliquely protruding fine tilted wedges is clear; diffuse, smooth boundary.
30-60 cm Au3	clay; dry; 2.5Y 4/2;10YR-2.5Y 4/2,d; very weak angular blocky with a distinct bicuneate substructure, showing as a lamination on the profile wall; few white ca-granules and rare grey ca-nodules; frequent fine roots; diffuse, smooth boundary.
60-90 cm Bw1	clay; dry, with depth to moist; (10YR)-2.5Y 3/2; extremely hard when dry, extremely firm when moist; almost structureless, but the profile wall shows a moderately distinct subhorizontal lamination; incipient peds have faintly shiny faces; some reddish-coated, some grey and some white ca-granules; some fine pockets of reddish soil; few fine (iron-)manganese mottles; few fine roots; diffuse, smooth boundary.
90-110 cm Bw2	clay; moist; 10YR 3/2; extremely firm; very weak structure, lamination weaker than in 60-90 cm; termite tunnels with debris; ca-concentrations and (iron-)manganese mottles as in 60-90 cm; some pockets of yellowish and reddish soil; few fine roots; gradual, smooth boundary.
110-150 cm Bwk1	clay; moist; 10YR 2.5/1; extremely firm; very weak angular and subangular blocky with faintly shiny ped faces; no lamination; common white ca-granules, sometimes occurring in nests, embedded in soft powdery lime; common pockets of reddish and yellowish soil; frequent termite tunnels; few fine roots; diffuse, smooth boundary.

150-190 cm+ Bwk2	clay; moist; 10YR 2.5/1; extremely firm; weak subangular blocky with distinctly shiny ped faces; common to many white and grey ca-nodules, 10 to 20 mm diameter; frequent pockets of reddish soil; few roots; a termite cavity at 190 cm.

Remarks:

1. There is hardly any vertical differentiation. Mainly for the sake of sampling the profile has been divided into 30 cm-steps (and 15 cm-steps for the first two samples). The only visible soil boundary is at 110 cm: a change of colour.
2. Cracks distinct till 60 cm, traceable till 90 cm.
3. Few shell fragments and few pieces of charcoal are found throughout the profile.
4. Effervescence with HCl: weak in 0-30 cm, none in the soil matrix below 30 cm.
5. The ca-granules that occur embedded in soft powdery lime (110-150 cm) may represent weathering of larger ca-nodules, or hardening nuclei in a large soft aggregate.
6. A yellowish-brown (?) substratum (2C) is not reached within 190 cm.
7. Manganese coatings around ca-nodules have not been found.

Summary profile description:

Vertisol profile with hardly any horizon differentiation; the surface soil (A horizon, 0-60 cm) has a colour 2.5Y 4/2, it overlies a Bw horizon (60-110 cm) with colour 10YR-2.5Y 3/2, merging with a 10YR 2.5/1 Bwk horizon.

Structure is weak angular to subangular blocky with a parallelepiped substructure till 110 cm; shiny ped faces occur below 60 cm, and are most distinct in 150-190 cm.

Fine white ca-granules occur throughout; reddish-coated and grey ca-granules are found below 60 cm; white ca-granules embedded in soft powdery lime occur below 110 cm.

Manganese or (iron-)manganese mottles are few below 60 cm.

Laboratory data of profile 12, Jebel Abel

horizon nr., depth (cm)	particle size distribution, µm; % of fine earth								pH		$CaCO_3$ %	org. carbon %
	sand						silt	clay				
	2000-1000	1000-500	500-250	250-100	100-50	total	50-2	<2	H_2O	0.01M $CaCl_2$		
1 0-15	0.1	0.8	3.4	6.3	3.2	13.8	18.4	67.8	7.6	7.2[1)]	0.5	0.6
2 15-30	0.1	0.6	2.5	4.8	3.5	11.5	19.6	68.9	8.0	7.5	2.0	0.4
4 60-90		0.4	1.9	3.9	3.1	9.3	18.8	71.9	8.5	7.9	0.7	0.3
5 90-110		0.4	1.8	4.3	3.0	9.5	16.0	74.6	8.5	8.0	0.9	0.3
6 110-150		0.2	1.5	3.6	2.8	8.1	11.0	81.0	8.6	8.0	4.2	0.2
7 150-190		0.3	1.2	3.2	2.4	7.1	18.1	74.8	8.6	8.2	2.1	0.2

horizon nr., depth (cm)	exchangeable Na		CEC % mmol/kg	$CaSO_4$ %	water-soluble Na mmol/kg	EC mS/cm	extract for EC determination g/ml
	mmol/kg	%					
1 0-15	38	7.0	542		6	0.4	1:1.5
2 15-30	71	13.0	545		8	0.4	1:1.5
4 60-90	137	24.2	566		13	0.7	1:2
5 90-110	154	26.3	585		15	0.9	1:2
6 110-150	178	27.3	652				
7 150-190	179	26.5	676		16	0.9	1:2

horizon nr., depth (cm)	elemental composition of the fine earth (% by weight)												
	SiO_2	Fe_2O_3	Al_2O_3	TiO_2	MnO	CaO	MgO	Na_2O	K_2O	FeO	P_2O_5	SO_3	H_2O+
1 0-15	54.4	8.5	16.5	1.2	0.1	2.1	2.6						
2 15-30	54.2	8.9	17.0	1.1	0.1	2.0	2.7						
4 60-90	52.3	9.1	17.6	1.2	0.1	2.1	2.7						
5 90-110	52.9	9.1	17.8	1.2	0.1	1.7	2.9						
6 110-150	49.7	8.9	17.3	1.1	0.1	3.6	2.9						
7 150-190	51.7	9.1	18.0	1.2	0.1	2.5	2.6						

horizon nr., depth (cm)				molar ratios			
	free Fe_2O_3	free Al_2O_3	amorphous Fe_2O_3	SiO_2/ R_2O_3	SiO_2/ Al_2O_3	SiO_2/ Fe_2O_3	Al_2O_3/ Fe_2O_3
1 0-15				4.2	5.6	17.1	3.1
2 15-30				4.1	5.1	16.2	3.0
4 60-90				3.8	5.1	15.3	3.0
5 90-110				3.8	5.1	15.5	3.1
6 110-150				3.7	4.9	14.9	3.1
7 150-190				3.7	5.5	15.2	3.1

horizon nr., depth (cm)	elemental composition of the clay fraction (% by weight)												
	SiO_2	Fe_2O_3	Al_2O_3	TiO_2	MnO	CaO	MgO	Na_2O	K_2O	FeO	P_2O_5	SO_3	H_2O+
1 0-15	45.9	11.9	21.0	1.2	0.1								
2 15-30	45.4	11.8	21.1	1.1	0.1								
4 60-90	45.4	12.2	20.6	1.1	0.1								
5 90-110	45.5	11.7	20.5	1.1	0.1								
6 110-150	45.0	11.5	20.2	1.1	0.1								
7 150-190	45.7	11.3	20.1	1.1	tr								

horizon nr., depth (cm)				molar ratios			
	free Fe_2O_3	free Al_2O_3	amorphous Fe_2O_3	SiO_2/ R_2O_3	SiO_2/ Al_2O_3	SiO_2/ Fe_2O_3	Al_2O_3/ Fe_2O_3
1 0-15				2.7	3.7	10.3	2.8
2 15-30				2.7	3.7	10.3	2.8
4 60-90				2.7	3.8	9.9	2.6
5 90-110				2.8	3.8	10.4	2.8
6 110-150				2.8	3.8	10.5	2.8
7 150-190				2.8	3.9	10.8	2.8

[1] pH in saturated CaSO4 instead of 0.01 M CaCl2

TOZI (NR. 13)

date of description :	12/5/1963
USDA Soil Taxonomy :	Entic Pellustert, very-fine, montmorillonitic, isohyperthermic
FAO/UNESCO :	Pellic Vertisol (1974); Calcic Vertisol (1988)
location :	20 km from Tozi Agricultural Research Station, on road to Jebel Abel; topo map 1:250,000, sheet 55-O; 12°37'N - 34°04'E.
elevation :	455 m
landform :	alluvial plain of the Blue Nile; the profile is situated in a wide, shallow depression
soil slope class :	flat
microrelief :	uneven surface but no gilgai; there are probably two factors causing the irregular surface: firstly, the site is in a wide depression and there may be a pattern of very small khors; secondly, there has been much cutting of trees for charcoal burners.
surface :	a finely cracked, brittle surface crust (10YR 4/1; 10YR 6/1-2.5Y 6/2,d) overlies a fine-sandy clay soil that easily breaks into a 1 to 3 mm crumb mulch; the crust contains embedded grains of medium and coarse sand and white ca-granules; cracks 2 cm wide, partly obscured by mulch.
parent material :	fine-textured alluvium of the Blue Nile
vegetation or land use :	woodland savannah strongly affected by man (see under ' microrelief'), with *Acacia mellifera* and other shrubs, and scattered trees of *Balanites aegyptiaca*; grasses few, *Chloris virgata* and other species.

Profile description :

0-30 cm	clay; dry; 10YR(-2.5Y) 4/1;10YR 5/1,d; slightly hard, except for the thin surface mulch that is loose; structure below mulch is weak coarse, medium and fine subangular blocky;cracks 1 to 2 cm wide; common white ca-nodules; coarse sand grains, medium, fine and fibrous roots; diffuse, smooth boundary.
30-60 cm	clay; slightly moist, with depth to moist; 10YR(-2.5Y) 4/1; extremely firm; very weak fine angular blocky to structureless, massive; cracks narrowing with depth and ending at about 60 cm; many white, partly reddish-coated ca-granules; coarse sand grains; few fine roots; termite tunnels; diffuse, smooth boundary.
60-90 cm	clay; moist; like 30-60 cm except for the absence of cracks; there is a cavity with an inclined slickenside face that is wet; diffuse, smooth boundary.
90-120 cm	clay; moist; 10YR 4/2; extremely firm; weak bicuneate structure with finest peds appearing as a faint lamination of the profile wall; ca-granules and sand grains as in 30-90 cm; distinct pockets of reddish soil; termite tunnels with debris; diffuse, smooth boundary.
120-150 cm	clay; moist; 10YR 4/1; extremely firm; moderate bicuneate structure and lamination of the profile wall; many white and partly reddish-coated ca-granules; common fine, distinct ferric mottles; pockets of reddish soil; pockets of lighter-coloured sandy soil; few fine roots; diffuse, smooth boundary.
150-170 cm+	clay, with about 30% pockets of coarser-textured soil with glittering primary sand-size minerals (mica, quartz) and few ferric mottles; colours: 10YR 4.5/2 (clay matrix), 2.5Y4/2 (sandy pockets), 10YR 4/4 (ferric mottles); bicuneate structure, but lamination of the profile wall faint; ca-granules and ferric mottles as in 120-150 cm; few fine roots.

Remarks:

1. Cracks 1-2 cm wide in 0-30 cm, narrower below, and ending at about 60 cm.
2. The wet slickenside surface described in 60-90 cm shows that the adjoining void is connected with cracks that have transmitted recent rain to the subsoil.
3. The vertic structure is weakly developed, strongest in 120-150 cm. The lamination of the profile wall, caused by slightly protruding (fine) wedge-shaped peds is only present - and weakly expressed - in 90 to 150 cm.
4. Reddish-coloured sandy pockets (7.5YR 4/4) between 90 and 170 cm are, in part, filled-in termite tunnels; they show micaceous minerals and have few ferric mottles.
5. There is hardly any profile differentiation, and therefore no horizon symbols are added; there is a slight change in colour with depth, mainly caused by the increasing amounts of reddish (7.5YR 4/4) and greyish (2.5Y 5/2) sandy pockets.
6. The ferric mottles in the lower part of the solum are perhaps primary minerals, subject to hydrolysis and release of iron, that subsequently pigments the (remnants) of the mineral grains.
7. The clay sediment is probably not much thicker than 170 cm.

Summary profile description:

An Entic Pellustert with uniform colour of the clay matrix of 10YR 4/1 throughout; below 90 cm there is an increasing amount (till 30% in 150-170 cm) of reddish (7.5YR 4/4) and greyish (2.5Y 5/2) sandy pockets with micaceous minerals and fine ferric mottles. Some of the sandy pockets are infilled termite tunnels and cavities.

The structure is weakly vertic between 90 and 170 cm depth.

Few to frequent white or partly reddish-coated ca-granules occur throughout the profile; no other forms of ca-concentration are present. Horizon differentiation is practically nil; there are slight changes in grade of structure, and a with depth increasing amount of sandy pockets. Horizon symbols have been omitted.

Laboratory data of profile 13, Tozi

horizon nr., depth (cm)	particle size distribution, µm; % of fine earth								pH		$CaCO_3$ %	org. carbon %
	sand						silt	clay				
	2000-1000	1000-500	500-250	250-100	100-50	total	50-2	<2	H_2O	0.01M $CaCl_2$		
1 0-15 / 2 15-30	0.3	1.2	2.1	8.3	8.2	20.1	23.1	56.8	8.1	7.5[1]	16.6	0.8
4 60-90	0.2	0.5	2.1	5.6	6.4	14.8	22.6	62.6	8.8	7.9	15.5	0.5
5 90-120	0.1	0.7	2.0	6.5	6.9	16.2	24.5	59.3	8.8	7.9	15.3	0.5
6 120-150		0.4	1.4	5.1	6.1	13.0	23.0	64.0	9.0	7.9	15.6	0.4
7 150-170		0.6	1.7	5.3	5.4	13.0	23.2	60.8	9.0	7.9	15.4	0.6

horizon nr., depth (cm)	exchangeable Na		CEC % mmol/kg	$CaSO_4$ %	water-soluble Na mmol/kg	EC mS/cm	extract for EC determination g/ml
	mmol/kg	%					
1 0-15	28	9.2	303		9	0.8	1:1
2 15-30	117	34.6	338		12	0.8	1:1.5
4 60-90	159	48.5	338		12	0.8	1:1.5
5 90-120	155	47.6	326		12	0.8	1:1.5
6 120-150	163	52.6	310				
7 150-170	176	51.3	343		12	0.8	1:1.5

horizon nr., depth (cm)	elemental composition of the fine earth (% by weight)												
	SiO_2	Fe_2O_3	Al_2O_3	TiO_2	MnO	CaO	MgO	Na_2O	K_2O	FeO	P_2O_5	SO_3	H_2O+
1/2 0-30	48.1	6.6	13.0	1.0	0.2	10.2	4.9						
4 60-90	47.1	7.0	13.9	1.1	0.1	9.7	5.0						
5 90-120	47.1	6.9	13.2	1.1	0.1	9.5	5.6						
6 120-150	47.3	6.9	13.6	1.1	0.1	9.2	5.7						
7 150-170	46.7	7.1	13.8	1.1	0.1	9.2	6.2						

horizon nr., depth (cm)				molar ratios			
	free Fe_2O_3	free Al_2O_3	amorphous Fe_2O_3	SiO_2/ R_2O_3	SiO_2/ Al_2O_3	SiO_2/ Fe_2O_3	Al_2O_3/ Fe_2O_3
1/2 0-30				4.8	6.3	19.5	3.1
4 60-90				4.4	5.8	17.9	3.2
5 90-120				4.6	6.1	18.3	3.0
6 120-150				4.5	5.9	18.3	3.1
7 150-170				4.3	5.8	17.4	3.0

horizon nr., depth (cm)	elemental composition of the clay fraction (% by weight)												
	SiO_2	Fe_2O_3	Al_2O_3	TiO_2	MnO	CaO	MgO	Na_2O	K_2O	FeO	P_2O_5	SO_3	H_2O+

horizon nr., depth (cm)				molar ratios			
	free Fe_2O_3	free Al_2O_3	amorphous Fe_2O_3	SiO_2/ R_2O_3	SiO_2/ Al_2O_3	SiO_2/ Fe_2O_3	Al_2O_3/ Fe_2O_3

[1] pH in saturated CaSO4 instead of 0.01 M CaCl2

DAMAZEEN (NR. 14)

date of description :	13/5/1963
USDA Soil Taxonomy :	both profiles, A and B: Typic Chromustert, very-fine, montmorillonitic, isohyperthermic
FAO/UNESCO :	profile A, depression site: Chromic Vertisol (1974); Eutric Vertisol (1988);
profile B, mound site:	Chromic Vertisol (1974); Calcic Vertisol (1988)
location :	10 km west of Damazeen town; topo map 1:250,000, sheet 66-C; 11°51'N - 34°15'E.
elevation :	480 m
landform :	alluvial plain of the Blue Nile
soil slope class :	flat
microrelief :	distinct normal gilgai: wavelength 8-12 m, amplitudo 20-30 cm. In lowest part of the gilgai depression there is usually a distinct sinkhole, 50-100 cm diameter and 20-40 cm deep.
surface :	well-developed surface mulch; gilgai mounds are covered with many white ca-nodules; wide cracks are closed at the surface due to sloughing of mud after recent rains.
parent material :	fine-textured alluvium of the Blue Nile
vegetation or land use :	woodland savannah with *Combretum hartmannianum* dominant (with fresh leaves after recent rain), *Acacia seyal* subdominant, and some *Zizyphus spina-christi*; surface cover of fresh green grass, about 5 cm high.

Separate profile descriptions are given for the gilgai depression and the gilgai mound sites.
Profile description of gilgai depression, Damazeen A :

0-15 cm	clay; moist; 2.5Y(-10YR) 3/2; slightly hard; strong fine subangular blocky with wedge-shaped peds giving the profile wall a finely laminated appearance; some grey, white and reddish ca-nodules; many sand grains; diffuse, smooth boundary.
15-30 cm	clay; moist; 2.5Y 3/2; friable; weak medium and coarse angular blocky, with a distinct parallelepiped substructure; ca-nodules and sand grains as in 0-15 cm; diffuse, smooth boundary.
30-60 cm	clay; moist; 2.5Y 4/2; moderate coarse, medium and fine angular blocky with wedge-shaped peds protruding obliquely from the profile wall; common grey (iron-) manganese nodules (no effervescence with HCl), leaving a coating when taken from the soil; some pockets with sandy soil; diffuse, smooth boundary.
60-90 cm	clay; moist to wet; 2.5Y 4/2; very firm; structure as in 30-60 cm, and peds have shiny faces; grey (iron-)manganese nodules and -coatings and sandy pockets as in 30-60 cm; diffuse, smooth boundary.
90-120 cm	clay; moist; 2.5Y 3/2; moderate angular blocky with tilted wedges that have slickensided ped faces, a finer lamination is present as a visible structure only; few grey (iron-)manganese nodules; pockets of sandy soil, and of sand mixed with clay; diffuse, smooth boundary.
120-150 cm	clay; moist; 2.5Y 3/2; the same features as described for 90-120 cm occur in this layer; in addition: few white ca-nodules, 2 to 10 mm diameter; diffuse, smooth boundary.
150-180 cm+	clay; moist; 2.5Y 4/2; otherwise as 120-150 cm.

Remarks :
1. Changes with depth are very gradual; there is no horizon differentiation, and horizon symbols have been omitted.
2. Cracks are open, except for the surface, till 180 cm and deeper.

Profile description of gilgai mound, Damazeen B:

0-15 cm	clay; wet; 10YR-2.5Y 3/2; bicuneate structure, but finest peds are crumb; many ca-specks and white ca-nodules; common grey ca-nodules; pockets of sandy soil; diffuse, smooth boundary.
15-30 cm	clay; moist; 10YR-2.5Y 3.5/2; bicuneate structure well-defined, finest peds, with dimensions of 1 to 5 mm, are discrete; grey ca-nodules leave a faint coating of (iron-)manganese when removed from the soil; ca-specks and white ca-nodules as above; diffuse, smooth boundary.
30-60 cm	clay; moist; 2.5Y 3/2; moderate coarse, medium and fine angular blocky with wedge-shaped peds that have slickensided faces; a finer lamination is present but parallelepipeds are not discrete; ca-nodules and -granules as in 15-30 cm; grey ca-nodules leave a distinct (iron-)manganese coating when removed from the soil; all forms of ca-concentration are decreasing in abundance with depth; diffuse, smooth boundary.
60-90 cm	clay; moist; 2.5Y 3/2; moderate to strong very coarse, coarse and medium angular blocky with wedge-shaped and slickensided ped faces; structure is strongest near cracks; otherwise as 60-90 cm in profile A, but grey nodules contain carbonate, and are more common; diffuse, smooth boundary.
90-120 cm	clay; moist; 2.5Y 3/2; otherwise as 90-120 cm in profile A, but grey nodules contain carbonate, and are more common; diffuse, smooth boundary.
120-150 cm	clay; moist; 2.5Y 3/2; otherwise as 120-150 cm in profile A, but grey nodules contain carbonate and are slightly more common; diffuse, smooth boundary.
150-180 cm+	clay; moist; 2.5Y 3/2; otherwise as 150-180 cm in profile A, but grey nodules contain carbonate and are perhaps slightly more common.

Remarks:
1. Changes with depth are very gradual; no horizon differentiation, no horizon symbols.
2. Frequent fine roots throughout the profile.
3. Soil is wet till 15 cm due to recent rains.

Summary description of the two profiles :
There are two profiles from the Damazeen site: one is from a gilgai depression (profile A), the other from the adjoining gilgai mound (profile B). The trench pit was too short to place the profiles at the very highest and very lowest point of the microrelief. The profiles are alike in colour, lack of horizon differentiation and structure.
Colours are uniform 2.5Y 3/2 (with sometimes 10YR 3/2 and 2.5Y 4/2). Vertic structure is well-developed, with fine tilted wedges in the surface soil, causing a lamination of the profile wall, and a coarser bicuneate structure with slickensided ped faces below about 60 cm.
Different between the two profiles are, in 0-60 cm, the amount and nature of grey nodules: in profile A these are dominantly non-carbonatic and common, in profile B carbonatic and more abundant. In addition, in profile B there is soft powdery lime (ca-specks) in 0-30 cm. In 60-120 cm there is a similar difference, but less distinct: in profile A both carbonatic and non-carbonatic grey nodules are probably present. In 120-180 cm carbonatic grey nodules occur in both profiles, but they are more common in profile B.

Laboratory data of profile 14A, Damazeen A (depression)

horizon nr., depth (cm)	particle size distribution, µm; % of fine earth								pH		$CaCO_3$ %	org. carbon %
	sand						silt	clay				
	2000-1000	1000-500	500-250	250-100	100-50	total	50-2	<2	H_2O	0.01M $CaCl_2$		
1 0-15 / 2 15-30	0.1	1.7	9.1	12.2	5.6	28.7	13.7	57.7	6.6	6.5	0.2	0.6
3 30-60 / 4 60-90	0.1	1.5	12.1	10.6	5.2	29.5	11.1	59.4	7.4	7.1	0.2	0.4
5 90-120	0.2	2.2	9.8	10.2	4.8	26.2		73.8	8.1	7.6	0.3	0.4
6 120-150 / 7 150-180	0.1	1.9	9.3	8.4	5.0	24.7	0.6	74.8	8.3	7.5	1.2	0.3

horizon nr., depth (cm)	exchangeable Na		CEC % mmol/kg	$CaSO_4$ %	water-soluble Na mmol/kg	EC mS/cm	extract for EC determination g/ml
	mmol/kg	%					
1 0-15	1	0.3	294				
2 15-30	1	0.3	303				
3 30-60	1	0.3	317				
4 60-90	3	1.0	310				
5 90-120	8	2.6	306				
6 120-150	18	5.7	314				
7 150-180	24	7.5	318				

horizon nr., depth (cm)	elemental composition of the fine earth (% by weight)												
	SiO_2	Fe_2O_3	Al_2O_3	TiO_2	MnO	CaO	MgO	Na_2O	K_2O	FeO	P_2O_5	SO_3	H_2O+
1/2 0-30	59.9	7.6	15.4	1.0	0.1	1.7	1.9						
3/4 30-90	58.6	7.7	15.6	1.0	0.1	1.8	1.9						
5 90-120	56.9	7.6	15.4	1.0	0.1	2.3	2.0						
6/7 120-180	59.3	7.3	15.0	1.0	0.1	1.6	1.8						

horizon nr., depth (cm)				molar ratios			
	free Fe_2O_3	free Al_2O_3	amorphous Fe_2O_3	SiO_2/R_2O_3	SiO_2/Al_2O_3	SiO_2/Fe_2O_3	Al_2O_3/Fe_2O_3
1/2 0-30				5.0	6.6	21.1	3.2
3/4 30-90				4.9	6.4	20.4	3.2
5 90-120				4.8	6.3	20.0	3.2
6/7 120-180				5.1	6.7	21.6	3.2

horizon nr., depth (cm)	elemental composition of the clay fraction (% by weight)												
	SiO_2	Fe_2O_3	Al_2O_3	TiO_2	MnO	CaO	MgO	Na_2O	K_2O	FeO	P_2O_5	SO_3	H_2O+

horizon nr., depth (cm)				molar ratios			
	free Fe_2O_3	free Al_2O_3	amorphous Fe_2O_3	SiO_2/R_2O_3	SiO_2/Al_2O_3	SiO_2/Fe_2O_3	Al_2O_3/Fe_2O_3

Laboratory data of profile 14 B, Damazeen (mound)

horizon nr., depth (cm)	particle size distribution, µm; % of fine earth								pH		$CaCO_3$ %	org. carbon %
	sand						silt	clay				
	2000-1000	1000-500	500-250	250-100	100-50	total	50-2	<2	H_2O	0.01M $CaCl_2$		
1 0-15	-	1.3	8.6	10.0	4.8	24.7	16.6	58.6	7.5	7.0	0.3	0.6
2 15-30	0.2	1.0	7.6	9.0	5.3	23.1	17.0	59.9	8.0	7.6	1.4	0.5
3 30-60 } 4 60-90 }	0.1	1.3	7.3	9.4	4.7	22.8	16.8	60.3	8.4	7.7	3.8	0.4
5 90-120	0.5	1.2	7.9	7.9	4.9	22.4	15.0	62.6	8.3	7.7	1.4	0.4
6 120-150 } 7 150-180 }	0.1	1.1	7.1	8.6	4.7	21.6	18.2	62.5	8.4	7.7	2.7	0.4

horizon nr., depth (cm)	exchangeable Na		CEC % mmol/kg	$CaSO_4$ %	water-soluble Na mmol/kg	EC mS/cm	extract for EC determination g/ml
	mmol/kg	%					
1 0-15	-	0	535				
2 15-30	-	0	542				
3 30-60	-	0	556				
4 60-90	3	0.6	528				
5 90-120	16	3.2	504				
6 120-150	19	3.4	551				
7 150-180	23	4.2	549				

horizon nr., depth (cm)	elemental composition of the fine earth (% by weight)												
	SiO_2	Fe_2O_3	Al_2O_3	TiO_2	MnO	CaO	MgO	Na_2O	K_2O	FeO	P_2O_5	SO_3	H_2O+
1 0-15	57.8	7.7	16.2	1.1	0.1	1.7	2.2						
2 15-30	56.6	7.7	15.7	1.1	0.1	2.0	2.5						
3/4 30-90	54.1	7.6	15.6	1.1	0.1	3.3	2.4						
5 90-120	55.6	7.9	16.3	1.1	0.1	2.1	2.5						
6/7 120-180	54.4	7.8	16.1	1.1	0.1	2.3	2.6						

horizon nr., depth (cm)				molar ratios			
	free Fe_2O_3	free Al_2O_3	amorphous Fe_2O_3	SiO_2/R_2O_3	SiO_2/Al_2O_3	SiO_2/Fe_2O_3	Al_2O_3/Fe_2O_3
1 0-15				4.7	6.1	19.9	3.3
2 15-30				4.7	6.1	19.7	3.2
3/4 30-90				4.5	5.9	19.0	3.2
5 90-120				4.4	5.8	18.8	3.3
6/7 120-180				4.4	5.8	18.5	3.2

horizon nr., depth (cm)	elemental composition of the clay fraction (% by weight)												
	SiO_2	Fe_2O_3	Al_2O_3	TiO_2	MnO	CaO	MgO	Na_2O	K_2O	FeO	P_2O_5	SO_3	H_2O+

horizon nr., depth (cm)				molar ratios			
	free Fe_2O_3	free Al_2O_3	amorphous Fe_2O_3	SiO_2/R_2O_3	SiO_2/Al_2O_3	SiO_2/Fe_2O_3	Al_2O_3/Fe_2O_3

BOZI (NR. 15)

date of description :	22/3/1966
USDA Soil Taxonomy :	Typic Chromustert, very-fine, montmorillonitic, isohyperthermic
FAO/UNESCO :	Chromic Vertisol (1974); Calcic Vertisol (1988)
location :	13 km north of Jebel Bozi, on road to Jebel Dali; topo map 1:250,000, sheet 55-O; 12°34'N - 33°27'E.
elevation :	475 m
landform :	relatively high-lying and apparently flat part of gently and widely undulating clay plain with inselbergs
soil slope class :	flat
microrelief :	normal gilgai, wavelength 2-3 m, amplitudo 5-20 cm, often with sinkholes in the depressions
surface :	brittle surface flake, colour 2.5Y 4/2, 4.5/2 when dry, overlying a fine to medium crumb surface mulch, 2 to 5 cm thick; mulch is thickest on mounds, where it partly obscures cracks, it is thinner in depressions where cracks, 2.5 cm wide, are distinct; many ca-nodules, up to 5 cm across, on mounds, much less on depressions; some subrounded quartz gravel.
parent material :	colluvio/alluvial clay, derived from weathering of Basement Complex rock
vegetation or land use :	*Acacia mellifera* bush, varying from open to very dense, and in the latter case more or less excluding other woody vegetation; other small trees include *Acacia seyal* and *A.senegal*; there are some trees of *Balanites aegyptiaca* and bushes of *Cadaba ssp.* The ground cover of grasses consists mainly of *Aristida ssp.*, 30-40 cm high, and some *Cymbopogon nervatus.* Part of the area around the pit has been burnt.

Profile description :

0-30 cm A	clay; dry; 2.5Y 3/2; 10YR-2.5Y 3/2,d; moderate medium and coarse subangular, with depth angular blocky, with a moderately distinct parallelepiped substructure; abundant fine white ca-granules, 0.5-3 mm across, and common grey ca-nodules, generally about 5 mm,but up to 1 cm across; few quartz gravel; strong effervescence with HCl; termite activity; common fine and fibrous roots; diffuse, smooth boundary.
30-60 cm Bw1	clay; dry, with depth to moist; 10YR-2.5Y 3/1.5; moderate fine and medium subangular blocky with wedge-shaped peds; visible structure (lamination) distinct; ca-granules and -nodules as above, fewer but still common; strong effervescence with HCl; termite activity; fibrous roots; diffuse, smooth boundary.
60-100 cm Bw2	clay; moist; 2.5Y 3/1; weak structure, but visible structure distinct: fine tilted wedges, with finest peds 5 mm long, 2 mm high, 3 mm wide; ped surfaces are slickensided; ca-granules and -nodules as above, the granules often concentrated along slickensides; few quartz gravel; strong effervescence with HCl; soil more compact than overlying soil; few fine and fibrous roots; diffuse, smooth boundary.
100-140 cm Bwk	clay; very moist; 10YR-2.5Y 3/l; structure as in 60-100 cm; ca-nodules and -granules as in 60-100 cm; ca-accumulations in vertical pockets, consisting of nests of granules and/or soft powdery lime; strong effervescence with HCl; common termite nests, some of them derelict and partly infilled with soil; few fine and fibrous roots; diffuse, smooth boundary.

140-170 cm B/Cwk	clay; very moist; heterogeneous soil, dominant colour is 10YR-2.5Y 3/2; structure as in overlying horizons, but the tilted wedges are more distinct and can be taken from the profile wall; medium slickensides, larger than in overlying horizons; ca-concentrations in the form of 4 cm high and 1 cm wide groups of white granules, or of soft powdery lime, or of both; strong effervescence with HCl; termite nests as in overlying horizon; few fibrous roots on slickensides; diffuse, smooth boundary.
170-200 cm+ C/Bwky	clay; very moist; soil dominantly 10YR-2.5Y 3/3, some soil is 10YR-2.5Y 3/2; structure as in overlying horizon; very small, irregularly tilted slickensides; many, partly grey-coated ca-nodules, 3-5 mm diameter; common ca-concentrations as described in overlying horizon; very fine, 1-3 mm, grey ca-granules, leaving a distinct iron-manganese coating when removed from the soil; few iron-manganese mottles, colour 10YR 3/1; common clear gypsum crystals, 1 mm, sometimes 2 to 3 mm across, in nests (abundance of gypsum varies from few to abundant); violent effervescence with HCl; termite nests as in overlying horizons.

Remarks :

1. The ca-concentrations in the soil below 100 cm depth have the appearance of decaying nodules, rather than of soft powdery lime in the process of hardening.
2. The greyish-coated ca-nodules, 3-5 mm diameter, do not leave an iron-manganese coating when removed from the soil.
3. A krotovina is found at 35 cm depth.
4. Cracks extend till 70 cm.

Summary profile description :

Deep profile developed in colluvio/alluvial clay. Horizon boundaries are diffuse to the extent of non-existing. The surface soil (A) has a colour of 10YR-2.5Y 3/2, the B-horizon is 10YR-2.5Y3/1, the transition to the substratum (B/C- and C/B-horizons, 140-200 cm) is 10YR-2.5Y 3/2 to 3/3. Vertic structure throughout, distinct slickensides from 60 to 200 cm+ . Hard carbonate nodules and granules are present between 0 and 140 cm; soft carbonate concentrations are restricted to depths below 100 cm. Iron-manganese mottles and -cutans occur only in the C/B-horizon, below 170 cm depth. Effervescence with HCl is strong throughout. Cracks extend till a depth of 70 cm.

Laboratory data of profile 15, Bozi

horizon nr., depth (cm)	particle size distribution, µm; % of fine earth								pH		$CaCO_3$ %	org. carbon %
	sand						silt	clay				
	2000-1000	1000-500	500-250	250-100	100-50	total	50-2	<2	H_2O	0.01M $CaCl_2$		
1 0-30	0.6	1.4	2.3	2.5	1.7	8.5	17.1	73.7	7.6	7.3	2.7	0.2
2 30-60	0.3	0.8	1.7	2.4	1.8	7.0	22.3	70.7	6.8	6.6	1.9	0.5
3 60-100	0.3	0.9	1.9	2.6	1.9	7.6	18.8	73.5	8.4	7.7	5.2	0.94
100-140	0.3	0.7	1.6	2.2	1.7	6.5	17.1	76.4	7.8	7.7	1.8	0.3
5 140-170	0.3	0.5	1.1	1.8	1.6	5.3	17.5	77.3	8.3	7.8	4.8	0.3
6 170-200	0.2	0.4	1.0	1.6	1.6	4.8	17.9	77.3	8.0	7.7	10.4	0.3

horizon nr., depth (cm)	exchangeable Na		CEC % mmol/kg	$CaSO_4$ %	water-soluble Na mmol/kg	EC mS/cm	extract for EC determination g/ml
	mmol/kg	%					
1 0-30	38	5.7	668		5	0.5	1:1
2 30-60	86	12.5	687		6	0.6	1:1
3 60-100	108	14.7	736		10	0.5	1:1.5
4 100-140	129	17.4	742		14	0.9	1:1.5
5 140-170	128	18.5	691				
6 170-200	126	25.9	487	1.0	35	3.7	1:1

horizon nr., depth (cm)	elemental composition of the fine earth (% by weight)												
	SiO_2	Fe_2O_3	Al_2O_3	TiO_2	MnO	CaO	MgO	Na_2O	K_2O	FeO	P_2O_5	SO_3	H_2O+
1 0-30	52.8	8.7	15.9	1.4	0.1	3.8	3.1	0.7	0.2	0.3	0.1		13.3
2 30-60	54.1	9.1	15.2	1.5	0.1	2.8	3.2	0.9	0.1	0.1	0.1		11.6
3 60-100	53.0	8.8	15.4	1.4	0.2	4.4	3.1	0.9	0.1	0.1	0.1		13.3
4 100-140	55.6	9.2	16.5	1.5	0.2	2.4	3.2	1.0	0.1	0.2	0.1		12.3
5 140-170	52.4	9.1	15.8	1.4	0.2	4.4	3.4	1.1	0.2	0.1	0.1		12.3
6 170-200	49.6	8.4	15.6	1.3	0.1	6.4	3.1	1.0	0.2		0.1		14.3

horizon nr., depth (cm)				molar ratios			
	free Fe_2O_3	free Al_2O_3	amorphous Fe_2O_3	SiO_2/R_2O_3	SiO_2/Al_2O_3	SiO_2/Fe_2O_3	Al_2O_3/Fe_2O_3
1 0-30	3.2			4.2	5.7	15.8	2.8
2 30-60	3.2			4.4	6.1	15.7	2.6
3 60-100	3.3			4.3	5.9	15.9	2.7
4 100-140	3.5			4.2	5.7	15.8	2.8
5 140-170	3.5			4.1	5.6	15.2	2.7
6 170-200	3.4			4.0	5.4	15.2	2.8

horizon nr., depth (cm)	elemental composition of the clay fraction (% by weight)												
	SiO_2	Fe_2O_3	Al_2O_3	TiO_2	MnO	CaO	MgO	Na_2O	K_2O	FeO	P_2O_5	SO_3	H_2O+
2 30-60	48.0	12.0	19.7	1.2	0.1		2.7	0.2	0.2	0.3	0.2		12.3
6 170-200	50.2	11.5	19.2	1.2	0.1		2.9	0.3	0.2	0.4	0.2		11.0

horizon nr., depth (cm)				molar ratios			
	free Fe_2O_3	free Al_2O_3	amorphous Fe_2O_3	SiO_2/R_2O_3	SiO_2/Al_2O_3	SiO_2/Fe_2O_3	Al_2O_3/Fe_2O_3
2 30-60				3.0	4.1	10.4	2.5
6 170-200				3.2	4.4	11.3	2.5

ULU (NR. 16)

date of description :	20/3/1966
USDA Soil Taxonomy :	Typic Chromustert, very-fine, montmorillonitic, isohyperthermic
FAO/UNESCO :	Chromic Vertisol (1974); Calcic Vertisol (1988)
location :	5 km north-west of Ulu village, on the road to Tibeilab; topo map 1:250,000, sheet 66-G; 10°42'N - 33°32'E.
elevation :	between 400 and 500 m
landform :	gently undulating clay plain
soil slope class :	gently sloping
microrelief :	gilgai, wavy to lattice type, with wavelength of 7 m (6-8 m) and amplitudo 15 cm (10-20 cm); the micro-ridges are parallel to each other, regular, and straight to slightly wavy; they are about 1 m wide and run with the slope.
surface :	On gilgai microridges there is a distinct accumulation of white ca-nodules (3-20 mm diameter), and sometimes some fine quartz gravel (3-5 cm diameter); the mulch is 1-2 cm thick, covered by a brittle flake, and it obscures the cracking pattern for about 50%. On microvalleys the mulch is less than 1 cm thick, and it may also appear covered by a brittle flake; the cracking pattern is clear, the cracks are 3-8 cm wide, and enclose polygons of 15 to 30 cm diameter. Surface colour: 2.5Y 4/2, moist and dry.
parent material :	colluvio/alluvial clay, derived from weathering of Basement Complex rock
vegetation or land use :	open woodland with dominant *Acacia seyal*, small and crooked *Combretum hartmannianum* and scattered *Balanites aegyptiaca*. On spots young, green *Ziziphus spina-christi*, forming dense stands, about 30 cm high.

Profile description (the profile has been dug across a gilgai microridge, showing half a gilgai wave on cross-section; the description below is from the microridge) :

0-30 cm A	clay; dry till 20 cm, moist below; 2.5Y 3/2; weak coarse angular to subangular blocky with a very fine bicuneate substructure; ca-granules/nodules varying from 1 to 25 mm, white or partly coated; few coarse sand grains and fine gravel (2-4 cm); weak effervescence with HCl; termite activity; biopores; fine roots; diffuse, smooth boundary.
30-70 cm Bw1	clay; moist to wet; 2.5Y 3/2; moderate medium to coarse angular blocky, peds are tilted wedges with prominent slickensided surfaces (with depth there is a gradual change from fine to slightly coarser tilted wedges); ca-granules/nodules as in overlying horizon; few dark-grey ca-nodules, 1-2, seldom 3 mm, rounded, leaving an iron-manganese imprint when removed from the soil; moderate effervescence with HCl; termite activity; fine and few fibrous roots; diffuse, smooth boundary.
70-110 cm Bw2	clay; moist to wet; 2.5Y 3/2; structure as in overlying horizon but slightly coarser; common ca-nodules, up to 4 cm; very few, very fine (under 2mm) white ca-granules; dark-grey ca-nodules as in overlying horizon; few gravel and few quartz sand grains; moderate effervescence with HCl; termite activity; few fine roots on slickensides; diffuse, smooth boundary.
110-150 cm Bwk	clay; moist to wet; 2.5Y 3/2; structure as in overlying horizon, but slightly weaker grade and slightly coarser class; slickensides prominent; white and dark-grey ca-nodules as in overlying horizon; some nests of ca-granules; moderate effervescence with HCl; termite activity; few fibrous roots on slickensides; diffuse, smooth boundary.

150-190 cm+ Ck	clay; moist to wet; 2.5Y-10YR 4/3; structure very weak due to common occurrence of ca-nodules; ped faces are small and indistinct slickensides; whitish ca-granules and nodules as in overlying horizon, but there are more dark-grey ca-nodules; fine iron-manganese mottles; some rusty patches around ca-nodules; moderate effervescence with HCl; termite activity; few fibrous roots on slickensides and in the soil matrix.

Remarks to microridge profile:
1. Cracks reach till 80 cm depth.
2. Soil structure is weak due to high moisture content of the soil, and the same applies to effervescence with HCl.
3. Termite activity is high throughout the profile, but especially in 0-10 cm.
4. The nests of ca-granules, that are only found in 110-190 cm, may be either desintegrating, larger hard ca-nodules, or large accumulations of soft powdery lime with enclosed hard ca-granules that are due to a process of hardening of the soft powdery lime.
5. Horizon boundaries are diffuse to the extent of non-existing; characteristics change very gradually with depth; only at 150 cm is a change in soil colour and soil structure.

Profile in microvalley; differences with the microridge profile:
Structure: grade of structure the same; distinct very fine lamination almost from the surface.
White to light-grey ca-nodules and -granules in 0-150 cm: few fine (1-3 mm) ca-granules and rare large (1-2 cm) ca-nodules, a great difference with microridge profile.
Dark-grey ca-nodules only below 110 cm; few iron-manganese mottles in 70-110 cm.
Soil colour and root development: as in microridge profile.
Termite activity slightly higher; very high in 0-5 cm.

Remarks to microvalley profile:
1. Cracks extend till 40 cm depth.
2. Soil more compact than microridge site (due to less intensive cracking).
3. No boundaries between horizons, except at 150 cm.
4. The zone 110-150 cm is transitional to the substratum, it shows slight changes in colour and there are dark-grey nodules.
5. Termite nests in 110-150 cm.

Remarks to both profiles:
1. Is absence of dark-grey ca-nodules (ca-nodules impregnated and coated by manganese and perhaps iron) in the microvalley site related to the paucity of ca-nodules in general? But then there could be iron-manganese nodules, which do not occur either.
2. It is astonishing that a soil with such a high moisture content (field estimates) well into the dry season, does not support more than an *Acacia*-savannah type of vegetation. And there is no fresh grass sprouting after burning. Very much water must be bound by the clay.

Summary profile description (microridge profile):
Deep profile developed in colluvio/alluvial clay. Horizon boundaries are diffuse to the extent of non-existing, except for the change in soil colour and structure between B horizon and BC horizon, at 150 cm. The colour of A and B horizons is 2.5Y 3/2, that of the BC horizon 2.5Y-10YR 4/3. Vertic structure throughout, but very weak in the BC horizon; slickensides are prominent in the B horizon (30-150 cm). Hard carbonate nodules and granules are present throughout; soft carbonate concretions are restricted to depths below 110 cm. Dark-grey ca-nodules with an 'in situ' black coating of manganese (and iron) occur below 30 cm; they are more frequent, and accompanied by (iron)-manganese mottles and cutans, below 150 cm. Cracks extend till 80 cm depth.

Laboratory data of profile 16, Ulu

horizon nr., depth (cm)	particle size distribution, µm; % of fine earth								pH		$CaCO_3$ %	org. carbon %
	sand						silt	clay				
	2000-1000	1000-500	500-250	250-100	100-50	total	50-2	<2	H_2O	0.01M $CaCl_2$		
1 0-30	1.8	2.6	1.7	2.2	2.6	10.9	28.5	60.6	7.0	6.7	1.3	1.3
2 30-70	0.6	2.3	1.4	2.2	2.2	8.7	30.8	60.5	7.1	6.9		1.1
3 70-110	0.8	2.5	1.8	2.5	2.3	9.9	22.9	67.2	7.6	7.3		1.1
4 110-150	1.4	2.2	1.5	2.4	2.7	10.2	27.8	62.0	7.8	7.3	0.6	1.0
5 150-190	4.6	7.0	3.7	3.9	3.2	22.4	22.6	55.0	7.8	7.6	8.7	1.0

horizon nr., depth (cm)	exchangeable Na		CEC % mmol/kg	$CaSO_4$ %	water-soluble Na mmol/kg	EC mS/cm	extract for EC determination g/ml
	mmol/kg	%					
1 0-30	13	3.4	386				
2 30-70	7	1.6	428				
3 70-110	15	3.5	432				
4 110-150	19	4.1	461				
5 150-190	19	3.9	488				

horizon nr., depth (cm)	elemental composition of the fine earth (% by weight)												
	SiO_2	Fe_2O_3	Al_2O_3	TiO_2	MnO	CaO	MgO	Na_2O	K_2O	FeO	P_2O_5	SO_3	H_2O+
1 0-30	61.8	8.3	16.0	1.6	0.1	1.2	1.2	0.2	0.2	0.2	tr		9.5
2 30-70	63.1	8.3	15.9	1.6	0.1	1.2	1.1	0.2	0.2	0.2	tr		8.9
3 70-110	62.9	8.3	16.0	1.5	0.1	1.3	1.2	0.2	0.1	0.2	tr		8.7
4 110-150	59.9	7.9	15.6	1.5	0.1	1.8	1.2	0.2	0.1	0.2	tr		9.3
5 150-190	55.4	7.0	15.4	1.4	0.1	6.2	1.4	0.2	0.2	0.1	tr		11.7

horizon nr., depth (cm)				molar ratios			
	free Fe_2O_3	free Al_2O_3	amorphous Fe_2O_3	SiO_2/R_2O_3	SiO_2/Al_2O_3	SiO_2/Fe_2O_3	Al_2O_3/Fe_2O_3
1 0-30	3.6	1.8	0.3	4.9	6.4	19.8	3.1
2 30-70	4.6	2.2	0.2	5.0	6.6	20.2	3.1
3 70-110	4.1	2.0	0.2	5.0	6.6	20.2	3.1
4 110-150	4.8	2.1	0.2	5.0	6.7	20.4	3.1
5 150-190	4.2	2.0	0.1	4.7	6.1	20.9	3.4

horizon nr., depth (cm)	elemental composition of the clay fraction (% by weight)												
	SiO_2	Fe_2O_3	Al_2O_3	TiO_2	MnO	CaO	MgO	Na_2O	K_2O	FeO	P_2O_5	SO_3	H_2O+
1 0-30	46.2	11.1	22.5	1.5	0.1	0.1	1.3	tr	0.1	0.3	tr		10.9
2 30-70	46.8	11.0	22.6	1.5	0.1	0.1	1.3	0.1	tr	0.2	tr		10.6
3 70-110	46.9	11.2	22.4	1.5	0.1	0.1	1.4	0.2	0.1	0.3	tr		10.7
4 110-150	46.5	10.9	21.9	1.5	0.1	0.1	1.4		0.1	0.3	tr		10.7
5 150-190	47.7	10.3	21.3	1.4	0.1	0.2	1.8	tr	0.1	0.2	tr		10.4

horizon nr., depth (cm)				molar ratios			
	free Fe_2O_3	free Al_2O_3	amorphous Fe_2O_3	SiO_2/R_2O_3	SiO_2/Al_2O_3	SiO_2/Fe_2O_3	Al_2O_3/Fe_2O_3
1 0-30				2.7	3.5	11.2	3.2
2 30-70				2.7	3.5	11.3	3.2
3 70-110				2.7	3.6	11.2	3.1
4 110-150				2.7	3.6	11.4	3.2
5 150-190				2.9	3.8	12.4	3.3

KHADIGA (NR. 17)

date of description :	18/3/1966
USDA Soil Taxonomy :	Typic Chromustert, fine, mixed, isohyperthermic
FAO/UNESCO :	Chromic Vertisol (1974); Eutric Vertisol (1988)
location :	6 km east of Khadiga village (Khor Yabus area, Southern Kenana). Khadiga is located 24 km east of Boing village (see profile nr. 18); topo map 1:250,000, sheet 66-K; 9°57'N - 34°01'E.
elevation :	approximately 500 m
landform :	footslope of small, smooth inselberg; slight slope towards north
soil slope class :	gently sloping
microrelief :	see 'surface'
surface :	thin brittle crust (5-7.5YR 2.5/3; 3/3,d) attached to the soil (no mulch); many stones and rock fragments, usually smaller than 20 cm diameter, some up to 40 cm; cracks 1-3 cm wide, irregularly distributed, and not forming a distinct polygonal network; cracks increase downslope in density, width and regularity of distribution; downslope of the soil there is a weak gilgai microrelief with wavelength 3 m and amplitudo 20 cm.
parent material :	profile developed 'in situ' from weathering of Basement Complex rock (identified as hornblende-epidote-amphibolite)
vegetation or land use :	woodland savannah with *Combretum hartmannianum*, *Boswellia papyrifera* and other broad-leaved species; few *Acacia seyal* and *Balanites aegyptiaca*; tall grasses

Profile description :

0-20 cm A	clay loam; dry; 5YR3/2, moist and dry; (rubbed soil: 5YR 4/3; 3/3,d); extremely hard; coarse subangular to angular blocky with weak parallelepiped substructure; gradual, smooth boundary.
20-40 cm Bw1	clay; very slightly moist; 5YR 3/2 (rubbed soil 5YR 3/3); extremely hard; weak angular blocky with weak parallelepiped substructure, showing shiny ped faces; gradual, smooth boundary.
40-50/60 cm Bw2	clay; moist; 5YR 3/3, moist and dry, (rubbed soil 5YR 3/3); spots with different colours: 2.5Y 5/6, 10YR 5/6, 5YR 3/8, 7.5YR 5/8 (these are colours of weathering rock fragments); weak angular blocky with wedge-shaped peds that have slickensided surfaces; (iron-)manganese mottles with colour N 3.5; clear, wavy boundary.
50/60-70/90 cm Cr	weathering rock; moist; rock fagments can easily be broken; soil of colour 5YR 3/3 (moist and dry) coats the rock fragments; colour of the rock fragments as in overlying horizon; the lower boundary is clear and for the major part smooth; pockets of soil penetrate into the underlying weathering rock, and at such spots the lower boundary is wavy.
70/90 cm+ R	slightly weathered rock

Remarks :

1. Cracks, 1 cm wide, extend till 60 cm.
2. Common fine roots and termite activity throughout.

Summary profile description :

Moderately deep Vertisol developed ' in situ' on weathering hornblende-epidote-amphibolite. Vertic structure is well-developed. Matrix colours are 5YR 3/2 to 5YR 3/3. (Iron-)manganese mottles (colour N 3.5) occur only in 40-50/60 cm. A 20 to 40 cm thick C horizon of weathering rock overlies relatively unweathered rock at 70/90 cm depth.

Laboratory data of profile 17, Khadiga

horizon nr., depth (cm)	particle size distribution, µm; % of fine earth								pH		$CaCO_3$ %	org. carbon %
	sand						silt	clay				
	2000-1000	1000-500	500-250	250-100	100-50	total	50-2	<2	H_2O	0.01M $CaCl_2$		
1 0-20	1.0	2.0	5.3	9.1	8.0	25.4	19.4	55.2	7.9	6.8		0.9
2 20-40	1.1	2.1	3.6	7.8	7.1	21.7	21.0	57.3	7.4	6.5		0.7
3 40-50/60	1.4	2.1	3.8	8.6	8.1	24.5	24.5	51.5	8.3	6.9		0.8
4 50/60-70/90	5.6	4.2	6.6	13.7	15.7	45.8	27.2	26.9	7.4	6.1		0.4

horizon nr., depth (cm)	exchangeable Na		CEC % mmol/kg	$CaSO_4$ %	water-soluble Na mmol/kg	EC mS/cm	extract for EC determination g/ml
	mmol/kg	%					
1 0-20			282				
2 20-40			235				
3 40-50/60			256				
4 50/60-70/90			178				

horizon nr., depth (cm)	elemental composition of the fine earth (% by weight)												
	SiO_2	Fe_2O_3	Al_2O_3	TiO_2	MnO	CaO	MgO	Na_2O	K_2O	FeO	P_2O_5	SO_3	H_2O+
1 0-20	40.5	13.3	16.1	2.8	0.3	3.3	1.4	0.9	0.2	2.7	0.2		8.6
2 20-40	40.3	14.7	17.1	2.3	0.3	3.3	2.6	1.1	0.2	2.1	0.1		8.8
3 40-50/60	43.3	15.5	17.2	2.3	0.3	3.2	2.6	0.5	0.4	2.2	0.1		8.8
4 50/60-70/90	36.0	18.0	16.8	2.1	0.3	4.4	3.6	0.5	0.2	3.8	tr		7.0
5 >70/90 (rock)	35.2	8.8	15.1	0.9	0.2	10.9	2.7	2.0	0.2	8.5	tr		

horizon nr., depth (cm)				molar ratios			
	free Fe_2O_3	free Al_2O_3	amorphous Fe_2O_3	SiO_2/R_2O_3	SiO_2/Al_2O_3	SiO_2/Fe_2O_3	Al_2O_3/Fe_2O_3
1 0-20	9.9	1.2		2.5	4.3	6.1	1.4
2 20-40	10.1	1.2		2.4	4.0	6.1	1.5
3 40-50/60	10.6	3.3		2.6	4.3	6.3	1.5
4 50/60-70/90	10.2	3.3		1.9	3.7	4.1	1.1
5 >70/90 (rock)				2.3	4.0	5.5	1.4

horizon nr., depth (cm)	elemental composition of the clay fraction (% by weight)												
	SiO_2	Fe_2O_3	Al_2O_3	TiO_2	MnO	CaO	MgO	Na_2O	K_2O	FeO	P_2O_5	SO_3	H_2O+
1 0-20	38.2	17.4	23.7	0.4	0.1								
2 20-40	39.9	17.8	23.7	0.4	0.1								
3 40-50/60	40.9	18.4	25.0	0.6	0.1								
4 50/60-70/90	39.5	18.4	23.6	0.5	0.1								

horizon nr., depth (cm)				molar ratios			
	free Fe_2O_3	free Al_2O_3	amorphous Fe_2O_3	SiO_2/ R_2O_3	SiO_2/ Al_2O_3	SiO_2/ Fe_2O_3	Al_2O_3/ Fe_2O_3
1 0-20				1.9	2.7	5.9	2.1
2 20-40				1.9	2.9	6.0	2.1
3 40-50/60				1.9	2.8	5.9	2.1
4 50/60-70/90				1.9	2.8	5.7	2.0

BOING (NR. 18)

date of description :	19/3/1966
USDA Soil Taxonomy :	Typic Pellustert, very-fine, montmorillonitic, isohyperthermic
FAO/UNESCO :	Pellic Vertisol (1974); Eutric Vertisol (1988)
location :	14 km east of Boing village that is situated at Khor Yabus, Southern Kenana; topo map 1:250,000, sheet 66-K; 9°58'N - 33°52'E.
elevation :	approximately 475 m
landform :	undulating clay plain with hills and groups of hills; the pit is situated on top of a smooth, rounded hill that is covered by a soil mantle.
soil slope class :	at site of pit: level; general aspect of the area: undulating
microrelief :	surface slightly irregular to weak gilgai
surface :	fragments of igneous rock and quartz gravel, both up to 20 cm diameter, as well as 'baked' soil fragments (due to burning) occur concentrated on small spots, especially on the top of the hill, e.g. at the site of the pit. Few, very fine (2-3 mm) white ca-granules. Brittle surface flake breaking into a mulch that sloughs into the cracks and obscures the cracking pattern for about 75%; sloughing is promoted by the trodding of cattle. Cracks are 5 cm wide at the surface; they enclose polygons of 10-15 cm diameter. Some small termite mounds. Surface colour is 10YR 3/2 and 2/2, 10YR 3/2 and 4/2 when dry.
parent material :	profile developed 'in situ' from weathered rock of Basement Complex (identified as hornblende-epidote-amphibolite)
vegetation or land use :	shifting cultivation and grazing. Burnt tall grasses. At the site scattered *Balanites aegyptiaca*. More downslope also *Combretum hartmannianum*, *Anogeissus schimperi* and palms (*Hyphaene* or *Borassus*).

Profile description :

0-40 cm A	clay; dry, below 30 cm moist; 10YR 3/1, moist and dry; cracks at surface 2 cm wide, at 40 cm depth 0.5 cm; coarse subangular to angular blocky with a substructure consisting of a fine, sub-horziontal lamination, that has not developed to such an extent that tilted wedges can be taken from the profile wall; common fine (1-3 mm, seldom larger) brownish-white, partly coated ca-granules; few sand grains; few pieces of red pottery; slight effervescence with HCl; termite activity; many fibrous roots; diffuse, smooth boundary.
40-70 cm Bw1	clay; moist to wet; 10YR or 2.5Y 3/1; moderate medium angular blocky; peds are tilted wedges, and ped surfaces distinct fine slickensides (structure relatively weakly developed due to high moisture content of the soil); ca-granules as in surface horizon; few fine black spots; pieces of pottery; few reddish patches (decayed pottery?); few sand grains; moderate effervescence with HCl; termite activity; many living fibrous roots and parts of decaying roots on slickensides; diffuse, smooth boundary.
70-100 cm Bw2	clay; moist to wet; 10YR or 2.5Y 3/1; structure and slickensides as in overlying horizon, but weaker developed; few fine ca-granules, generally smaller than 1 mm; pieces of red pottery (?); many pieces of charcoal; moderate effervescence with HCl; high termite activity and some termite nests; diffuse, smooth boundary.
100-125/140 cm BCw	clay; moist; 2.5Y 3/1.5; structure and slickensides as in overlying horizon but slightly stronger developed, the soil being less wet; ca-granules as in 0-100 cm; the granules occur mainly concentrated in certain spots; some iron-manganese nodules, that can be broken by nail; fine, 1-4 mm, fragments of weathering rock; termite nests; wavy boundary, clear to Ckr horizon, abrupt to R horizon (the Ckr is an intermittent horizon).

125/140-125/160 cm
Ckr

weathered rock that can be broken by hand; where this horizon is deep (e.g. under an almost unweathered piece of rock in the Bcw), there is a distinct concentration of carbonates, forming irregularly shaped nodules, 1 to 2, seldom 3 cm diameter, but in other parts of the horizon a concentration of carbonates is missing; abrupt, wavy boundary.

125/160 cm+
R

slightly weathered rock that can not be broken by hand, but easily by hammer.

Remarks:
1. Munsell notations are not entirely reliable, because of cloudy weather.
2. In horizons 4 and 5 (100-125/160 cm) the irregularly-shaped and variegated-coloured ca-granules can not be easily differentiated from fragments of weathering rock, that do have similar yellowish-brownish colours. Probably they occur inter- mixed, with gradual transitions.

Summary profile description:
Moderately deep profile, developed 'in situ' on basic metamorphic rock. The texture is clay throughout. Colour of the A horizon (0-40 cm) and of the B horizons (40-100 cm) is 10YR-2.5Y 3/1, that of the BC horizon (100-125/140 cm) is 2.5Y 3/1.5. The soil has a moderately developed vertic structure. Fine ca-granules (1-3 mm) occur throughout the solum. Slightly hard iron-manganese nodules are only found in the BC horizon. The C horizon (125/140 - 125/160 cm) consists of weathering rock; an 'in situ' concentration of carbonate nodules, 1 to 2 cm diameter, marks the boundary to unweathered rock (R). In some parts of the pit C horizon and carbonate concentrations are lacking.

Laboratory data of profile 18, Boing

horizon nr., depth (cm)	particle size distribution, μm; % of fine earth								pH		$CaCO_3$ %	org. carbon %
	sand						silt	clay				
	2000-1000	1000-500	500-250	250-100	100-50	total	50-2	<2	H_2O	0.01M $CaCl_2$		
1 0-40	0.4	0.8	2.0	7.0	9.1	19.3	19.3	61.5	7.3	6.8	3.0	1.2
2 40-70	0.8	1.1	1.8	6.8	7.7	18.2	18.4	63.5	7.2	6.8	2.9	1.2
3 70-100	0.5	0.7	1.4	4.5	6.1	13.2	17.0	69.8	7.1	6.9	3.3	1.5
4 100-125/140	0.6	0.9	1.2	3.6	4.6	10.9	13.4	75.7	7.2	6.9	3.7	0.7
5 125/140-125/160	9.4	8.6	9.0	9.0	7.2	43.2	12.7	43.9	7.3	7.0	3.7	0.3

horizon nr., depth (cm)	exchangeable Na		CEC % mmol/kg	$CaSO_4$ %	water-soluble Na mmol/kg	EC mS/cm	extract for EC determination g/ml
	mmol/kg	%					
1 0-40		0	383				
2 40-70	3	0.8	400				
3 70-100	6	1.3	452				
4 100-125/140	9	1.7	516				
5 125/140-125/160	8	2.5	325				

horizon nr., depth (cm)	elemental composition of the fine earth (% by weight)												
	SiO_2	Fe_2O_3	Al_2O_3	TiO_2	MnO	CaO	MgO	Na_2O	K_2O	FeO	P_2O_5	SO_3	H_2O+
1 0-40	50.6	11.1	25.8	1.4	0.2	2.3	2.0	1.1	1.4	0.3	0.4		9.6
2 40-70	50.3	10.4	26.4	1.3	0.2	3.1	2.0	0.9	1.0	0.3	0.4		10.0
3 70-100	48.9	10.9	26.7	1.3	0.2	2.9	2.1	0.8	0.8	0.3	0.2		10.4
4 100-125/140	48.6	11.3	28.3	1.4	0.2	2.5	2.3	0.8	0.5	0.5	0.3		10.1
5 125/140-125/160	41.8	11.1	28.0	1.2	0.2	7.8	4.2	0.9	0.1	0.8	0.3		7.0
6 >125/160 (rock)	29.6	4.6	18.8	0.3	0.1	11.1	3.7	2.1	0.2	2.3	0.3		

horizon nr., depth (cm)				molar ratios			
	free Fe_2O_3	free Al_2O_3	amorphous Fe_2O_3	SiO_2/R_2O_3	SiO_2/Al_2O_3	SiO_2/Fe_2O_3	Al_2O_3/Fe_2O_3
1 0-40	5.2	1.7		2.7	3.3	13.7	4.1
2 40-70	5.2	1.5		2.6	3.6	13.6	4.2
3 70-100	5.5	1.8		2.5	3.1	12.2	3.9
4 100-125/140	5.8	1.8		2.3	2.9	11.5	3.9
5 125/140-125/160	3.5	1.3		2.0	2.5	10.0	3.9
6 >125/160 (rock)				2.2	2.7	11.9	4.5

horizon nr., depth (cm)	elemental composition of the clay fraction (% by weight)												
	SiO_2	Fe_2O_3	Al_2O_3	TiO_2	MnO	CaO	MgO	Na_2O	K_2O	FeO	P_2O_5	SO_3	H_2O+
1 0-40	42.3	12.1	17.6	1.0	0.1								
2 40-70	44.3	12.1	18.0	1.0	0.1								
3 70-100	44.9	12.1	18.4	1.0	0.1								
4 100-125/140	41.6	11.8	18.1	1.0	0.1								
5 125/140-125/160	45.2	11.8	18.7	1.0	0.1								

horizon nr., depth (cm)				molar ratios			
	free Fe_2O_3	free Al_2O_3	amorphous Fe_2O_3	SiO_2/R_2O_3	SiO_2/Al_2O_3	SiO_2/Fe_2O_3	Al_2O_3/Fe_2O_3
1 0-40				2.8	4.1	9.3	2.3
2 40-70				2.9	4.2	9.7	2.3
3 70-100				2.9	4.1	10.0	2.4
4 100-125/140				2.8	3.9	9.4	2.4
5 125/140-125/160				2.9	4.1	10.2	2.5

RENK (NR. 19)

date of description :	16/5/1963
USDA Soil Taxonomy :	Typic Chromustert, very-fine, montmorillonitic, isohyperthermic
FAO/UNESCO :	Chromic Vertisol (1974); Eutric Vertisol (1988)
location :	10 km east of Renk, on road to Jebel Guli; topo map 1:250,000, sheet 66-B; 11°44'N - 32°55'E.
elevation :	380 m
landform :	very gently undulating pediplain of the Kenana, merging with the White Nile alluvial plain
soil slope class :	flat
microrelief :	none
surface :	wide cracks, largely obscured by mulch, and by mud that sloughs into the cracks after recent rains; below a dry, 3 mm thick, finely cracked, surface crust, the soil is wet; many white ca-nodules and -granules; reddish-coated sand grains; many unbroken cone-shaped shells.
parent material :	colluvio/alluvial clay, derived from weathering of local Basemnet Complex rock
vegetation or land use :	rather dense bush of *Acacia mellifera* with fresh green leaves; some bushes of *Caddaba ssp.* and other species. *Cymbopogon nervatus* and other grasses.

Profile description :

0-15 cm	clay; surface 3 mm dry, below wet; 2.5Y 3/2; crumb to almost structureless, massive (wet soil); few white ca-granules and coarse sand grains; diffuse, smooth boundary.
15-30 cm	clay; wet, with depth to dry; 2.5Y 3/2; subangular blocky with distinct fine parallelepiped substructure; few white ca-granules; coarse sand grains; diffuse, smooth boundary.
30-60 cm	clay; dry; 2.5Y 3/2, dry; weak coarse and medium subangular blocky with a prominent parallelepiped substructure of peds with dimensions 5-10x5x3 mm; ca-granules and sand grains as in overlying horizons; diffuse, smooth boundary.
60-90 cm	clay; dry; 2.5Y 3/2; very weak subangular to angular blocky with a distinct lamination caused by fine parallelepipeds that, however, cannot be taken from the profile wall; ca-granules and sand grains as in overlying horizons; diffuse, smooth boundary.
90-120 cm	clay; slightly moist; 2.5Y 3/2; distinct bicuneate structure showing as a lamination on the profile wall, but only part of the laminae have developed into - shiny - ped surfaces; irregularly dark-grey coated white ca-nodules,up to 2 cm diameter; reddish-coated quartz grains; diffuse, smooth boundary.
120-150 cm	clay; slightly moist; 2.5Y 3/2; almost structureless, but a moderately distinct lamination suggests a tendency towards a fine bicuneate structure; ca-nodules and quartz grains as in 90-120 cm; diffuse, smooth boundary.
150-180 cm+	clay; moist; 10YR-2.5Y 3/2; distinct wedge-shaped peds with shiny faces that have a colour of 10YR 2/1; ca-nodules and quartz grains as in 90-150 cm; some pockets of sandy soil that are more strongly calcareous than the clay matrix.

Remarks :

1. Changes with depth in the profile are very gradual; there is no horizon differentiation and horizon codes could not be given.
2. Consistency of the soil: extremely hard when dry; very firm when slightly moist; friable when moist; plastic and sticky when wet.
3. Cracks distinct till 60 cm, then suddenly narrowing, but traceable till 100 cm.
4. Common fine and medium roots in 0-60 cm; few fine roots, often on ped surfaces, in 60-180 cm.
5. Termite activity throughout the profile.
6. Soil matrix non-calcareous.

Summary profile description :

A deep, very uniform Vertisol profile. Colour throughout the 180 cm profile is 2.5Y 3/2. Cracks are distinct till 60 cm, traceable till 100 cm.

Vertic structure - including parallelepipeds that show as a lamination on the profile wall - is distinct throughout; parallelepipeds are discrete peds in 0 to 60 cm only. Shiny ped faces occur below 90 cm, but there are no distinct slickensides. Few white ca-granules are found in 0-90 cm; in 90-180 cm larger carbonate concentrations (ca-nodules) occur, that are whitish with a reddish coating on spots. The soil matrix is non-calcareous.

EL GELHAK (NR. 20)

date of description :	17/3/1966
USDA Soil Taxonomy :	Udic Pellustert, very-fine, mixed, isohyperthermic
FAO/UNESCO :	Pellic Vertisol (1974); Eutric Vertisol (1988)
location :	83 km south-east of Gelhak, on road to Khor Yabus; topo map 1:250,000, sheet 66-G; 10°35'N - 33°10'E.
elevation :	approximately 350 m
landform :	floodplain of the White Nile or of 'khors' draining into the White Nile; the site is subject to annual flooding.
soil slope class :	flat
microrelief :	weakly expressed gilgai microrelief with wavelength 1.5 m and amplitudo 20 cm, but the soil is uneven over both gilgai mounds and gilgai depressions.
surface :	slightly hard, 4 mm thick surface crust (2.5Y 3/1; 4/1,d), with decaying plant remains; the crust breaks into a mulch that is coarse crumb or fine to medium granular; cracks 2-10 cm wide and 15 to 30 cm apart; mulch sloughing into cracks; many unbroken (subrounded) and broken shells.
parent material :	recent alluvium of the White Nile (or of 'khors' draining into the White Nile)
vegetation or land use :	grass plain, burnt, but fresh grass is appearing; grass growing in tufts; the site is a shallow depression of a few kilometers wide, bordered by higher ground with a dense bush of *Acacia seyal.*

Profile description :

0-15 cm A	clay; dry; weak coarse angular blocky with a fine bicuneate substructure; many fine roots, often marked as linear ferric mottles (colours 7.5YR 4/4 and 5/4); great termite activity; gradual,smooth boundary.
15-30 cm Bwg	clay; moist; 10YR 3/0.5; distinct slickensides; distinct very fine ferric mottles (5YR 4/4) and grey mottles (N 4); no effervescence with HCl; gradual, smooth boundary.
30-90 cm(+) BCwg1	clay; wet; 10YR 3/0.5; very sticky and very plastic; distinct intersecting slickensides in an otherwise structureless, wet soil; along a crack the soil is slightly drier and shows a moderate development of coarse tilted wedges; linear ferric mottles along fibrous roots; few grey mottles (N4-5); some pockets with colour 10YR 5/6; no effervescence with HCl.
90 - 270 cm :	augering observations
90-125 cm BCwg2	clay; wet; as above as far as can be ascertained
125-180 cm Ck	clay; wet; uniform soil with colour 10YR 3.5/1; few ca-nodules; no effervescence with HCl in soil matrix.
180-240 cm	clay; wet, with depth to moist; gradual change in colour; a twin nodule of carbonate and iron-manganese; soft iron-manganese nodules.
240-270 cm	clay; moist; 10YR-2.5Y 3/2; distinct yellowish-white aggregates of soft powdery lime, increasing with depth; common ca-nodules, increasing in number with depth; moderate effervescence of soil matrix with HCl.
270 cm+	clay; moist; 10YR 5/4 (matrix) with distinct mottles of 7.5YR 5/8 and 10YR 4/1, and iron-manganese mottles; ca-nodules; ca-aggregates of soft powdery lime,containing hard ca-nodules that are partly ferri-coated; strong effervescence of soil matrix with HCl.

Remarks:
1. Cracks are open till at least 90 cm depth.
2. The grey mottles with colour N4-5 in 30-90 cm may be iron-manganese mottles, or charcoal, or a coating of slickensides.
3. The soil between 240 and 270 cm depth resembles the substratum of the Shuheit series in the Seinat area (repr.profile Seinat B 50 (nr. 26), a Typic Chromustert).
4. The soil pit is only 90 cm deep; below 90 cm the description is based on augering observations; the horizon symbols in 90-180 cm are tentative.

Summary profile description:
A deep profile developed in alluvial clay, subject to annual inundation. Low chroma (0.5-1.0) occurs from the surface till 240 cm depth; in 240-270 cm the colour is 10YR 3/2, below 270 cm 10YR 5/4. The surface 30 cm has a weak vertic structure, between 30 and 90 cm there are distinct intersecting slickensides in an otherwise wet, structureless soil. Below 90 cm the structure could not be described, as observations were based on soil augering. In 0-180 cm there are no carbonates, in 180-270 cm ca-nodules and soft powdery lime. Ferric and grey mottles, the former often along fine roots, occur in 0-90 cm. Below 180 cm iron-manganese mottles and soft nodules have been found.

Laboratory data of profile 20, El Gelhak

horizon nr., depth (cm)	particle size distribution, µm; % of fine earth								pH		$CaCO_3$ %	org. carbon %
	sand						silt	clay				
	2000-1000	1000-500	500-250	250-100	100-50	total	50-2	<2	H_2O	0.01M $CaCl_2$		
1 0-15	0.8	3.4	3.5	4.2	2.0	13.9	6.0	80.1	7.1	6.3		0.8
2 15-30	0.9	3.1	3.7	3.8	2.0	13.5	5.9	80.5	6.8	6.2		0.5
3 30-60	1.6	3.3	2.8	3.2	2.1	13.0	10.9	76.2	6.5	5.4		0.3
4 60-90	1.3	3.8	2.5	2.8	2.1	12.5	10.2	77.3	6.6	5.6		0.3

horizon nr., depth (cm)	exchangeable Na		CEC % mmol/kg	$CaSO_4$ %	water-soluble Na mmol/kg	EC mS/cm	extract for EC determination g/ml
	mmol/kg	%					
1 0-15			472				
2 15-30	1	0.2	446				
3 30-60	2	0.4	466				
4 60-90	6	1.2	481				

horizon nr., depth (cm)	elemental composition of the fine earth (% by weight)												
	SiO_2	Fe_2O_3	Al_2O_3	TiO_2	MnO	CaO	MgO	Na_2O	K_2O	FeO	P_2O_5	SO_3	H_2O+
1 0-15	58.1	8.2	17.7	1.0	0.1	0.5	1.3	1.7	0.7	0.1	tr		9.8
2 15-30	56.1	8.5	18.2	1.0	0.1	0.5	1.4	0.5	0.8	0.2	tr		10.1
3 30-60	55.2	9.1	17.9	1.1	0.1	1.5	1.1	0.3	0.7	0.1	tr		9.4
4 60-90	57.2	8.3	13.3	1.1	0.1	2.2	1.2	0.2	0.6	0.1	tr		9.4

horizon nr., depth (cm)				molar ratios			
	free Fe_2O_3	free Al_2O_3	amorphous Fe_2O_3	SiO_2/ R_2O_3	SiO_2/ Al_2O_3	SiO_2/ Fe_2O_3	Al_2O_3/ Fe_2O_3
1 0-15	3.7	3.0		4.3	5.6	19.0	3.4
2 15-30	3.4	2.1		4.0	5.3	17.6	3.4
3 30-60	3.0	1.8		4.0	5.3	16.1	3.1
4 60-90	2.9	1.9		5.2	7.3	18.3	2.5

horizon nr., depth (cm)	elemental composition of the clay fraction (% by weight)												
	SiO_2	Fe_2O_3	Al_2O_3	TiO_2	MnO	CaO	MgO	Na_2O	K_2O	FeO	P_2O_5	SO_3	H_2O+
1 0-15	49.6	10.5	23.6	1.3	0.1								
2 15-30	49.9	10.4	21.7	1.3	0.1								
3 30-60	44.0	9.1	20.9	1.1	0.1								
4 60-90	45.0	9.3	21.4	1.1	0.1								

horizon nr., depth (cm)				molar ratios			
	free Fe_2O_3	free Al_2O_3	amorphous Fe_2O_3	SiO_2/ R_2O_3	SiO_2/ Al_2O_3	SiO_2/ Fe_2O_3	Al_2O_3/ Fe_2O_3
1 0-15				2.8	3.6	12.6	3.5
2 15-30				3.0	3.9	12.8	3.3
3 30-60				2.8	3.6	12.9	3.6
4 60-90				2.8	3.6	12.9	3.6

SIMSIM B27 (NR. 21)

date of description :	14/12/1965
USDA Soil Taxonomy :	Typic Chromustert, very-fine, montmorillonitic, isohyperthermic
FAO/UNESCO :	Chromic Vertisol (1988); Calcic Vertisol (1988)
location :	Umm Simsim proposed M.C.P.S., at D8; topo map 1:250,000, sheet 55-L; 13°17'N - 35°11'E.
elevation :	479 m
landform :	colluvio/alluvial clay plain with inselbergs, rocky hills and non-rocky elevations
soil slope class :	flat to gently undulating
microrelief :	gilgai, normal type, wavelength 6 m, amplitudo 25 cm, with few sinkholes
surface :	on gilgai mounds well-developed surface mulch and white to grey carbonate nodules
parent material :	colluvio/alluvial clay derived from the weathering of Basement Complex rock and/or basalt, the latter forming the Gedaref-Gallabat ridge.
vegetation or land use :	open savannah of stunted *Combretum hartmannianum*,few *Acacia seyal* and other small trees; diameter of trees at 120 cm height generally below 15 cm; bushes of *Acacia campylacantha*; grasses and herbs burnt.

Profile description (gilgai mound) :

0-5 cm Au1	clay; dry; 10YR 3.5/2; 4/2,d; loose; moderate fine to coarse crumb (mulch); common fine and medium white ca-nodules, often partially coated with dark grey; slight effervescence with HCl; abrupt, wavy boundary.
5-50 cm Au2	clay; dry, with depth to moist; hard when dry, firm when moist; moderate medium and coarse subangular, with depth to angular blocky, with a parallelepiped substructure; slickensides, increasing in size with depth; common fine and medium white ca-nodules, often partially coated with dark grey; slight effervescence with HCl; common fine, medium and large roots; few medium and large biopores; termite activity; diffuse, smooth boundary.
50-95/105 cm Bw	clay; moist; 10YR 3/2; firm; moderate medium and coarse angular blocky with wedge-shaped peds; surfaces of smaller peds are shiny, those of larger peds are distinct slickensides; common fine and medium white ca-nodules, often partially coated with dark grey; slight effervescence with HCl; common fine, and few large roots; few medium and large biopores; termite activity; gradual, wavy boundary.
95/105-130/140 cm Bwk	clay; moist; 10YR-2.5Y 3/2; firm; weak to moderate, medium and coarse angular blocky with wedge-shaped peds; surfaces of smaller peds are shiny, those of larger peds are moderately distinct slickensides; common fine and medium white ca-nodules, often partially coated with dark grey; few medium and coarse, prominent segregations of soft powdery lime containing hard ca-nodules; slight effervescence with HCl; few fine roots; few medium and large biopores; termite activity; gradual, wavy boundary.
130/140-170 cm+ Cky	clay; moist; 10YR 3/3, variegated with 10YR 3/2 and 10YR 4/3; firm; almost structureless, massive, with only few slickensides; common fine and medium white ca-nodules, often partially coated with dark grey; common coarse, distinct segregations of soft powdery lime containing hard ca-nodules; many coarse (3-16 mm long) distinct gypsum crystals, yellowish-opaque, and having a weathered appearance; few roots; no biopores.

Remark:
Cracks, 0.5-1 cm wide at the surface, extend till about 60 cm depth.

Summary profile description:
Deep profile developed in colluvio/alluvial clay. There is a distinct surface mulch of 5 cm. The main soil colour is 10YR 3/2, in the Au1 10YR 4/2, and in the Cky 10YR 3/2, 3/3, 4/3. Horizon boundaries are diffuse to gradual, and often wavy; These boundaries mark small differences in structure, colour, type of carbonate concentrations and presence or absence of gypsum. Vertic structure throughout, most clearly expressed in Bw, and almost absent in Cky. Hard carbonate nodules, white with grey patches, occur throughout; segregations of soft powdery lime containing hard ca-nodules occur in the Bwk and Cky (i.e. below 95/105 cm). In Cky coarse gypsum crystals with weathered appearance. Cracks extend till 60 cm depth.

Laboratory data of profile 21, Simsim B27

horizon nr., depth (cm)	particle size distribution, µm; % of fine earth								pH		$CaCO_3$ %	org. carbon %
	sand						silt	clay				
	2000-1000	1000-500	500-250	250-100	100-50	total	50-2	<2	H_2O	0.01M $CaCl_2$		
1/2 0-50						9.0	22.3	68.7	7.9	7.3		0.8
3 50-95/105						6.3	20.4	73.3	7.6	6.9		0.3
4 95/105-130/140						5.5	21.7	72.8	7.5	6.9	0.4	0.2
5 130/140-175						8.6	22.8	68.6	7.1	6.8	6.2	0.5

horizon nr., depth (cm)	exchangeable Na		CEC % mmol/kg	$CaSO_4$ %	water-soluble Na mmol/kg	EC mS/cm	extract for EC determination g/ml
	mmol/kg	%					
1/2 0-50	2	0.8	248				
3 50-95/105	25	8.5	294				
4 95/105-130/140	42	8.1	520				
5 130/140-175	25	4.7	527	12.6			

horizon nr., depth (cm)	elemental composition of the fine earth (% by weight)												
	SiO_2	Fe_2O_3	Al_2O_3	TiO_2	MnO	CaO	MgO	Na_2O	K_2O	FeO	P_2O_5	SO_3	H_2O+
1/2 0-50	57.0	10.8	18.1	1.5	0.2	1.5	2.0	0.2		0.2	0.1		10.5
3 50-95/105	54.4	11.2	18.9	1.5	0.2	1.8	2.2	0.3		0.3	0.1		10.1
4 95/105-130/140	54.3	11.3	18.8	1.5	0.1	2.2	2.3	0.3		0.2	0.1		10.4
5 130/140-175	47.0	9.5	15.1	1.2	0.1	9.3	2.1	0.4		0.2	0.1		11.5

horizon nr., depth (cm)				molar ratios			
	free Fe_2O_3	free Al_2O_3	amorphous Fe_2O_3	SiO_2/R_2O_3	SiO_2/Al_2O_3	SiO_2/Fe_2O_3	Al_2O_3/Fe_2O_3
1/2 0-50	6.5	2.5		3.9	5.4	14.4	2.7
3 50-95/105	7.0	2.6		3.6	4.9	13.0	2.7
4 95/105-130/140	6.7	2.5		3.6	4.9	13.3	2.7
5 130/140-175	5.1	3.1		3.8	5.3	13.9	2.6

horizon nr., depth (cm)	elemental composition of the clay fraction (% by weight)											
	SiO_2	Fe_2O_3	Al_2O_3	TiO_2	MnO	CaO	MgO	Na_2O	K_2O	FeO	P_2O_5	SO_3	H_2O+
1/2 0-50	45.6	12.7	23.7	1.4	0.1	1.8	1.8			n.d.	0.4		11.1
3 50-95/105	46.4	13.2	24.7	1.3	0.1	1.8	1.7			n.d.	0.3		11.8
4 95/105-130/140	46.1	13.3	24.0	1.3	0.1	2.1	1.9			n.d.	0.4		11.4
5 130/140-175	45.4	13.4	24.4	1.3	0.1	1.8	1.8			n.d.	0.4		11.8

horizon nr., depth (cm)				molar ratios			
	free Fe_2O_3	free Al_2O_3	amorphous Fe_2O_3	SiO_2/R_2O_3	SiO_2/Al_2O_3	SiO_2/Fe_2O_3	Al_2O_3/Fe_2O_3
1/2 0-50				2.4	3.3	9.6	2.9
3 50-95/105				2.4	3.2	9.3	2.9
4 95/105-130/140				2.4	3.3	9.2	2.8
5 130/140-175				2.3	3.2	9.1	2.9

[1] Na-H clay

SEINAT B7 (NR. 22)

date of description :	13 and 21/1/1966
USDA Soil Taxonomy :	Typic Chromustert, fine, mixed, isohyperthermic
FAO/UNESCO :	Chromic Vertisol (1974); Eutric Vertisol (1988)
location :	Umm Seinat Proposed M.C.P.S., between K11 and L11; topo map 1:250,000, sheet 55-L; 13°17'N - 35°35'E.
elevation :	518 m
landform :	clay plain with inselbergs, rocky hills and non-rocky elevations; profile is situated near a 'khor' at the foot of Qulei'at Ed Darot, a group of low rocky hills where the Basement Complex outcrops.
soil slope class :	flat
microrelief :	very slightly irregular
surface :	hard, smooth surface crust, tied to the underlying soil. Cracks, 2-3 cm wide, separate polygons of 10 to 40 cm across; finer cracks, 2-5 mm wide, separate parts of the surface within a polygon into units of 3 to 5 cm diameter. Sand, fine gravel and few quartz cobbles. Large, dome-shaped termite mounds.
parent material :	colluvio/alluvial clay derived from the weathering of Basement Complex rock
vegetation or land use :	woodland with 50% canopy of *Acacia seyal, A.senegal, Combretum hartmannianum, Balanites aegyptiaca* and *Anogeissus schimperi*; diameter of trees varies from less than 15 to over 30 cm (at 120 cm height); few shrubs, grasses and herbs.

Profile description :

0-30 cm A	slightly gravelly clay (gravel is 2-4 mm diameter); 7.5YR 2/2; 3.5/2,d; extremely hard; weak coarse subangular blocky; many fine (1-3 mm), faint,reddish-coated, iron-manganese nodules that can be broken between nails; colour of these nodules on cross-section N3, dry; weak effervescence with HCl; common fine, and few medium and large roots; common fine, medium and large biopores; termite activity; diffuse, smooth boundary.
30-150 cm Bw	slightly gravelly clay (gravel is 2-4 mm diameter); 10YR 3/3; 4/3.5,d; greyish, non-continuous coatings on slickensides have colour N4,d; extremely hard; compound weak coarse, and weak medium and fine angular blocky; peds are wedge-shaped and have moderately distinct slickensided ped surfaces; iron-manganese nodules as in 0-30 cm; weak effervescence with HCl; few fine roots; common fine, medium and large biopores; termite activity; diffuse, smooth boundary.
150-200 cm+ BCwk	clay; 10YR 3/3; 4/3,d; some patches of soil are 10YR 3/2; 4/2,d; faint, greyish non-continuous coatings on slickensides have colour N4,d; few rusty mottles are 5YR 4/8,d; extremely hard; moderate medium angular blocky; peds are weakly defined tilted wedges, with indistinct slickensided surfaces; few, faint, fine and medium segregations of soft powdery lime, containing hard ca-granules and -nodules; strong effervescence with HCl; few fine roots; common fine, medium and large biopores; many termite nests and tunnels.

Remarks :

1. Soil moisture status at time of description not recorded : profile wall was strongly dessicated.
2. No ca-granules or -nodules in A and Bw horizons.
3. Compared to most Typic Chromusterts in Umm Seinat, this profile has a less developed vertic structure and a crusty surface rather than a surface mulch.
4. Cracks extend till 80 to 100 cm depth.

Summary profile description

Deep profile, developed in slightly gravelly and sandy, colluvio-alluvial clay, overlying non-gravelly clay of the same origin. There is no surface mulch, but a fine surface crust. The soil has a weak vertic structure below 30 cm. Horizon boundaries are diffuse, and differentiation is based on colour differences, and - for Bw to BCwk - on presence or absence of soft powdery lime. Segregations of soft powdery lime, containing hard ca-granules and -nodules, occur in the BCwk. Fine iron-manganese nodules occur throughout the profile. Cracks extend till 80 cm depth.

Laboratory data of profile 22, Seinat B7

horizon nr., depth (cm)	particle size distribution, µm; % of fine earth								pH		$CaCO_3$ %	org. carbon %
	sand						silt	clay				
	2000-1000	1000-500	500-250	250-100	100-50	total	50-2	<2	H_2O	0.01M $CaCl_2$		
1 0-30	4.7	5.5	9.2	7.1	3.6	30.1	28.1	41.8	6.3	6.0		0.7
2 30-100	3.7	6.1	8.9	6.3	3.5	28.5	28.0	43.5	6.0	5.2		0.3
3 100-150	2.8	5.6	9.1	6.0	2.8	26.3	29.3	44.4	6.5	6.3		0.5
4 150-200	1.3	5.2	8.5	5.8	2.9	23.7	27.7	48.6	7.6	7.2		0.3

horizon nr., depth (cm)	exchangeable Na		CEC % mmol/kg	$CaSO_4$ %	water-soluble Na mmol/kg	EC mS/cm	extract for EC determination g/ml
	mmol/kg	%					
1 0-30	2	0.9	222				
2 30-100	4	1.8	222				
3 100-150	5	1.9	258				
4 150-200	5	1.7	296				

horizon nr., depth (cm)	elemental composition of the fine earth (% by weight)												
	SiO_2	Fe_2O_3	Al_2O_3	TiO_2	MnO	CaO	MgO	Na_2O	K_2O	FeO	P_2O_5	SO_3	H_2O+
1 0-30	68.1	6.7	10.4	0.8	0.3	0.5	0.4	0.7	0.9	0.2	0.1		6.2
2 30-100	64.2	8.7	14.5	1.0	0.7	0.7	0.6	0.8	1.0	0.3	0.1		7.1
3 100-150	64.5	9.1	14.3	1.0	0.5	0.7	0.6	0.7	1.1	0.3	0.1		7.0
4 150-200	64.3	9.3	14.7	1.0	0.3	0.7	0.6	0.8	1.1	0.3	0.1		7.1

horizon nr., depth (cm)				molar ratios			
	free Fe_2O_3	free Al_2O_3	amorphous Fe_2O_3	SiO_2/R_2O_3	SiO_2/Al_2O_3	SiO_2/Fe_2O_3	Al_2O_3/Fe_2O_3
1 0-30	5.0	1.2	1.3	7.9	10.2	27.0	2.4
2 30-100	6.8	1.4	1.2	5.4	7.5	19.8	2.6
3 100-150	7.0	1.5	1.0	5.4	7.7	18.9	2.5
4 150-200	6.7	1.4	0.7	5.3	7.4	18.4	2.5

horizon nr., depth (cm)	elemental composition of the clay fraction (% by weight)												
	SiO_2	Fe_2O_3	Al_2O_3	TiO_2	MnO	CaO	MgO	Na_2O	K_2O	FeO	P_2O_5	SO_3	H_2O+
1 0-30	45.5	13.9	26.3	1.0	0.1			0.5	1.9	0.2	0.4		11.6
2 30-100	46.4	13.7	25.1	0.9	0.1			0.5	1.8	0.3	0.4		10.3
3 100-150	46.8	13.4	25.1	0.9	0.1			0.5	1.8	0.2	0.4		11.5
4 150-200	47.4	13.1	24.3	0.9	0.1			0.5	1.8	0.2	0.3		11.1

horizon nr., depth (cm)				molar ratios			
	free Fe_2O_3	free Al_2O_3	amorphous Fe_2O_3	SiO_2/R_2O_3	SiO_2/Al_2O_3	SiO_2/Fe_2O_3	Al_2O_3/Fe_2O_3
1 0-30				2.2	2.9	8.7	3.0
2 30-100				2.3	3.2	9.0	2.9
3 100-150				2.4	3.2	9.3	2.9
4 150-200				2.5	3.3	9.6	2.9

SEINAT B10 (NR. 23)

date of description :	13/1/1966
USDA Soil Taxonomy :	Lithic Ustorthent, loamy-skeletal, mixed, isohyperthermic
FAO/UNESCO :	Eutric Regosol (1974); Eutric Regosol (1988)
location :	Umm Seinat proposed M.C.P.S., between K11 and L11; topo map 1:250,000, sheet 55-L; 13°16'N - 35°35'E.
elevation :	530 m
landform :	profile is situated at highest point of smooth, rocky hill (Qulei'at Ed Darot) that, with irregular concave slopes, rises from a colluvio/alluvial clay plain.
soil slope class : s	loping (6-13%)
microrelief :	slightly irregular
surface :	covered with many quartz gravel, stones and boulders, up to 50 cm diameter, and few platy fragments of metamorphic rock of Basement Complex
parent material:	soil formed 'in situ' on weathering Basement Complex rock (identified as mica-schist)
vegetation or land use :	open woodland of broad-leafed species: *Terminalia brownii*, *Lannea humilis*, *Combretum hartmannianum* and others.

Profile description :

0-15 cm A	gravelly to bouldery loam; 7.5YR 2/2; 3.5/2,d; there is some variation in colour due to rock fragments present, viz. quartz fragments and pieces of mica-schist; structureless, massive, but brittle due to the many rock fragments present; no effervescence with HCl; common fine roots; common fine and medium biopores; clear, smooth boundary.
15-25 cm AR	mica-schist (colour N4 to N8) with some quartz gravel (colour N8) and some soil (loam; dry; colour 5YR 3/2.5; 4/3,d); no effervescence with HCl; few fibrous and fine roots; common fine and medium biopores; gradual, smooth boundary.
25-55 cm R1	mica-schist (colour N4 to N8), with some quartz fragments (colour N8), all coated with soil (colour 5YR 3.5/3; 4.5/3,d); no effervescence with HCl; few fibrous and fine roots; common fine and medium biopores; gradual, smooth boundary.
55 cm+ R2	almost unweathered mica-schist, colour N4 to N8.

Remarks :

1. The gravel, stones and boulders of quartz that are common at the surface, are probably derived from quartz dykes, originally present in the parent rock.
2. The mica-schist fragments in 0 to 55 cm depth can be split easily along slightly inclined, but almost horizontal planes into brittle flakes that have a soapy feeling.

Summary profile description :

A shallow, 25 cm deep weathering profile 'in situ' overlying mica-schist. The rock produces a loamy soil. The solum does not contain free carbonates. Soil colours are in hue 7.5YR to 5YR.

Laboratory data of profile 23, Seinat B10

horizon nr., depth (cm)	particle size distribution, µm; % of fine earth								pH		$CaCO_3$ %	org. carbon %
	sand						silt	clay				
	2000-1000	1000-500	500-250	250-100	100-50	total	50-2	<2	H_2O	0.01M $CaCl_2$		
1 0-15	12.7	11.3	12.5	10.5	6.0	53.0	27.3	19.7	7.0	6.8		2.9
2 15-25	7.5	7.8	9.0	13.0	6.0	43.3	31.5	25.2	7.5	6.8		1.9
3 25-55	11.9	11.3	11.6	11.6	6.2	52.7	25.8	21.5	7.5	6.6		0.7

horizon nr., depth (cm)	exchangeable Na		CEC % mmol/kg	$CaSO_4$ %	water-soluble Na mmol/kg	EC mS/cm	extract for EC determination g/ml
	mmol/kg	%					
1 0-15	2	1.9	104				
2 15-25	2	2.2	92				
3 25-55	3	3.5	86				

horizon nr., depth (cm)	elemental composition of the fine earth (% by weight)												
	SiO_2	Fe_2O_3	Al_2O_3	TiO_2	MnO	CaO	MgO	Na_2O	K_2O	FeO	P_2O_5	SO_3	H_2O+
1 0-15	57.8	12.5	13.8	1.2	1.1	1.0	0.5	5.2	3.3	0.5	0.3		9.6
2 15-25	55.1	12.0	16.3	1.3	2.1	0.7	0.4	5.7	3.6	0.2	0.2		8.2
3 25-55	57.0	13.3	16.9	1.2	1.9	0.4	0.3	4.2	3.8	0.2	0.2		6.2
4 >55 (saprolite)	55.4	12.5	18.2	0.9	0.6	0.2	0.3	2.7	2.4		0.3		4.6
5 rock	66.6	8.5	15.1	0.7	0.6	0.2	0.2	2.3	2.0	0.1	0.2		3.6

horizon nr., depth (cm)				molar ratios			
	free Fe_2O_3	free Al_2O_3	amorphous Fe_2O_3	SiO_2/R_2O_3	SiO_2/Al_2O_3	SiO_2/Fe_2O_3	Al_2O_3/Fe_2O_3
1 0-15	9.6	0.9		4.4	7.1	11.8	1.7
2 15-25	7.8	0.8		3.9	5.7	12.0	2.1
3 25-55	9.7	1.5		3.8	5.7	11.2	2.0
4 >55 (saprolite)	9.5	0.3		3.6	5.2	11.8	2.3
5 rock	6.8	0.2		5.5	7.5	20.6	2.8

horizon nr., depth (cm)	elemental composition of the clay fraction (% by weight)												
	SiO_2	Fe_2O_3	Al_2O_3	TiO_2	MnO	CaO	MgO	Na_2O	K_2O	FeO	P_2O_5	SO_3	H_2O+
1 0-15	40.6	11.2	20.7	0.7	0.3								
2 15-25	40.2	9.8	23.0	0.7	0.2								
3 25-55	41.0	10.0	24.8	0.7	0.3								

horizon nr., depth (cm)				molar ratios			
	free Fe_2O_3	free Al_2O_3	amorphous Fe_2O_3	SiO_2/ R_2O_3	SiO_2/ Al_2O_3	SiO_2/ Fe_2O_3	Al_2O_3/ Fe_2O_3
1 0-15				2.5	3.3	9.7	2.9
2 15-25				2.3	3.0	10.9	3.7
3 25-55				2.2	2.8	11.0	3.9

SEINAT B47 (NR. 24)

date of description :	30/1/1966
USDA Soil Taxonomy :	Typic Ustropept, fine, mixed, isohyperthermic
FAO/UNESCO :	Vertic Cambisol (1974); Vertic Cambisol (1988)
location :	Umm Seinat proposed M.C.P.S.; topo map 1:250,000, sheet 55-L; 13°22'N - 35°35'E.
elevation :	519 m
landform :	non-rocky elevation in colluvio/alluvial clay plain; the profile is situated on the lower footslope of a non- rocky elevation, and is subject to overwash with sand and fine gravel.
soil slope class :	flat (downslope towards NW; less than 2%)
microrelief :	normal gilgai, wavelength 10 m, amplitudo 10 to 20 cm; distinct sinkholes in the depressions
surface :	hard crust covers a generally smooth surface; much pea-iron gravel (up to 1 cm across) and few ca-nodules of approximately 1 cm diameter occur at the surface; next to large cracks, 1-3 cm wide at the surface, there are fine surface cracks.
parent material :	colluvium weathered from Basement Complex rock
vegetation or land use :	open woodland of *Combretum hartmannianum, Acacia seyal, Anogeissus schimperi* and other trees, with trunk diameter at 120 cm height, up to 30 cm; few shrubs, and, on spots, tall grasses.

Profile description :

0-20/40 cm A	heterogeneous soil varying between coarse sand and clay, as an average: coarse sandy clay loam; dry; average colour 10YR 3.5/2; soft (sandy pockets) to hard (clayey pockets); moderate medium and coarse subangular blocky; common fine, medium and coarse pea-iron gravel; slight effervescence with HCl; common fine and medium roots; common fine, medium and large biopores; clear, wavy boundary.
20/40-115 cm Bw1	clay loam; dry, with depth to moist; 10YR 3/3; very hard when dry, and extremely firm when moist; compound weak, coarse and weak,medium angular blocky, the finer peds being tilted wedges; common ca-granules and few ca-nodules; common (with depth to few) medium and coarse pea-iron gravel; very slight effervescence with HCl; few fine and medium roots; fine, medium and large biopores, decreasing with depth from common to few; diffuse, smooth boundary.
115-170 cm Bw2	clay; moist; 10YR-2.5Y 4/4; extremely firm; structure as in Bw1-horizon; common ca-granules and few ca-nodules; few, with depth to very few, pea-iron gravel; strong effervescence with HCl; few fine roots; few fine, medium and large biopores; clear, smooth boundary.
170-175 cm Ck	calcareous clay; moist; 10YR 4/3; moderate medium angular to subangular blocky, structure defined by ca-granules and -nodules, that take about half of the soil mass by volume and give the total soil (clay + carbonates) a 'brittle' consistence; very few pea-iron gravel, colour on cross-section 10R 3/3; violent effervescence with HCl; abrupt, smooth boundary.
175 cm + 2C	cemented pea-iron gravel, size of the gravel 0.5 to 3 cm diameter; some angular quartz gravel.

Remarks :

1. Cracks extend till 70 cm depth.
2. In another part of the profile walls there are distinct sandy strata.
3. No roots and no biopores in Ck and 2C.

Summary profile description :
The profile is developed in a mixture of coarse sand and clay, that overlies a clay loam, with depth merging into a clay. The solum has a weak vertic structure and narrow cracks. Pea-iron gravel (pisolithic ironstone) is present throughout, decreasing with depth; ca-granules and -nodules are only found in the Bw horizon (20/40 - 170 cm).
The solum overlies abruptly a 5 cm thick C-horizon that for half of the volume consists of ca-granules and -nodules, and which in turn overlies a 2C-horizon, consisting of cemented pea-iron gravel and some quartz fragments.

Laboratory data of profile 24, Seinat B47

horizon nr., depth (cm)	particle size distribution, µm; % of fine earth								pH		$CaCO_3$ %	org. carbon %
	sand						silt	clay				
	2000-1000	1000-500	500-250	250-100	100-50	total	50-2	<2	H_2O	0.01M $CaCl_2$		
1 0-20/40	4.3	7.3	12.9	13.8	3.6	41.9	13.2	44.9	6.3	5.3		0.7
2 40-70	6.2	7.2	14.1	16.0	3.4	46.9	13.9	39.2	6.0	5.1		0.3
3 80-110	5.5	6.2	8.8	9.0	2.6	32.1	16.4	51.5	7.6	7.1		0.4
4 115-170	3.8	4.9	7.2	7.5	2.5	25.9	17.8	56.3	7.4	7.6	2.8	0.3
5 170-175	2.2	2.6	5.3	7.0	2.7	19.8	20.5	59.7	8.2	7.6	6.4	0.4

horizon nr., depth (cm)	exchangeable Na		CEC % mmol/kg	$CaSO_4$ %	water-soluble Na mmol/kg	EC mS/cm	extract for EC determination g/ml
	mmol/kg	%					
1 0-20/40			227				
2 40-70	7	3.4	208				
3 80-110	14	5.1	272				
4 115-170	17	5.5	309				
5 170-175	18	5.8	311				

horizon nr., depth (cm)	elemental composition of the fine earth (% by weight)												
	SiO_2	Fe_2O_3	Al_2O_3	TiO_2	MnO	CaO	MgO	Na_2O	K_2O	FeO	P_2O_5	SO_3	H_2O+
1 0-20/40	70.5	6.5	12.9	0.6	0.1	0.5	0.6	0.1	0.2	0.1	0.1		6.5
2 40-70	74.1	5.7	12.6	0.5	tr	0.4	0.4	0.1	0.2	0.2	tr		5.6
3 80-110	69.0	7.0	14.5	0.6	tr	0.7	0.6	0.1	0.2	0.2	tr		6.8
4 115-170	65.4	7.1	15.1	0.6	0.1	1.6	0.6	0.1	0.3	0.2	tr		7.8
5 170-175	61.2	7.4	15.5	0.6	0.1	3.8	0.7	0.1	0.3	0.2	0.1		9.6

horizon nr., depth (cm)				molar ratios			
	free Fe_2O_3	free Al_2O_3	amorphous Fe_2O_3	SiO_2/R_2O_3	SiO_2/Al_2O_3	SiO_2/Fe_2O_3	Al_2O_3/Fe_2O_3
1 0-20/40	4.7	1.5		7.1	9.3	28.6	3.1
2 40-70	4.2	1.2		7.6	10.0	34.3	3.2
3 80-110	5.2	1.8		6.1	6.1	26.1	3.2
4 115-170	4.9	1.5		5.6	7.3	24.8	3.2
5 170-175	5.0	1.4		5.1	6.7	22.2	3.2

horizon nr., depth (cm)	elemental composition of the clay fraction (% by weight)												
	SiO_2	Fe_2O_3	Al_2O_3	TiO_2	MnO	CaO	MgO	Na_2O	K_2O	FeO	P_2O_5	SO_3	H_2O+
1 0-20/40	47.0	12.9	24.9	1.3	tr		0.6	0.1	0.3	0.3	0.5		12.0
2 40-70	48.0	13.0	24.4	1.4	tr		0.6	0.1	0.3	0.2	0.5		11.4
3 80-110	47.8	12.7	24.6	1.4	tr		0.6	0.1	0.3	0.2	0.5		11.6
4 115-170	48.8	11.9	24.4	1.4	tr		0.6	0.1	0.3	0.2	0.4		11.3
5 170-175	49.7	11.8	24.7	1.2	tr		0.8	0.1	0.3	0.2	0.4		11.4

horizon nr., depth (cm)				molar ratios			
	free Fe_2O_3	free Al_2O_3	amorphous Fe_2O_3	SiO_2/R_2O_3	SiO_2/Al_2O_3	SiO_2/Fe_2O_3	Al_2O_3/Fe_2O_3
1 0-20/40	9.3	4.6	1.2	2.4	3.2	9.7	3.0
2 40-70	9.0	4.2	1.0	2.5	3.3	9.7	2.9
3 80-110	8.7	4.4	0.8	2.5	3.3	10.1	3.1
4 115-170	8.3	4.9	0.9	2.6	3.4	11.0	3.2
5 170-175	7.8	5.0	0.9	2.6	3.4	11.3	3.3

SEINAT B 48 (NR.25)

date of description :	30/1/1966
USDA Soil Taxonomy :	Ultic Paleustalf, fine-loamy, kaolinitic, isohyperthermic
FAO/UNESCO :	Dystric Nitosol(?) (1974); Haplic Nitisol(?) (1988)
location :	Umm Seinat proposed M.C.P.S., between G12 and H12, 300 m west of the traverse; topo map 1:250,000, sheet 55-L; 13°22'N - 35°35'E.
elevation :	519 m
landform :	non-rocky elevation in colluvio/alluvial clay plain; the profile is situated on top of a gently sloping, smooth-surfaced, low hill without rock outcrops
soil slope class :	almost flat
microrelief :	very slightly irregular
surface :	smooth, hard, covered with reddish-coated sand and fine gravel; large steep-sided termite mounds.
parent material :	profile developed 'in situ' on weathered Basement Complex rock
vegetation or land use :	woodland with about 50% canopy. Trees: *Combretum hartmannianum, Lannea humilis, Anogeissus schimperi* and *Acacia seyal*; tree diameter at 120 cm height is up to 30 cm, some *Anogeissus* trees are larger; few shrubs and on spots tall grasses.

Profile description :

0-10 cm A	loamy sand; dry; 7.5YR 2/2;4/2,d; slightly hard; structureless, massive; no effervescence with HCl; common fine, medium and large roots; many fine, few medium and large biopores; gradual, smooth boundary.
10-30 cm AB	sandy loam; dry; 5YR 3/2; 3.5/2.5,d; some patches are 7.5YR 2/2; 4/2,d; otherwise like A-horizon; gradual, smooth boundary.
30-60 cm Bt1	sandy clay loam; dry; 5YR 3/3; 2.5/3,d; slightly hard to hard; structureless, massive; few fine roots; many fine, few medium and large biopores; gradual, smooth boundary.
60-85 cm B2t	coarse sandy clay; slightly moist; 2.5YR 4/6, m and d; hard (very firm), but brittle due to many pores; with depth from structureless, massive to weak coarse and medium subangular to angular blocky, with faint, shiny cutans (2.5YR 3/6,d) on peds; some fine angular quartz gravel; roots and biopores as in Bt1; gradual, smooth boundary.
85-105 cm Bt3	coarse sandy clay; slightly moist; 2.5YR 4/6, m and d; hard (very firm), but brittle due to many pores; the clay has a soapy feeling; weak coarse and medium subangular to angular blocky, with faint, shiny cutans (2.5YR 3/6,d) on peds; few grey streaks in termite tunnels; some fine angular quartz gravel; roots and biopores as in Bt1 and Bt2; gradual, smooth boundary.
105-135 cm BC	fine-gravelly, coarse sandy clay; slightly moist; 2.5YR 4/6, with streaks of N4/N5 and patches of 5YR 4/6; hard (very firm), but brittle due to presence of fine gravel; structureless, massive; iron-manganese nodules; few fine roots; common medium and large biopores; gradual, smooth boundary.
135-160 cm C	fine-gravelly, coarse sandy clay; slightly moist; colour varying from 10R 4/6 to 7.5YR 4/6, with spots of N4 to N6, and fine iron-manganese mottles of N3; hard (very firm); structureless, massive, but in the lowest part of the horizon there are shiny ped faces with grey cutans; iron-manganese granules; much fine, angular quartz gravel; few fine roots; common fine and medium biopores; clear, smooth boundary.

160 cm+ 2C	gravel; 10YR 3/3 to 4/6,d; loose to slightly cemented; structureless, single grain, on spots massive; gravel is pisolithic ironstone (pea-iron gravel), and the colour of the profile wall is that of gravel in cross-section; fine angular quartz gravel.

Remarks :

1. Few fine cracks, 1 mm wide, till 30 cm depth.
2. The soapy feeling of the clay in the Bt3 horizon suggests a kaolinitic clay mineralogy.
3. The shiny ped faces in the C horizon are either clay cutans or fine slickensides.

Summary profile description :

A loamy to clayey weathering profile with a distinct argillic horizon. The colours range from hue 7.5YR in the A horizon to 10R in the 2C horizon. The A, AB and Bt1 horizons are structureless, massive, the Bt2 and Bt3 have a weak subangular to angular blocky structure, the BC, C and 2C are structureless. The soil consistence is hard/very firm. The 2C horizon is loose to slightly cemented pea-iron.

Laboratory data of profile 25, Seinat B48

horizon nr., depth (cm)	particle size distribution, µm; % of fine earth								pH		$CaCO_3$ %	org. carbon %
	sand						silt	clay				
	2000-1000	1000-500	500-250	250-100	100-50	total	50-2	<2	H_2O	0.01M $CaCl_2$		
1 0-10	6.0	15.6	32.1	23.4	5.1	82.2	13.6	4.2	6.7	6.6		0.5
2 10-30	10.6	23.3	27.4	14.8	3.3	79.4	5.5	15.1	7.1	6.1		0.6
3 30-60	7.3	18.2	29.5	14.0	3.4	72.4	4.9	22.7	6.2	4.7		0.3
4 60-85	10.4	18.5	17.1	10.2	2.3	58.5	8.9	32.6	6.1	4.5		0.3
5 85-105	9.4	12.9	17.6	9.6	2.7	52.2	2.7	45.1	6.2	4.3		0.2
6 105-135	10.2	13.9	15.5	10.0	2.6	52.2	8.4	39.4	6.3	4.4		0.1
7 135-160	17.3	11.7	12.8	7.8	2.6	52.2	9.2	38.6	6.4	4.7		tr

horizon nr., depth (cm)	exchangeable Na		CEC % mmol/kg	$CaSO_4$ %	water-soluble Na mmol/kg	EC mS/cm	extract for EC determination g/ml
	mmol/kg	%					
1 0-10			3				
2 10-30			40				
3 30-60			59				
4 60-85			118				
5 85-105			121				
6 105-135			131				
7 135-160			136				

horizon nr., depth (cm)	elemental composition of the fine earth (% by weight)												
	SiO_2	Fe_2O_3	Al_2O_3	TiO_2	MnO	CaO	MgO	Na_2O	K_2O	FeO	P_2O_5	SO_3	H_2O+
1 0-10	94.3	1.5	2.1	0.3	tr	0.2	0.1	tr	0.1	tr	tr		0.4
2 10-30	88.3	2.6	4.4	0.6	tr	0.2	0.2	0.1	0.1	0.1	0.1		2.6
3 30-60	83.5	3.1	6.6	0.6	tr	0.1	0.2	0.1	0.2	tr	0.1		2.6
4 60-85	77.6	4.8	9.8	0.7		0.1	0.3	0.1	0.2	0.1	0.1		4.6
5 85-105	72.3	6.1	12.3	0.8	tr	0.1	0.3	0.1	0.3	0.2	0.1		5.7
6 105-135	74.7	6.3	11.9	0.9	tr	0.2	0.3	0.1	0.2	0.2	0.1		5.1
7 135-160	75.4	6.0	11.0	0.8	0.1	0.2	0.3	0.1	0.2	0.1	0.1		4.8

horizon nr., depth (cm)				molar ratios			
	free Fe_2O_3	free Al_2O_3	amorphous Fe_2O_3	SiO_2/ R_2O_3	SiO_2/ Al_2O_3	SiO_2/ Fe_2O_3	Al_2O_3/ Fe_2O_3
1 0-10	1.1	0.4		52	76	168	2.2
2 10-30	2.1	0.5		24	34	82	2.4
3 30-60	2.8	0.7		15.6	21	58	2.7
4 60-85	5.0	1.0		10.1	13.5	40	3.0
5 85-105	3.9	1.1		7.6	10.0	30	3.0
6 105-135	5.2	1.0		8.0	10.7	31	2.9
7 135-160	4.7	1.0		8.7	11.7	33	2.9

horizon nr., depth (cm)	elemental composition of the clay fraction (% by weight)												
	SiO_2	Fe_2O_3	Al_2O_3	TiO_2	MnO	CaO	MgO	Na_2O	K_2O	FeO	P_2O_5	SO_3	H_2O+
1 0-10	49.8	13.8	22.3	2.0	0.1		0.4	0.2	0.7	0.3	0.6		12.8
2 10-30	48.3	11.8	25.6	1.4	tr	tr	0.5	tr	0.5	0.8	0.4		11.4
3 30-60	49.6	11.6	24.1	1.5	0.1	0.1	0.5	tr	0.5	0.7	0.3		12.1
4 60-85	49.2	12.2	25.6	1.4	tr	0.1	0.5	tr	0.5	0.7	0.4		11.7
5 85-105	48.6	12.2	26.5	1.3	0.1	0.1	0.5	tr	0.5	0.9	0.4		11.8
6 105-135	47.7	11.6	26.8	1.3	tr	0.2	0.5	tr	0.4	0.8	0.4		11.8
7 135-160	49.7	10.7	26.0	1.3	0.1	tr	0.5	tr	0.4	0.8	0.4		11.5

horizon nr., depth (cm)				molar ratios			
	free Fe_2O_3	free Al_2O_3	amorphous Fe_2O_3	SiO_2/ R_2O_3	SiO_2/ Al_2O_3	SiO_2/ Fe_2O_3	Al_2O_3/ Fe_2O_3
1 0-10	11.4	3.1		2.7	3.8	9.7	2.6
2 10-30	9.4	1.5		2.4	3.2	9.8	3.1
3 30-60	9.1	1.6		2.6	3.5	10.8	3.1
4 60-85	9.8	1.5		2.4	3.3	9.7	3.0
5 85-105	9.6	1.7		2.3	3.1	8.5	2.7
6 105-135	8.9	1.3		2.3	3.0	10.3	3.4
7 135-160	7.4	1.2		2.6	3.2	11.8	3.7

SEINAT B50 (NR.26)

date of description :	2/2/1966
USDA Soil Taxonomy :	Typic Chromustert, very-fine, montmorillonitic, isohyperthermic
FAO/UNESCO :	Chromic Vertisol (1974); Eutric Vertisol (1988)
location :	Umm Seinat proposed M.C.P.S., R10; topo map 1:250,000, sheet 55-L; 13°10'N - 35°35'E.
elevation :	493 m
landform :	clay plain with inselbergs, rocky hills and non-rocky elevations; profile is situated on the clay plain.
soil slope class :	flat
microrelief :	gilgai, normal type, wavelength 3-7 m, amplitudo 15-25 cm.
surface :	soft, brittle flake with many sand grains, breaking into a mulch. Cracks are distinct in gilgai depressions where surface mulch is thin, whereas they are obscured by thick mulch on mounds. Gilgai mounds show a distinct accumulation of carbonate nodules and - but to a lesser extent - quartz gravel and stones; gilgai depressions have little gravel and no carbonatic nodules.
parent material :	colluvio/alluvial clay derived from the weathering of Basement Complex rock and/or basalt, the latter forming the Gedaref-Gallabat ridge.
vegetation or land use :	open woodland of *Acacia seyal, Balanites aegyptiaca* and *Combretum hartmannianum* with tree diameter at 120 cm height generally under 30 cm; shrubs of *Acacia campylacantha*. The ground cover of tall grasses has been burnt.

Profile description (from gilgai mound) :

0-30 cm A	slightly gravelly clay; dry; 2.5Y 4/2; 3.5/2,d; extremely hard; weak coarse subangular blocky, with depth to angular blocky; common ca-granules and ca-nodules; slight effervescence with HCl; common fine and fibrous roots; common biopores; termite activity; diffuse, smooth boundary.
30-90 cm Bw1	clay with few gravel; 2.5Y 3/2; very firm; strong coarse, medium and fine angular blocky; peds are tilted wedges with slickensided faces; common ca-granules and ca-nodules; slight effervescence with HCl; few fine and fibrous roots; few biopores; termite activity; diffuse, smooth boundary.
90-130 cm Bw2	like Bw1, except for grade of structure: moderate coarse, and strong medium and fine angular blocky; diffuse, smooth boundary.
130-200 cm B/Cwk	clay; moist; 10YR 3/3, with patches of 10YR 4/3; extremely firm; soil structure as in Bw2; common ca-granules and ca-nodules; common iron- and manganese-impregnated ca-granules, 1-3 mm across; common segregations of soft powdery lime containing hard ca-nodules; strong effervescence with HCl; fibrous roots on slickensides; few biopores; termite activity; diffuse, smooth boundary.
200-250 cm Ck	clay; moist; 10YR 4/3; weak subangular blocky, peds separated by short, non-intersecting slickensides and abundant segregations of soft powdery lime; peds are sharp-edged tilted wedges; few large slickensides; hard ca-nodules occur embedded in soft powdery lime segregations; common ca-granules and -nodules; each nodule or granule, when removed from the soil leaves a manganese coating on the surface; many iron- and manganese- impregnated ca-nodules, 1-3 mm across; few (iron)-manganese mottles on slickensides have colour N4-5.
250-470 cm	observations from augering

250-350 cm	clay; moist; 10YR 4/3; segregations of soft powdery lime, containing hard ca-nodules that are partly grey/black-coated; (iron)-manganese mottles and iron-manganese-impregnated ca-nodules, leaving an imprint when removed from the soil; strong effervescence with HCl.
350-375 cm	similar to 250-350 cm, but the ca-nodules are harder and are stronger grey/black-coated; grey mottles and grey patches of soil.
375-470 cm+	clay; moist; 10YR 4/4; rusty mottles, 7.5YR 5/8; grey mottles and soil patches, 10YR 5/1; hard ca-nodules with black and rusty-coloured coatings; rather soft (iron)-manganese nodules, leaving an imprint when removed from the soil.

The profile of the gilgai-depression differs from the mound profile in the following:

0-30 cm	Afew ca-granules
30-130 cm	Bwfew ca-granules
130-180 cm	ACkas mound site
180-250 cm	Ckas mound site.

Remarks:

1. Profile pit is 3 m long, stretching from gilgai mound to gilgai depression.
2. Cracks extend till 60 cm depth.
3. The shiny imprints of ca-granules and -nodules in the Ck horizon have the appearance of micro-slickensides.

Summary profile description:

Vertisol profile with remarkable uniformity till great depth (augering observations till 470 cm) . Vertic structure most distinct in Bw1 (30-90 cm), gradually disappearing in Ck (200cm+). The substratum is characterised by soft powdery lime segregations with hard ca-nodules, by iron-manganese-impregnated ca-nodules and -granules, and by (iron)-manganese mottles, till approximately 350 cm. Below 350 cm there are rusty and grey mottles, ca-nodules with rusty and black coatings and (iron)-manganese nodules. All coated nodules in the substratum leave an imprint when removed from the soil.

Laboratory data of profile 26, Seinat B50

horizon nr., depth (cm)	particle size distribution, µm; % of fine earth								pH		$CaCO_3$ %	org. carbon %
	sand						silt	clay				
	2000-1000	1000-500	500-250	250-100	100-50	total	50-2	<2	H_2O	0.01M $CaCl_2$		
1 0-30						7.2	16.6	76.2	7.3	6.7	4.6	0.5
2 30-90						6.2	18.9	74.9	7.8	7.0	4.3	0.2
3 90-130						5.5	17.3	77.2	8.2	7.2	5.8	0.4
4 130-200						4.0	18.8	77.2	8.0	7.6	4.9	0.2
5 200-250						3.9	19.3	76.8	8.1	7.5	7.9	0.1
6 250-470[1)]						3.5	18.5	78.0	8.2	7.6	7.0	tr

horizon nr., depth (cm)	exchangeable Na		CEC % mmol/kg	$CaSO_4$ %	water-soluble Na mmol/kg	EC mS/cm	extract for EC determination g/ml
	mmol/kg	%					
1 0-30	3	0.5	581				
2 30-90	38	7.0	543				
3 90-130	58	10.3	564				
4 130-200	59	10.9	542				
5 200-250	52	9.1	570				
6 250-470[1)]	56	9.1	616				

horizon nr., depth (cm)	elemental composition of the fine earth (% by weight)												
	SiO_2	Fe_2O_3	Al_2O_3	TiO_2	MnO	CaO	MgO	Na_2O	K_2O	FeO	P_2O_5	SO_3	H_2O+
1 0-30	59.2	10.8	17.0	1.4	0.1	1.5	2.5	0.2	tr	0.4	0.1		10.0
2 30-90	57.1	10.9	17.2	1.5	0.1	1.3	2.5	0.4	tr	0.3	0.1		9.5
3 90-130	56.2	10.5	17.2	1.4	0.1	1.9	2.5	0.4	tr	0.3	0.1		10.0
4 130-200	55.2	10.5	17.6	1.4	0.1	1.9	2.8	0.4	tr	0.4	0.1		9.8
5 200-250	54.7	10.5	17.0	1.4	0.1	2.5	2.9	0.6	0.2	0.3	0.1		10.0
6 250-470[1)]	54.8	10.5	15.9	1.2	0.2	1.6	3.1	0.5	0.3	0.3	0.1		9.5

horizon nr., depth (cm)				molar ratios			
	free Fe_2O_3	free Al_2O_3	amorphous Fe_2O_3	SiO_2/R_2O_3	SiO_2/Al_2O_3	SiO_2/Fe_2O_3	Al_2O_3/Fe_2O_3
1 0-30	5.4	5.0		4.2	5.9	14.3	2.4
2 30-90	5.3	4.8		4.0	5.7	13.6	2.4
3 90-130	5.7	5.7		3.9	5.5	13.7	2.5
4 130-200	5.0	4.7		3.8	5.3	13.4	2.5
5 200-250	4.9	4.5		3.9	5.5	13.5	2.5
6 250-470[1)]	5.0	4.7		4.1	5.9	13.5	2.3

horizon nr., depth (cm)	elemental composition of the clay fraction (% by weight)												
	SiO_2	Fe_2O_3	Al_2O_3	TiO_2	MnO	CaO	MgO	Na_2O	K_2O	FeO	P_2O_5	SO_3	H_2O+
1 0-30	47.5	12.2	21.8	1.3	0.1	tr	1.8	0.2	0.1	0.7	0.2		13.2
2 30-90	46.8	12.6	22.4	1.2	0.1	tr	1.7	0.2	0.1	0.7	0.2		13.6
3 90-130	46.6	12.3	22.2	1.3	tr	tr	1.9	0.1	tr	0.7	0.2		13.9
4 130-200	47.5	12.0	22.3	1.0	tr	tr	1.7	0.1	tr	0.7	0.2		13.4
5 200-250	48.6	11.9	21.1	1.3	tr	tr	2.1	0.1	0.1	0.8	0.2		12.8
6 250-470[1)]	50.1	11.5	19.6	1.1	tr	tr	2.1	0.1	0.2	0.8	0.2		12.8

horizon nr., depth (cm)				molar ratios			
	free Fe_2O_3	free Al_2O_3	amorphous Fe_2O_3	SiO_2/ R_2O_3	SiO_2/ Al_2O_3	SiO_2/ Fe_2O_3	Al_2O_3/ Fe_2O_3
1 0-30		2.7	3.7	10.0 2.7			
2 30-90		2.6	3.6	9.5 2.7			
3 90-130		2.6	3.6	9.6 2.7			
4 130-200		2.7	3.6	10.0 2.8			
5 200-250		2.8	3.9	10.3 2.6			
6 250-470[1)]		3.1	4.3	11.2 2.6			

[1)] Sample 400-470

SEINAT B55 (NR. 27)

date of description :	8/2/1966
USDA Soil Taxonomy :	Entic Pellustert, very-fine, montmorillonitic, isohyperthermic
FAO/UNESCO :	Chromic Vertisol (1974); Eutric Vertisol (1988)
location :	Umm Seinat proposed M.C.P.S., between D11 and C11; topo map 1:250,000, sheet 55-L; 13°25'N - 35°35'E.
elevation :	525 m
landform :	clay plain with inselbergs, rocky hills and non-rocky elevations
soil slope class :	flat
microrelief :	weak gilgai, normal type, with wavelength 6 m and amplitudo 15 cm. On a smaller scale the surface is very uneven within the area of one crack-surrounded polygon.
surface :	well-developed surface mulch sloughing into cracks; surface colour 10YR 3.5/ 1.5,d.
parent material :	colluvio/alluvial clay derived from the weathering of basalt that forms the Gedaref-Gallabat ridge, with an admixture of clay derived from Basement Complex rock.
vegetation or land use :	woodland with a 50% canopy of dominant *Acacia seyal*, with *A.fistula*, *A.senegal* and *Balanites aegyptiaca*; tree diameter at 120 cm height generally less than 15 cm.

Profile description :

0-30 cm A	clay; dry; 10YR 4/1.5; 3/1,d; extremely hard; moderate medium and coarse subangular blocky, with depth grading into angular blocky that has a parallelepiped substructure appearing as a faint lamination; common white ca-granules, 0.5-3 mm diameter; few fine roots; fine and medium biopores; termite activity; diffuse, smooth boundary.
30-90 cm Bw1	clay; moist/wet; 10YR3/1.5; 3/1,d; firm; strong coarse, medium and fine angular blocky, peds are tilted wedges separated by prominent slickensides; few white ca-granules; few fine roots; few fine and medium biopores; termite activity; diffuse, smooth boundary.
90-150 cm Bw2	clay; moist; 10YR 3/1, m and d; moderate coarse, medium and fine angular blocky, the peds are tilted wedges separated by prominent to distinct slickensides; few white ca-granules; slight effervescence with HCl; few fine roots; common medium and large biopores; distinct termite tunnels and Fungus-gardens; diffuse, smooth boundary.
150-180 cm+ BCwk	clay; moist; 10YR 2.5/1.5; moderate coarse and medium angular blocky, some of the peds are tilted wedges separated by distinct slickensides; few white ca-granules; faint, fine segregations of soft powdery lime, grey-coloured and with the vertical dimension larger than the horizontal dimensions; strong effervescence with HCl; fine fibrous roots on slickensides; common medium and large biopores; distinct termite tunnels and Fungus gardens

Remarks :

1. An uneven surface area within one crack-bordered polygon is often found in Sudan Vertisols in khor beds and other sites subject to flooding for long periods.
2. There are no carbonate nodules or granules on the soil surface.
3. Cracks are 2-5 cm, sometimes up to 10 cm wide at the surface; they extend till 60 to 100 cm depth.

Summary profile description :
Deep Vertisol profile developed in colluvio/alluvial clay. Horizon boundaries are diffuse. The colour is more or less uniform at about 10YR 3/1.5. Vertic structure with parallelepiped substructure in A horizon, tilted wedges and prominent to distinct slickensides in Bw and BCwk horizons. Few fine ca-granules occur throughout the solum, with inconspicuous fine segregations of soft powdery lime in the BCwk horizon. Termite tunnels and Fungus-gardens occur below 90 cm, at lesser depths termite activity is less. Cracks extend till a depth of 60 to 100 cm.

Laboratory data of profile 27, Seinat B55

horizon nr., depth (cm)	particle size distribution, µm; % of fine earth								pH		$CaCO_3$ %	org. carbon %
	sand						silt	clay				
	2000-1000	1000-500	500-250	250-100	100-50	total	50-2	<2	H_2O	0.01M $CaCl_2$		
1 0-30						1.9	20.3	77.8	7.2	6.6	0.7	0.9
2 30-90						2.1	19.4	78.5	7.8	7.2	1.2	0.9
3 90-150						1.4	17.4	81.2	8.0	7.3	1.2	0.7
4 150-180						0.7	19.9	79.4	8.0	7.3	1.5	0.4

horizon nr., depth (cm)	exchangeable Na		CEC % mmol/kg	$CaSO_4$ %	water-soluble Na mmol/kg	EC mS/cm	extract for EC determination g/ml
	mmol/kg	%					
1 0-30	7	1.0	701				
2 30-90	64	9.0	713				
3 90-150	68	9.7	702				
4 150-180	74	10.2	723				

horizon nr., depth (cm)	elemental composition of the fine earth (% by weight)												
	SiO_2	Fe_2O_3	Al_2O_3	TiO_2	MnO	CaO	MgO	Na_2O	K_2O	FeO	P_2O_5	SO_3	H_2O+
1 0-30	52.4	9.3	17.0	1.5	0.2	3.0	0.9	0.4	0.3	0.8	0.2		10.7
2 30-90	52.4	9.3	17.0	1.5	0.1	3.1	0.9	0.6	0.3	0.6	0.2		10.5
3 90-150	51.9	9.3	16.8	1.5	0.2	3.5	0.9	0.6	0.2	0.7	0.1		10.2
4 150-180	52.8	12.1	19.8	1.0	0.1	0.3	1.6	0.1	0.2	0.5	0.3		10.6

horizon nr., depth (cm)				molar ratios			
	free Fe_2O_3	free Al_2O_3	amorphous Fe_2O_3	SiO_2/R_2O_3	SiO_2/Al_2O_3	SiO_2/Fe_2O_3	Al_2O_3/Fe_2O_3
1 0-30	5.1	2.9	0.4	3.9	5.2	15.0	2.9
2 30-90	6.2	4.0	0.3	3.9	5.2	16.7	2.9
3 90-150	5.7	3.0	0.4	3.9	5.3	14.8	2.8
4 150-180	6.3	4.0	0.4	3.8	5.2	14.6	2.8

horizon nr., depth (cm)	elemental composition of the clay fraction (% by weight)												
	SiO_2	Fe_2O_3	Al_2O_3	TiO_2	MnO	CaO	MgO	Na_2O	K_2O	FeO	P_2O_5	SO_3	H_2O+
1 0-30	51.6	12.3	20.2	1.1	0.1		1.6	0.1	0.2	0.2	0.4		10.5
2/3 30-150	52.6	12.8	19.4	1.1	0.1		1.5	0.2	0.2	0.1	0.4		10.7
4 150-180	52.8	12.1	19.8	1.0	0.1	0.3	1.6	0.1	0.2	0.5	0.3		10.6

horizon nr., depth (cm)				molar ratios			
	free Fe_2O_3	free Al_2O_3	amorphous Fe_2O_3	SiO_2/R_2O_3	SiO_2/Al_2O_3	SiO_2/Fe_2O_3	Al_2O_3/Fe_2O_3
1 0-30	6.9	5.3	0.5	3.1	4.3	11.2	2.6
2/3 30-150	7.1	4.8	0.7	3.3	4.6	11.0	2.4
4 150-180	6.3	4.0	0.4	3.3	4.5	11.6	2.6