Mechanical replacement processes in mobile soft calcic horizons; their role in soil and landscape genesis in an area near Mérida, Spain

G. W. W. Elbersen

International Institute for Aerial Survey and Earth Sciences (ITC)

Mechanical replacement processes in mobile soft calcic horizons; their role in soil and landscape genesis in an area near Mérida, Spain

Centre for Agricultural Publishing and Documentation

Wageningen - 1982

CIP-GEGEVENS

Elbersen, G.W.W.

Mechanical replacement processes in mobile soft calcic horizons : their role in soil and landscape genesis in an area near Mérida, Spain / G.W.W. Elbersen. - Wageningen : Pudoc. - Ill. - (Agricultural research reports ; 919)
Met samenvattingen in het Frans, Nederlands, Spaans. - Proefschrift Wageningen. - Met bibliogr., lit. opg.
ISBN 90-220-0810-X
SISO 630 UDC 631/632
Trefw. : landbouw.

ISBN 90 220 0810 X

The author graduated on 12 November 1982 as Doctor in de Landbouwwetenschappen at the Agricultural University, Wageningen, the Netherlands, on a thesis with the same title and contents.

Abstract

Elbersen, G.W.W. (1982). Mechanical replacement processes in mobile soft calcic horizons; their role in soil and landscape genesis in an area near Mérida, Spain. Agric. Res. Rep. (Versl. landbouwk. Onderz.) 919, ISBN 90-220-0810-X, (xii) + 208 p., 47 figs, 16 tables, 204 refs, Eng., Du., Sp. and Fr. summaries.
Also: Doctoral thesis, Wageningen.

A mechanical replacement process is described to explain the way in which soft calcic horizons become 'mobile' and actively penetrate the soil. This model implies that the horizons are pedogenetic features which may be very old since they can escape exposure in a landscape subject to erosion. The lime they contain can be derived from the weathering strata through which they have passed in the course of time. The process is initiated by subterranean gilgaï formation which introduces soil material into the lower part of the calcic horizon which subsequently moves this material upward and expels it from the top. The transport process was re-created in the laboratory and monitored by stereo radiography. Its driving force is derived from air enclosure which occurs upon wetting of crystalline powdery lime. Field data from the study area have yielded evidence of the replacement process and indicate the main controlling factors. Rates of downward movement of the calcic horizons have been calculated to be of the same order of magnitude as representative erosion rates for the area. Implications of the process for soil science, agriculture, geomorphology and archeology are briefly treated.

Free descriptors: calcic horizons, caliche, calcrete, soft powdery lime, gilgaï, air enclosure, dating carbonates, erosion rates, carbonate leaching, petrocalcic horizons, genesis of calcic horizons.

Contents

Acknowledgments

The soils of the Mérida area have been the subject of study for many years for students and staff of the Soil Department of the ITC. They have gathered data and engaged in stimulating though often heated scientific discussions. Both these activities have yielded useful contributions which I gratefully acknowledge. The loyal cooperation of my colleagues in the department made it possible for me to take the time necessary to carry out this study.

To my promotor Prof. Dr. Ir. P. Buringh I am greatly indebted for his support from the very first moment that I discussed the subject with him and for his guidance and constructive criticism.

I gratefully acknowledge the help received from a great many people outside and inside ITC during the different stages of the investigation:

- From the staff of the International Soil Museum in Wageningen, in particular Drs. D. Creutzberg for the micromorphological descriptions; Dr. Ir. L.P. van Reeuwijk for the interpretation of the analyses carried out by Messrs. R. Smaal and J.R.M. Huting; Messrs. R.O. Bleyert and W. Bomer for photographic work.
- From the Department of Rural Survey of the ITC, Dr. H.G.J. Huizing for agro-climatological data.
- From the Department of Geology of the ITC, Drs. G.J. Krol for geohydrological data, Dr. Ir. N. Rengers for advice on soil mechanical aspects, Dr. B.N. Koopmans for long term erosion rates and Drs. D. Kovacs for mathematical aspects.
- From the Department of Geomorphology of the ITC, Dr. A.M.J. Meijerink for sediment yield estimates, Dr. R.A. van Zuidam for extensive references on calcic horizons and Drs. N.H.W. Donker for help with statistical problems.
- From the Soil Department of the ITC in particular Ir. E. Nieuwenhuis for his constructive criticism from the beginning of the investigation both in the field and in the office; Ir. E. Bergsma for data on soil loss and ex-staff member Dr. Ir. M. Knibbe for material on the Riola profile.
- Of the various service departments of the ITC, the Library, the Photographic Laboratory and the Development Workshop and in particular Mr. A. 't Hart for the precise manufacture of the containers for stereo radiography.
- Of the Department of Soil Science and Geology of the LH Wageningen, Ir. H. Rogaar for his help in the execution of the time consuming radiographic experiments and for his stimulating comments on their interpretation.
- Of the Netherlands Soil Survey Institute, Dr. Ir. J. Bouma for his advice on the set-up of the experiment under conditions of unsaturated flow and Dr. E.B.A. Bisdom

for micromorphological data on the Riola profile.
- To the Department of Zootechnology of the LH Wageningen, for putting at my disposal X-ray equipment and laboratory facilities.

A number of persons have been willing to review parts of my manuscript and offer constructive criticism for which I express my gratitude:
- Prof. Dr. A. Ruellan of the Ecole Nationale Supérieure Agronomique in Rennes, France twice granted me an interview to discuss his comments on the mechanical replacement process.
- Prof. Dr. Ir. G.H. Bolt of the Laboratory of Soils and Fertilizers of the LH Wageningen and Dr. Ir. F.F.R. Koenigs jointly reviewed the results of my experiments and offered their comments.
- Dr. Ir. N. van Breemen of the Department of Soil Science and Geology of the LH Wageningen, who reviewed the calculations of the rate of leaching of calcium carbonate.
- Dr. W. Salomons of the Haren Branch of the Delft Hydraulics Laboratory, who reviewed the interpretation of the stable isotope data of the Riola profile.
- Dr. J. van Brakel of the Laboratory for Chemical Engineering of the Delft University of Technology, who commented on the results of the stereo radiographic experiments and supplied data on the wetting of powders.
- Dr. Ir. P.A.C. Raats of the Institute of Soil Fertility in Haren, who reviewed the theoretical background of the air enclosure phenomena in crystalline lime.

I am indebted to many people who helped in various aspects of the publication of this study:
- At ITC Mr. E.A. van Leeuwen diligently drew the figures; Mrs. A.R. Morgan of the Publications Department edited the text with great understanding; Mrs. H.R. Rettensberger, Mrs. M. Völker and Mrs. A.M. van der Linde carefully typed and type-set the manuscript.
- Of the staff of PUDOC Wageningen in particular Mr. R.J.P. Aalpol, who resolved the final editorial points and planned and supervised the lay-out.

Agradezco al Consejo Superior de Investigaciones Cientificas de España por haber me permitido y facilitado la investigación efectuada en el territorio nacional.

I want to express my gratitude to the Directorate of the ITC for putting at my disposal time and services of the Institute for this investigation.

Finally a word of thanks is due to my family who have patiently endured my physical and mental absence, especially during the last stages of this project and to the many colleagues and friends who have kept me going by enquiring frequently and insistently about the well-being of the 'clay balls'.

1 Aim and progress of the study

In the Mérida area in S.W. Spain soft calcic horizons of remarkable purity and thickness occur at different depths in the soil. When near or at the land surface the upper part of these horizons is hardened forming a so-called petrocalcic horizon. The soft calcic horizons and the petrocalcic horizons are the main subject of this study. Several investigations dealing directly or indirectly with these horizons have been carried out by the Soils Department of the International Institute for Aerial Survey and Earth Sciences (ITC), of which the author is a staff member.

The following facts established in these studies are important:

- The calcic horizons are particularly well developed on Miocene clays which contain calcareous layers. They are also found on other materials that do not contain any lime and do not release lime in large quantities upon weathering either. These include schist, arkose and even granite.
- Calcic horizons often contain non-calcareous clay nodules, saprolite fragments and stones in peculiar distribution patterns.
- The pure calcic horizons are generally characterised by abrupt and smooth upper boundaries and abrupt and irregular lower boundaries in which stress phenomena occur.

In the study of the calcic horizons, the Soils Department of the ITC considered the similarity of their characteristics in the different landscapes. This stimulated efforts to formulate a theory on the genesis of these horizons which might have validity for all the occurrences. This led initially to a strong inclination towards geogenetic modes of origin (Jayaraman, 1974; Roy, 1974; Jung, 1974; Rao, 1975). In the course of the investigations, however, a number of observations were made that did not tally with this type of origin for the horizons in their present position:

- The lime occurs in the form of horizons parallel to the surface of undulating landscapes with a clear degradational history.
- Mineralogical similarity between soil horizons over and under the calcic horizon (Mahmood, 1979) for the schist landscape.

Attempts to explain the apparent mobility of these horizons by a pedogenetic process of dissolution and recrystallisation (unpublished notes by Knibbe, 1974b) failed upon testing to account for the presence of these horizons near the surface of landscapes with a degradational history. The fact that the calcic horizons, if established by a pedogenetic process at all, could remain intact at or near the surface of a soil profile subject to erosion, without becoming subject to this erosion as well, was not satisfactorily explained. If a process could be found, however, by means of which the calcic horizons could migrate downwards under the eroding surface with a velocity sufficient to avoid exposure, the pedogenetic model would be tenable. The idea that the clay nodules could be indicative of such a process initiated the research for the present study.

Experiments were carried out to study the behaviour of these clay nodules and other objects embedded in a matrix of soft lime under alternating moist and dry conditions. It turned out that an upward movement of these objects through the soft calcic matrix can be measured under certain conditions.

The combination of this finding with field data regarding swell and shrink of the soil materials at the lower boundary of the calcic horizon in the weathering zone, led to the description of a mechanical pedogenetic process. This process is capable of moving the entire soft calcic horizon downward with a speed sufficient to keep pace with the erosion of the land surface.

The process turned out to be useful in explaining a number of soil features in the survey area. Hardened petrocalcic surface horizons, locally encountered, are explained as resulting from failure of the process to match the erosion rates. Analyses of the reasons for such failure help to formulate the conditions governing the activity of the process.

Since the calcic horizons can accumulate lime gradually while moving downward, the search for their genesis can be narrowed to the search for a much thinner 'incipient soft calcic horizon'. The latter horizon is assumed to have formed from secondary carbonates that have crystallised in the soil and been transported mechanically downward towards the average groundwater table where they have accumulated.

The mechanical replacement process in soft calcic horizons that lends mobility to these horizons might have important implications for fields in soil science, agriculture, geomorphology and archeology.

2 Review of calcic horizons

The literature on calcic horizons is extensive since it contains contributions from many disciplines, the main ones being geology, geomorphology and soil science. In the last decade various monographs which deal with this subject have been published: Goudie (1973), FAO (1973) and Reeves (1976). It is not the purpose of this chapter to duplicate these nor to make a complete review of all aspects of calcic horizons, which would be outside the scope of this study anyway.

The aim here is to present background information needed as a reference in the discussion of various topics in the following chapters. Thus certain subjects receive a good deal of attention while others are referred to in a general way only. Terminology is also treated.

2.1 TYPES OF CALCIC HORIZONS AND THEIR NOMENCLATURE

The term 'calcic horizon' as used in this publication is defined in Soil Survey Staff (1975). Its most important equivalents encountered in the literature are: 'calcrete', 'croûte calcaire' and 'caliche' (Goudie, 1972ab). Aristarain (1971) traced the origin of the latter term especially in N. and S. America. He is in favour of redefining the term 'caliche', restricting its use to pedogenetic accumulations in the soil. According to Soil Survey Staff (1975) calcic horizons are horizons of accumulation of calcium carbonate or of calcium- and magnesium-carbonate. The accumulation may be located in the C horizon or in a variety of other horizons. Minimum requirements for thickness and carbonate content are set according to the nature of the other mineral constituents of the horizon and according to the character of the underlying material. For hard calcic horizons the following from Soil Survey Staff (1975) applies: 'The petrocalcic horizon is a continuous, cemented or indurated calcic horizon, that is cemented by calcium carbonate or in some places by calcium- and some magnesium-carbonate. The petrocalcic horizon is continuously cemented throughout the pedon to the degree that dry fragments do not slake in water.' Special depth and carbonate content requirements are set for laminar petrocalcic horizons resting directly on bedrock. For horizons with carbonate accumulation that do not fulfil the requirements of either calcic or petrocalcic horizons, the suffix 'ca' will be used.

In the horizon nomenclature for soil description, the only way to indicate a horizon with carbonate accumulation is the suffix 'ca', even when these horizons have morphologies dominated entirely by this material. In order to express this, Gile et al. (1965) propose the term 'K horizon'. They set new absolute limits for K1, K2 and

K3 horizons to indicate their degree of development as measured by the percentage of the so-called K-fabric (K from the German 'Kalk'). The observation that a mere suffix is insufficient to express such a distinct morphology is valid. It is felt, however, that as long that there is no concensus on the processes that cause the formation of this fabric, soil science is not in need of more arbitrary boundaries beyond those already set by Soil Survey Staff (1975). As such the K horizon terminology will not be used in this publication. See also the criticism of Bal (1975b) of the genetic implications of this term.

In this text the nomenclature of the Soil Survey Manual (Soil Survey Staff, 1951) and of the Guidelines for Soil Description (FAO, 1967) which has been derived from this, are used. Currently drafts are circulating of the 'National Soils Handbook' which will eventually replace the Soil Survey Manual (Soil Survey Staff, 1951). In this new handbook the accumulation of carbonates will be indicated by 'k', cementation by 'm' and a petrocalcic horizon by 'km'. This terminology was first introduced in the legend of the Soil Map of the World Vol. I (FAO-UNESCO, 1974) and was later adapted in the second revised edition of the Guidelines for Soil Description.

In the literature on calcic horizons and ca-horizons, numerous attempts are found to subdivide the phenomena covered by these terms. For a review see e.g. Mathieu (1974) and Zuidam (1976). The criteria below are used for subdivision.

a. Measurable characteristics of the horizons proper, i.e. (macro)morphology, carbonate content and hardness: Brown (1956), Durand (1959), Gile (1961), Wilbert (1962), Ruellan (1970), Soil Survey Staff (1975), Netterberg (1980).

b. Micromorphology: Blokhuis et al. (1968), Brewer (1972), James (1972), Siesser (1973), Bal (1975ab).

c. Like a, together with occurrence in the landscape: Dumas (1969), Lattman (1973).

d. Like a, together with age and/or degree of development: Gile et al. (1965), Gile et al. (1966), Netterberg (1969).

e. Like a, together with presumed genesis: Dumas (1969).

Of all these subdivisions those of type a are preferred over c, d, and e. The reason for this preference lies in the fact that there is no concensus of opinion about the genesis of the different types. As such age and degree of development are arbitrary values. Position in the landscape becomes insignificant if no reliable genetic conclusions can be drawn from it. Micromorphology is a useful tool for characterisation, if superimposed upon the types distinguished according to a.

As a good and complete example the classification of Ruellan (1970) is given which takes into account the observations of several French earth scientists who worked in N. Africa. Ruellan's translation of his own classification in FAO (1973) is given in Table 1. The following types of this table are of particular interest for this study and will be described in more detail:

'Concentrations discontinues' (2) are those accumulations in which the visible concentrations of lime are separated by zones of lower lime content. Of these the *'amas friables'* (2b) have the following characteristics: These are spots of lime of

Table 1. Main types of lime accumulations according to Ruellan in: FAO (1973). The terms written in italics refer to forms of particular interest for the survey area.

1. Distribution diffuse	1. Diffuse distribution
2. Concentrations discontinues	2. Discontinuous concentrations
a. Pseudo-myceliums	a. Pseudo-myceliums
b. *Amas friables*	b. *Friable accumulations*
c. Nodules	c. Nodules
3. Concentrations continues	3. Continuous concentrations
a. Encroûtements non-feuilletés	a. Non-laminated encrustations
a1. *Encroûtements massifs*	a1. *Massive encrustations*
a2. Encroûtements nodulaires	a2. Nodular encrustations
b. Encroûtements feuilletés	b. Laminated encrustations
b1. *Croûtes*	b1. *Crusts*
b2. *Dalles compactes*	b2. *Compact slabs*
b3. Encroûtements lamellaires (pellicules rubanées)	b3. Platy encrustations (ribboned pellicule)

variable shape and size and of a whitish colour. Their limits may be clear or diffuse. They are separated by zones of lower lime content. This form is equivalent to accumulations of soft powdery lime according to Soil Survey Staff (1975) and zones which show these phenomena generally qualify for calcic horizons. The word 'lime' as used in this text signifies calcium carbonate with or without magnesium carbonate admixed; a meaning also implied in the Soil Taxonomy System (Soil Survey Staff, 1975). This is contrary to the significance attributed to it in the Glossary of Geology (American Geological Institute, 1974), which attributes this term to CaO only.

Whenever lime in any form is accumulated to such an extent that the original soil colour is obliterated the term 'encroûtement' is applied. Lime content mostly exceeds 60% by weight in these cases. The following forms are important for the present study:

The *'encroûtements massifs'* (3a1). According to Ruellan (1970) these have a chalky or tuffaceous nature. Their structure is generally massive, but occasionally polyhedric. Their hardness is variable but generally they are soft. They have a homogeneous light colour. According to Soil Survey Staff (1975) these are calcic horizons.

The *'croûtes'* (3b1) have the following characteristics: According to Ruellan (1970) they show superposition of hard but not petrified platy elements which vary in thickness from a few millimetres to a few centimetres. The lime content of these horizons exceeds 70% by weight. They have a whitish colour. The platy elements are not continuous, they interweave (anastomose). The internal structure of the elements is

Table 2. The main types of calcic horizons of the survey area according to American (Soil Survey Staff, 1975) and French (Ruellan, 1970) terminology.

calcic horizons	(soft) calcic horizons	discontinuous	*'amas friables'*
		continuous	*'encroûtements massifs'*
	petrocalcic horizons	laminated	*'croûtes'*
		non-laminated	*'dalles compactes'*

similar to that of the 'encroûtements massifs'. According to Soil Survey Staff (1975) they are laminated petrocalcic horizons.

According to Ruellan (1970) the *'dalles compactes'* (3b2) consist of one or several lime plates which are extremely hard. They can be qualified as petrified. They are in general continuous and not vertically interrupted like the constituents of the other 'croûtes'. Their internal structure is massive and not finely laminated. Often fine cavities which look like shrink cracks are found. The colour is greyish and the thickness of the individual plates varies from a few cm to about 20 cm. The lime content of this type of horizon is generally over 70% by weight. In the terminology of Soil Survey Staff (1975) these are petrocalcic horizons.

For the present study the Soil Survey Staff (1975) nomenclature will be used, modifying the terms by adjectives where greater detail is required. It is not the purpose of this publication to propose this terminology as a new system or as an improvement of an existing system. The equivalent terms are given in schematic form in Table 2.

2.2 MICROMORPHOLOGY

The micromorphological literature on calcic horizons can be separated in two disciplines: micropedology and carbonate petrography. This is a reflection of the nature of the phenomena in calcic horizons: fields of study on the subject may span both disciplines.

Pedologists study these formations in order to decipher their genesis and to characterise certain properties important for agricultural use. Petrographers study both exposed and buried calcic horizons. Their main aim is to define criteria by which calcic horizons indicative of sub-aerial diagenesis can be distinguished from other formations with which they can be confused. Such horizons can serve as markers in stratigraphic columns. The main source of confusion seems to lie in their similarity to so-called algal marine stromatolites, e.g. Multer & Hoffmeister (1968), Nagtegaal (1969), James (1972).

The foregoing implies that micropedology occupies itself more with the aforementioned diffuse distributions and discontinuous concentrations (types 1 and 2abc of Table 1) while carbonate petrology gives more emphasis to the continuous concentrations (3ab of Table 1).

2.2.1 *Terminology*

The main author in the description of micropedological phenomena is Brewer (1976) who devised a system which is widely used. He distinguishes various levels of organisation in the soil. His system is strongly morphologic; he introduces criteria such as chemical composition of the constituents only at the lowest levels of his classification. Lime as a material does not receive special treatment in his system.

If the so-called plasma is almost completely made up of calcite crystals, its fabric is called by Brewer a *(fine or coarse) crystic fabric*. If, however, large calcite crystals occur embedded in non-calcitic plasma, they are treated as so-called pedological features and called *intercalary crystals*. The main occurrences of lime in the soil are classified as pedological features (which may exhibit crystic plasmic fabrics). The main ones in which lime plays a role are: glaebules (e.g. lime concretions); crystallaria (e.g. intercalary crystals); cutans (e.g. calcitans). For definitions of these terms see Brewer (1976).

Several authors have suggested improvements in this terminology which make it possible to account better for the different forms which are intergrades between crystic fabrics and intercalary crystals. Bal (1975a), following up a suggestion by Mulders, introduces a so-called *calcic plasmic fabric* to account for cases where more or less isodiametric calcium carbonate crystals are not close enough together to form a crystic fabric but do constitute an important part of the total mass. Other authors like Fedoroff (1975) reject the use of Brewer's system for the description of lime concentrations in the soil altogether and propose a separate system for carbonates exclusively.

Carbonate petrologists generally work according to a different system. They define a number of basic elements, by means of which they define a number of more complex structures. For a review see, for example, Goudie (1975). The three main basic elements are:

(1) Micrite. Very fine calcium carbonate crystals ranging in size from 1-4 µm. This size range is given by Goudie (1975) who quotes several authors. According to Bathurst (1971) the term includes both inorganic and biochemical precipitates. *Clotted micrite* is a fabric made up of discrete aggregated bodies (peloïds) composed of micrite (Bathurst, 1971). The French equivalent of this is *'pâte microcrystalline grumeleuse'* which according to Durand (1959) makes up the fabric of many hard and soft calcic horizons in Algeria.

(2) Spar. A mosaic of crystals larger than those of micrite (Bathurst, 1971). For neomorphic crystals he distinguishes *microspar* mainly in the size class 4-10 µm and *pseudospar* mainly in the size class 10-50 µm. Other terms frequently encountered in the literature refer to specific arrangements of silt-sized crystals: *drusy spar* implies spar lining a cavity, while *flowerspar* is applied to relatively elongated (bladed) crystals that occur in bunches at regular intervals.

(3) Needle fibres. Thin elongated calcite crystals with a diameter of up to 5 µm which have mainly grown along one axis, ranging in size from 10-300 µm are reported by James (1972) for calcareous crusts. He distinguishes furthermore between long *randomly orientated needle fibres* which may form felt-like mats and the shorter *tangentially orientated needle fibres* which often coat particles.

Folk (1965) developed a code system for methodical description of diagenetic calcite by means of four-component symbols in which the following characteristics are represented: mode of formation, gross shape of the crystals, crystal size and relation of the crystals to their surrounding (foundation). His shape classes are: *equant*, for calcite crystals that have length/width ratios of less than 1½:1; *bladed*, idem for ratios between 1½:1 and 6:1; *fibrous*, idem for ratios greater than 6:1.

Of the more complex structures that can be defined by means of the aforementioned basic elements, the two described below are important in calcic horizons.

(1) Laminar structures. These structures are common especially in petrocalcic horizons. The top is often crowned by a platy encrustation which Multer & Hoffmeister (1968) classify on the basis of micromorphology. For calcic horizons in Florida, they distinguish three types. The crusts which occur in the upper part of calcic horizons, decreasing in number and hardness with depth, have laminar structures which are described by James (1972). They are made up of numerous alternating light and dark laminae which consist alternatingly of micrite and needle fibres oriented parallel to the layering. Bands of drusy spar, densely packed concentric particles, peloïds, flowerspar and clear spar may also be included. James observes that thin crusts may merge with concentric particle coatings.

(2) Concentric structures. These structures are mainly found in the hardened parts of the calcic horizons. They have been extensively studied since they can be easily confused with marine oöids formed in turbulent waters. The concentric structures consist of several bands of micrite or of micrite and tangentially oriented needle fibres. Their nucleus may be a non-calcareous grain, a fragment of a fossil, plain micrite, or combinations of these. Apart from what is stated in the foregoing paragraph about the continuity of laminar and concentric features, several authors offer additional proof of the formation in the soil of these structures including Bretz & Horberg, 1949; James, 1972; Siesser, 1973; and Hay & Wiggins, 1980. This subject is further discussed in Section 4.5.3.1. These structures are named *diagenetic oöids* and

intraclasts by Siesser (1973) and spherulites by Nagtegaal (1969). This latter term does not have the same significance as Brewer (1964) attaches to it. He describes spherulites as crystallaria in which acicular crystals radiate from a centre.

Features commonly described in calcic horizons of all types are so-called *floating grains* of non-calcitic material (clasts), e.g. Dapples (1971), Gardner (1972) and Goudie (1975). Many of these are often corroded as mentioned by Degens & Rutte (1960) and Nagtegaal (1969). More details about this process are given in Section 2.2.2 and Section 6.6.2. Gile et al. (1965) consider the phenomenon of floating grains, which implies that lime forms a continuous phase, the main argument for the recognition of the K-fabric. Pressure exerted by the growth of the calcite crystals is the main process mentioned as the cause of this isolation of skeleton grains. This is discussed in more detail in Section 6.6.3.

2.2.2 *Processes and genetic concepts*

The following processes are evident from the micromorphology of calcic horizons:

(1) Crystallisation. This implies the formation of calcite crystals from a solution. Several factors influence shape and size of the resultant crystals.
- Speed of formation (Bathurst, 1971). The slower the formation, the larger the crystals formed. Bal (1975b) observes in this respect that large crystals form slowly in tubular voids in soils with a stable pH, while fine crystals are formed rapidly in soils with large pH differences within the profile, when the solution percolating from the acid upper part towards the alkaline lower part becomes supersaturated.
- Presence of fine particles that act as nucleation points is a factor mentioned by Wieder & Yaalon (1974). For example, the more clay particles there are, the more micrite will be formed. Larger crystals will form only if silicate clay particles are absent.
- Degree of supersaturation of the solution influences not only the size of the crystals because of its influence on the speed of formation, but according to Buckley (1951) also the form of the crystals. Elongated needle fibres, also known as 'whisker crystals', are formed from highly supersaturated solutions only. Presence of certain ions may also enhance the elongated character.

As well as crystallisation of calcite from solutions entering the profile, transformation of calcite crystals from one type to another occurs. A so-called aggrading form is the recrystallisation of micrite to microspar. Degrading forms are those in which a sparry fabric is transformed into micrite. James (1972) calls the latter process 'micritisation'.

(2) Brecciation. Brecciation phenomena are observable in calcic horizons on macro-, meso- and microscale. They occur in parent materials, non-calcitic inclusions and

neoformations in the horizon (Bretz & Horberg, 1949; Blank & Tynes, 1965; Dapples, 1971; and James, 1972). James applies the term 'exploded jigsaw puzzle' to characterise the microstructures present in calcic horizons. Some of the brecciated structures on a macroscale may be due to mechanical break up of exposed petrocalcic horizons followed by recementation. The main causal factor in this process, however, seem to be forces related to the crystallisation. See further Section 6.6.3.

(3) Dissolution of calcitic components. Dissolution of calcitic components is evident on the surface of many exposed calcic horizons. Karst phenomena such as pipes are reported, e.g. by Bretz & Horberg (1949) and Gile et al. (1966) for New Mexico, USA and by Goudie (1975) for several regions. Dissolution well within the horizons may also occur; this is discussed in Section 6.5.4.

(4) Dissolution of non-calcitic components. Corrosion of mineral grains as mentioned in the previous section in relation to the floating grains is presumed to be due to the high pH which can exist locally and temporarily in calcic horizons (Multer & Hoffmeister, 1968; Reeves, 1970). Substitution of quartz by lime is mentioned by Degens & Rutte (1960). Watts (1980) mentions the inverse solubility relationship between silica and calcite at high pH which favours calcite precipitation and silica solution. Nahon & Ruellan (1975) and Millot et al. (1977) describe isovolumetric substitution of a variety of materials by lime, which they call 'épigénie'. More details are given in Section 6.6.2. Reprecipitated products of the solution of silicates in the form of opal and chalcedony are commonly found in well developed petrocalcic horizons; for example, Reeves (1970) mentions their presence in 'mature caliche'.

(5) Biological processes. Knox (1977), Kahle (1977) and Harris et al. (1979) describe boring of calcic horizons by the action of fungi, blue green algae or roothairs of higher plants. Numerous ramifying tubes are described by James (1972) as evidence of boring by blue green algae in the upper part of petrocalcic horizons (Section 4.5.3.1). Truc (1975) stresses the role of micro-organisms in 'biocorrosion' and 'biosynthesis' of calcite in calcic horizons. Adolphe (1975) claims that certain types of lime concretions in the soil are formed by the action of micro-organisms.

Recognition of the original or primary minerals of a parent material and of the secondary products into which they are transformed is an important field of study in micropedology. Calcite is considered to be a very unstable mineral both in primary and in secondary form. Distinction between primary and secondary calcite on the basis of the observation of single isolated crystals is only rarely possible. For example, Sehgal & Stoops (1972) distinguish primary calcite grains in an aeolian sediment on the basis of rounding of the crystal grains.

Conclusions on the genesis of calcite crystals are mostly drawn on the basis of their occurrence in pedological features which may either be formed in situ or inherited from parent rock, parent material or from other soils. Wieder & Yaalon (1974) distinguish three types of carbonate nodules: *Orthic nodules* are formed in situ, they have skeleton grains and fabric similar to the surrounding soil matrix and they have a gradual transition towards it. *Disorthic nodules* have been formed in the soil but have been subjected to some pedoturbation. They have skeleton grains and a fabric resembling the surrounding matrix but they have sharp boundaries. *Allothic nodules* are those that have been transported towards the site they presently occupy in the soil. They have a matrix which differs in composition from that of the soil in which they are incorporated. Blokhuis et al. (1968) described various forms of pedogenetic carbonate in Vertisols of the Sudan. They conclude that in general soft powdery types such as diffuse nodules and channel neocalcitans are in situ formations while the various hard and discrete types do not occupy the position in which they were formed. Many concretions show features like mangans which they have acquired in the zone below the present churning activity. This churning process is supposed to have brought them upward towards the position which they presently occupy.

Some authors claim that the progression in the development of calcic horizons is evident in a specific succession of forms of carbonate (Gile et al., 1965; Brewer, 1972; Sehgal & Stoops, 1972). They claim that the general tendency is an increase of crystal size with age. Wieder & Yaalon (1974) do not agree with this. In their opinion crystal size is mainly dependent on the presence or absence of fine silicate clay particles that act as nucleation points, as explained in the beginning of this section.

2.3 TYPICAL HORIZON SEQUENCES

If all four main types of calcic horizons of Table 2 occur together in a soil profile, their normal sequence is the following:

1. thin discontinuous soil cover; A or A_{ca},
2. non-laminated petrocalcic horizon,
3. laminated petrocalcic horizon,
4. continuous soft calcic horizon,
5. discontinuous soft calcic horizon,
6. C horizon or C_{ca} horizon.

Horizon sequences which cover only part of this normal one are commonly found to occur, except for the following: The A or A_{ca} horizon which is thin and discontinuous when overlying a petrocalcic horizon, is normally thick and continuous when overlying a soft calcic horizon. Petrocalcic horizons not overlying soft calcic horizons normally rest on consolidated bedrock (R) instead of on a C horizon. Frequently occurs, e.g.

1	1	1	1	1
3	4	5	2	2
4	5	6	3	R
5	6		R	
6				

This last case is thought to be rare (Ruellan, 1970).

The horizon transitions are governed by rules (Ruellan, 1970), which can be summarised as follows: *'When in a profile the lime content increases with depth, the boundaries are abrupt or clear. When in a profile the lime content decreases with depth, the boundaries are normally gradual or diffuse.'* The richer in lime the next horizon, the more abrupt the transition. According to the last rule, the discontinuous soft calcic horizon (5) may have a gradual upper boundary, in the sequence 1/5/6. In the case of polygenetic profiles which show two or more cycles of lime accumulation superimposed, these rules do not apply in the contact zone of two calcic horizons. The topography of the horizon boundaries is mostly smooth with the exception of the transition of the continuous towards the discontinuous soft calcic horizon. Here we find irregular horizon boundaries (Wilbert, 1962; Dumas, 1969). In the profile descriptions of Chapter 4 this transition zone is referred to as the 'striped zone'.

2.4 OCCURRENCE ACCORDING TO CLIMATIC ZONES

According to Reeves (1970), well developed calcic horizons do not form in arid or in humid climates. In arid climates rainfall is apparently insufficient to allow for substantial accumulations of lime, while in humid climates the leaching is considered to be too strong. Blatt et al. (1972) state that in the USA 'caliche' occurs west of the line of 635 mm yearly precipitation in areas where the average yearly temperature is higher than 4.4 ^{o}C. Summarising it may be stated that calcic horizons occur where leaching is sufficient to wash lime into, but not out of, the soil.

Apart from precipitation, all other factors determining the drainage condition of the soil play a role. Lime content of the material on which the calcic horizon is developed is another influencing factor: Strongly calcareous materials may carry calcic horizons even in rather humid climates. Mediterranean climates, with most of the precipitation concentrated in the cool season, seem particularly likely to develop calcic horizons even where the rainfall is rather low.

Since petrocalcic horizons are very resistant to erosion, relicts of fossil calcic horizons can maintain themselves for long periods after climatic changes have occurred. This applies particularly to major desert areas which are now too arid for the formation of calcic horizons but which have experienced moister climates during the Pleistocene (Ruellan, 1968; Reeves, 1970).

The aforementioned factors make it difficult to establish a very specific climatic zone in which calcic horizons do occur. In general it can be stated that the zone in which they are encountered varies from arid to sub-humid. The major zone in which they still seem to be actively formed is semi-arid (Dumas, 1969; Franz & Franz, 1969). Ruellan (1968) states that calcic horizons have a tendency to become thinner and closer to the surface if one moves from areas with a precipitation range of 500-700 mm/yr towards drier zones. If the rainfall diminishes to 200 mm/yr they tend to disappear altogether. Thick soft calcic horizons are more common in the moister climatic range, while the occurrence of petrocalcic horizons increases progressively towards the drier areas. Tropical climates with poorly distributed precipitation up to 1500 mm/yr show calcic horizons on limestone (Florida: Multer & Hoffmeister, 1968; Barbados: James, 1972). Discontinuous soft calcic horizons are described as forming under 1400 mm/yr precipitation on calcareous metamorphic rocks in Senegal by Leprun & Blot (1978).

For details on the geographic distribution of calcic horizons see Goudie (1973), FAO (1973) and Reeves (1976).

2.5 GENESIS

Calcium is the seventh most abundant element of the earth's crust and hydrosphere (Delwiche, 1975). As such $CaCO_3$ is a constituent of many rocks. In many other cases in which it is not a constituent, calcium carbonate is formed in the weathering zone upon liberation of Ca-ions from minerals such as anorthite, titanite and augite. It is also found as a result of the reduction of gypsum by bacterial action. Notwithstanding these facts, the relation between calcic horizons and the materials upon which or within which they are encountered, is not always properly described by the term 'parent material' as will be illustrated in the following paragraphs.

Many authors, e.g. Mathieu (1975) and Vaudour & Clauzon (1976) put the question: 'Are calcic horizons deposits or soil horizons?' Either they ask this question in the context of calcic horizons in general, or for calcic horizons of a specific region or location. The fact that they do not agree on the main process could mean that indeed several basically different processes are to be held responsible for their formation, each under its own specific condition. It seems highly improbable, however, that formations which are so widespread in a certain climatic zone, covering such a wide range of materials and landscapes and showing so many striking similarities, would not generally have one main process in their genesis in common. It is certain that several different processes have affected the calcic horizons during their genesis and that several of them may still be active concurrently at this time. It must be stressed, however, that most of these processes are mere modifiers of the calcic horizon and not causal.

It is not uncommon to find in the literature cases where two entirely different modes of origin are postulated for two different types of calcic horizons overlying each other in a sequence that is representative of a large area (e.g. Durand, 1959 and Raynal & Gaucher quoted by Mathieu, 1975). It seems more logical to postulate in such instances a common origin for both and to hold a modifying process responsible for their later differentiation. Stable isotope analyses have provided evidence linking petrocalcic horizons with the underlying soft calcic horizons in several cases (Salomons et al., 1978).

In the literature there is little concensus about the main process. For a review of the different modes of origin postulated see e.g. Durand (1959), Mathieu (1975) and Zuidam (1976).

The main problem seems to lie in the origin of the often quite large quantities of lime. In most cases they are too large to be accounted for by simple leaching from the present surface soil. Another problem lies in the placement of pure or almost pure lime horizons within the soil leading to the question: 'What happened to the soil material that formerly occupied the space now taken up by the calcic horizon?'

Some authors are inclined on the basis of these two problems to answer Mathieu's question by stating that calcic horizons are deposits. In this way neither the quantity of the lime nor its placement in the soil become controversial issues, and arguments about the source of the lime and the replacement processes of the soil material are avoided. They are confronted, however, by the proponents of pedogenetic theories with a number of arguments in favour of this mode of formation which are difficult to counter. The main arguments for a pedogenetic origin of calcic horizons in general, apart from their occurrence in specific climatic zones, can be summarised from Bretz & Horberg (1949), Gile et al. (1965), Ruellan (1970) and Gardner (1972) as follows:

- They are parallel to the topography of the surface.
- They have a distinctive morphology and are laterally continuous.
- They occur in materials of various compositions and textures.
- They form a developmental sequence.
- They often show lime accumulations under stones and other objects.
- The fact that there are gradual lateral transitions between the various types of calcic horizons is a strong indication that they have important processes in their genesis in common.

A factor that adds to the confusion of the discussion is that most authors fail to mention whether they consider the calcic horizons which they study as static features formed in the position which they presently occupy, or as dynamic features capable of transforming themselves from one form into another and of migrating downwards in a downwearing landscape, adapting themselves in the process to the relief forms as they are shaped. This aspect will be dealt with in Chapter 6.

All the authors adhering to the geogenetic mode of origin apparently adhere rigidly to the static concept from which in fact they derive their main argument. Most proponents of a pedogenetic mode seem to do so too. Only in some of the pedogenetic concepts is the dynamic character of the calcic horizon implied: Price (1933) as quoted by Goudie (1973) develops the concept that gradual leaching lowers the zone of accumulation while erosion lowers the top of the soil. Bretz & Horberg (1949) have very similar concepts. Sabelberg & Rohdenburg (1975) consider most calcic horizons to have been formed in the soil and exposed by subsequent erosion of the material from which the lime originated. Ruellan et al. (1977) imply a dynamic model for landscapes in which a calcic horizon replaces underlying materials (épigénie).

Some authors prefer combinations of the aforementioned genetic options. In the following sections a review will be given of the different modes of origin postulated. In many cases the authors restrict themselves to proving by negative demonstration that their hypothesis is the only one tenable by trying to eliminate systematically all other possibilities.

2.5.1 Geogenetic modes of formation

Some authors claim a geogenetic formation for certain specific occurrences of calcic horizons. Others are in favour of a more generalised application of this concept.

Durand (1959) is a proponent of geogenetic origins for calcic horizons. He claims that calcareous lacustrine deposits are a general phenomenon in Algeria. He bases this mainly on detailed study of mineralogy and granulometry of non-calcitic grains contained in soft calcic horizons, which often show marked differences in these aspects with the horizons over- and underlying the calcic horizons. He considers the calcic horizons mainly as chemical deposits in lakes and invokes Ehrart's theory of biorhexistasie, to explain the typical sequences of petrocalcic and soft calcic horizons in red Mediterranean soils. In some of the calcic horizons he reports fossile snail shells. With the exception of one case, in which the species found near a spring was indicative of a swampy environment, he does not identify the species of the snails. Many completely sterile soft calcic horizons are pronounced lacustrine, even if they show a marked relationship with the present day topography. For some forms of calcic horizons on slopes he favours deposition from running waters. Not all authors consider the presence of snail shells in calcic horizons to be proof of lacustrine origin. Archer & Mäckel (1973) describe the presence of gastropods in dambo calcrete in Zambia. They reject a lacustrine origin for these calcretes, however, since at least one of the species of snails was found to be of terrestrial origin.

A number of authors apply concepts similar to those of Durand to a variety of occurrences of 'croûtes calcaires' in the Mediterranean environment. They propose lacustrine, palustrine-lacustrine or other sedimentary modes of origin mostly related to changes in the sedimentary cycles. They often mention the presence of snail fragments, without identifying the species in order to back up their claim of a genesis under wet circumstances:

Wilbert (1962) advocates a lacustrine origin for soft calcic horizons in level positions. For soft calcic horizons in non-level positions he advocates deposition in river courses. He states that the observed poor crystallinity of the lime contained in these horizons is proof of their genesis under wet circumstances. Noureddine (1979) describes quaternary calcareous muds deposited in basins in the Beqa'a valley in Lebanon. Vogt (1979) describes 'croûtes calcaires' which are in her opinion sediments of the same type as valley bottom travertines, for three quaternary river valleys in Mediterranean France. Ballais & Vogt (1979) describe sedimentation of lime in swampy environments as the mode of origin of 'croûtes calcaires' of some quaternary piedmonts in Algeria. These horizons are found on slopes of 2-3 % which the authors attribute to tectonic movements postdating their deposition. Tihay & Vogt (1979) describe 'croûtes calcaires' from two old-quaternary glacis in Algeria as calcareous swamp deposits.

2.5.2 Pedogenetic modes of formation

Leaving apart for the moment the problem of the replacement of the soil material by lime which is dealt with in Section 6.6, the pedogenetic modes of origin can be subdivided according to source and mode of transport of the lime. The question of whether the calcic horizons are considered to be dynamic or static cannot be avoided in this discussion. Cases could exist in which no mode of transport of lime towards the calcic horizon need be envisaged since the dynamic horizon can be assumed to be moving towards the lime and not vice versa.

Mode of transport and source are not independent factors since the assumption of a source implies the assumption of a mode of transport in accordance with the position of that source in relation to the position of the calcic horizon.

The following sources are frequently assumed in the literature: horizons overlying the calcic horizon which are recipients of lime contained in aeolian materials deposited on the surface; horizons and/or strata underlying the calcic horizon; materials at the surface located upslope from the point where the calcic horizon is located.

As mode of transport from the aforementioned sources towards the calcic horizon, most authors assume water as the agent that carries the lime in dissolved form as bicarbonate. The solutions can move downward, upward or in a lateral sense. Alternative modes of transport for lime are illuviation of carbonate particles (Gile, 1977) and diffusion. The latter mode of transport is treated by Reeves (1976) who concludes that it is probably not an important factor in the formation of 'caliche'. Bertouille (1976) mentions transport of colloidal $CaCO_3$ particles due to thermophoresis. Such colloids can form by precipitation from a bicarbonate solution. The transport proceeds from colder towards warmer zones.

The most common combinations of source and mode of transport, encountered in the literature, are discussed in the following sections, together with the option in which no transport has to be assumed since the calcic horizon moves towards the source of the lime.

2.5.2.1 Downward movement from a surface soil that contains lime and/or receives lime from aeolian additions

If the amounts of lime accumulated in soils are relatively minor they can be assumed to have been leached from the horizons presently overlying the accumulation zone. This is illustrated by computations of Jenny & Leonard (1939), as quoted by Reeves (1976), who established a relationship between precipitation and depth of carbonate horizons in soils of Kansas and Colorado (USA). Arkley (1963) improved upon Jenny's technique by taking into account excess of precipitation over evapotranspiration and waterholding capacity of the soil in order to find the mean depth of leaching. He established a good correlation between this latter value and the depth of the carbonate horizons for soils from California and Nevada (USA). All these relationships hold true, however, for relatively young soils only. When applied to older soils with thicker carbonate accumulations, complications arise due, for example, to the influence of the carbonate on the permeability of the horizon and lack of data about the climate of the past. In those soils, moreover the amount of calcite accumulated is so large that one cannot assume it to have been provided solely by the soil materials presently overlying the calcic horizon. In order to account for the discrepancy between the amount of lime and the thickness of the overlying horizon in such cases, many authors assume that aeolian additions to the surface soil have taken place. The magnitude of aeolian additions to soils, especially for areas bordering great deserts, is well documented both for the present and past. Lime often makes up an important part of these materials. The following authors are quoted: Buringh (1960) for Iraq, Yaalon & Ganor (1973) about aeolian dust and lime in general, Sidhu (1977) for India and Macleod (1980) for Greece.

The following authors are quoted as being in favour of downward leaching of lime towards the calcic horizon. Many assume aeolian aggradations to the surface soil.

Gile et al. (1966) postulate for New Mexico (USA) the formation of an impermeable zone at the depth of frequent wetting by unsaturated flow. The lime so deposited 'plugs' the horizon and causes the formation of a zone where percolating water accumulates. Evaporation of this water leads to the formation of a hard laminated crust. This formation will grow upwards, in the process gradually lifting the overlying soil.

Lattman (1973) discusses cases from Nevada (USA). He favours a pedogenetic origin and indicates carbonaceous windblown sand and silt, deposited on the top of the profile, as the main source of lime. For fans built of 'non-carbonate detritus' he finds the strongest cementation downwind of playas, high in carbonates. In a later article (Lattman & Lauffenburger, 1974) he suggests that areas downwind of major outcrops of gypsiferous rocks also carry thick caliche. In his opinion gypsum can be reduced in the soil by bacteria which leads ultimately to its transformation to $CaCO_3$, incorporating CO_2 from the soil and liberating H_2S.

According to Reeves (1970) who discusses caliche from Texas and New Mexico

(USA), soft calcic horizons form where solubles from the upper zone are carried downward and precipitated, when soil moisture is removed by evapotranspiration. He admits that some capillary rise may contribute in this stage too. Induration will take place very slowly, due to the gradual increase in lime content. Rapid induration will result if the soft calcic horizon looses most or all of its soil cover. Once the horizon becomes 'plugged', the process mentioned by Gile et al. (1966) will take over.

Brown (1956) considers the worldwide presence of a zone of calcium carbonate enrichment at the base of pedocal soils, as strong evidence that C_{ca} horizons and 'caliche' are genetically related. In the Llano Estacado, Texas (USA) he finds a perfect gradation in undisturbed sections from non-calcareous or very slightly calcareous topsoil, down into the 'caliche'. This he regards as strong proof that the whole 'caliche complex' is the result of identical or very nearly identical processes. He postulates an aeolian aggradation of lime-containing materials as having provided the lime. He bases this largely on proof by negative demonstration, invoking the fact that the rocks on which the caliche has been found to rest vary from Cretaceous limestones to non-calcareous sandstones.

Gardner (1972) studied a similar case from Nevada (USA) and reached a comparable conclusion. He calculated the age of a thick calcic horizon, taking into account the lime contained in airborne dust and rainwater.

Blümel (1979) assumes aeolian additions to the surface soil as one of the sources of the lime for cases in S.W. Africa and Spain, in which calcic horizons overlie materials out of which hardly any lime can be liberated by weathering.

2.5.2.2 Upward transport of lime by solutions ascending towards the accumulation zone

A common mechanism of transport envisaged is capillary rise. Other options are a fluctuating groundwater table and the pumping action of the vegetation. Many authors indicate that capillary rise of lime would imply transport of all kinds of soluble salts also. This would cause salinisation and alkalinisation of the profile. Lack of evidence of these processes is used as an argument against this mode of formation. The following quotes from the literature are of interest.

Goudie (1973) computed that 1 m of calcrete could be formed in 3600 years if 240 cm of water evaporated annually, derived by capillary rise from a groundwater that contains 150 g/m^3 carbonate.

Netterberg (1969) described the zones of lime cemented gravels and sands, over 9 m thick, of the Vaal river in S. Africa. He considers their thickness too great to assume pedogenesis in the strict sense of the word. The lime was deposited, in his opinion, by a fluctuating but steadily dropping water table, under semi-arid conditions.

Mathieu (1974) quotes a remark by Yankovitch who puts forward that lime which is dissolved by rainwater deeper in the profile will be left behind at a shallower depth after the water has been drawn up by the vegetation.

Boulaine (1966) invokes the role of the vegetation in bringing dissolved lime up towards the accumulation zone. He cites calcified roots as proof of this.

2.5.2.3 Lateral transport of lime formed or liberated from source materials located upslope from the point of accumulation

This refers to transport of lime mainly in the form of a solution over and under the soil surface and occasionally in the form of a suspension over the soil surface. The following literature quotes are of interest for this mode of formation.

Ruellan (1968) finds no relationship between thickness and lime concent of calcic horizons and those of the overlying horizons in soils from Morocco. For cases where calcic horizons are found on materials that do not contain lime and do not liberate calcium upon weathering, he concludes that lime must have been transported laterally from sources available upslope. He tested this relationship and found it valid over distances of several kilometres in the more arid areas but over tens of metres only in sub-humid areas.

Dumas (1969) presumes that the lime which constitutes the upper horizon of a sequence of petrocalcic and soft calcic horizons in S.E. Spain cannot be derived by leaching of the overlying soil. Neither does he find evidence of transport upwards of lime from the lower horizons. This leads him to the conclusion that lateral transport of lime through the overlying soil has provided the material for the petrocalcic horizon.

Gigout (1960) considers lateral transport of lime as one of the sources for calcic horizons in N. Africa.

Wilbert (1962) describes laminated petrocalcic horizons from Morocco as surface formations. He presumes surface flow of waters charged with lime to be the source of this formation. He admits that in the case of laminated petrocalcic horizons overlying soft calcic horizons, the source of the lime may have been the soft calcic horizons.

For lime in calcic horizons of S.W. Africa and S.E. Spain which overly non-calcic materials, Blümel (1979) takes various sources into account. He mentions lateral surface transport of lime derived from carbonaceous rocks upslope, both in suspension and in solution. Plugging of the soil due to infiltrating lime would render the profile impermeable and aid in provoking more runoff c.q. lateral lime transport.

2.5.2.4 Liberation or formation of lime from a parent material in the weathering zone directly underlying the calcic horizon

As mentioned before, this mode of formation envisages no transport towards the calcic horizon as it is assumed that this horizon moves downward with the weathering front into the parent material. It is discussed in detail in Chapter 6. This mode of formation is supposed to be accompanied by removal of the weathering products from the surface synchronous with the downward movement of calcic horizons and weathering front. As such it is mostly referred to in the literature as a degradational mode of formation. The following quotes from the literature are of interest in this context.

Lattman (1973) favours for S. Nevada (USA) the hypothesis of carbonaceous aeolian material as the main source of carbonate, as mentioned in Section 2.5.2.1. He reports, however, 'The extent and development of cementation are greatest on fans composed of carbonate and basic igneous rock detritus, less on fans built of silicious sedimentary detritus, and least on fans composed of acid igneous rock material'. In comparing the calcium content of weathered and unweathered local andesite, he did not find a significant difference, which led him to reject the hypothesis that the rock material is the source for the lime. He admits, however, that the relation between rock type and degree of development of the calcic horizon is not properly understood.

For Morocco, Wilbert (1962) and Ruellan (1970) report calcic horizons on rocks that do not contain lime but do contain calcium, e.g. basalts and also certain granites. Boulet & Paquet (1972) report similarly on a 'granito-gneiss à amphibole' which forms the parent material for Vertisols with calcareous nodules in Haute Volta.

Gardner (1972) treats 'caliche' from Nevada (USA) developed in an almost carbonate-free alluvial sand. He calculates that 36.5 m of this material is equivalent in lime content to the lime contained in the caliche. Had this same amount of lime been derived from calcium liberated on weathering, over 90 m of material would have been needed. He discards the hypothesis that the sand is the parent material, however, since the residue of this weathering is not present and no explanation for its uniform removal can be given.

For a case in N. Africa, Gigout (1960) shows that calcic horizons can develop due to the weathering of calcareous sandstones. The process may first lead to an enrichment in lime and secondly to induration of this lime. In certain cases a hard crust is formed directly upon the weathering rock.

Blank & Tynes (1965) report the formation of soft powdery lime, by in situ weathering of limestone in Texas (USA). They tried unsuccessfully to simulate the process, which they call 'chalkification', in the laboratory. They report that the soft powdery lime is not brought in from overlying soil or rocks by migrating water, but is due to in situ dissolution and reprecipitation, which transforms coarse calcite into microcrystalline calcium carbonate.

James (1972) reports the same for sub-aerial weathering of limestones on Barbados. Important evidence which he notes is the presence of fossils, also contained in the limestone rock, within the soft lime layer.

2.5.3 Conclusions

1. The relationship between calcic horizons and the materials within which or on top

of which they are encountered, is not always properly characterised by the term 'parent material'. In many cases 'host rock' or just 'underlying stratum' are to be preferred over 'parent material' which implies a strong genetic relationship.

2. There is a strong tendency amongst researchers to favour pedogenetic modes of origin for most calcic horizons, over other theories.

3. Many authors consider vertical profile sequences of calcic horizons as genetically related, their present differences being due to later differentiation.

4. Amongst an important group of American earth scientists, there is concensus on a model in which most thick 'caliche' complexes overlying a variety of rocks in the S.E. USA owe their origin to aeolian aggradation of lime-containing materials.

5. French soil scientists generally favour a lateral transport of lime, in order to account for calcic horizons in positions where surface soil and underlying material are incapable of supplying it.

2.6 INFLUENCE OF CALCIC HORIZONS ON LAND QUALITIES

The following definition of the term 'land quality' is given by FAO (1976): 'A land quality is a complex attribute of land, which acts in a distinct manner, in its influence on the suitability of land for a specific kind of use'. The main uses considered are the production of crops, of feed for animals and of wood.

Soil materials from calcic horizons have some application outside agriculture too. Netterberg (1975, 1978 and 1980) reports and classifies the utility of these materials for road building. Durand (1959) mentions their use as building materials and as raw material for the local manufacture of burned lime.

Artiola & Fuller (1980) describe the use of limestone as a liner for landfills consisting of municipal waste, in order to slow down the migration of certain metallic cations which would cause soil pollution. Soil materials from calcic horizons can be presumed to serve the same purpose.

Recently important commercial uranium deposits have been found in W. Australia, as mineralisations in caliche. Deposits of uranium minerals related to caliche are also reported from the USA (Reeves, 1976). According to Netterberg (1980), non-pedogenic calcretes are the most favourable for uranium occurrence.

In the following paragraphs a review will be given of the way in which the properties of the different kinds of calcic horizons influence, singly or in combination, the land qualities for agricultural use.

Availability of nutrients This quality depends on the volume of soil in contact with the root system and on the presence and solubility of the various nutrients in the soil mass. Petrocalcic horizons are largely impenetrable for roots, and restrict their growth to the generally shallow surface soil overlying the horizon. Soft calcic horizons are normally overlain by a thicker surface soil and are themselves penetrable for roots. The number of roots found is generally low, however, probably due to the relatively adverse chemical conditions. The high pH, generally around 8.2, restricts the availability of nutrients to plant roots. Of the major elements, N and P may be adversely affected. Nitrogen in the form of ammonia, or in forms that transform to ammonia, will be ineffective if surficially applied to calcareous soils due to the volatilisation of NH_3 (Fuering, 1973). Applied P is quickly transformed into insoluble forms. Of the micro-elements, Fe, Mn, B, Cu and Zn may become deficient (Jacob & Van Uexküll, 1963). In pure calcic horizons, relatively few nutrients can be stored, since an exchange complex is lacking. Lime in small quantities is beneficial for most of the common crops of Mediterranean areas. If lime is present in large quantities, however, it has a detrimental effect on the nutrient status of the soil. As such discontinuous soft calcic horizons do not effect the nutrient status of the soil to such an extent as continuous ones do.

Availability of moisture Availability of water is more adversely affected by petrocalcic horizons at shallow depth, than by soft calcic horizons which normally occur at a greater depth in the profile. Petrocalcic horizons are slowly permeable or impermeable. This leads to stagnation of water on top of the horizon, followed by runoff and evaporation losses. Roots penetrate the horizon only with utmost difficulty, in order to reach lower horizons moistened by groundwater. This applies mainly to such perennials as olives and grapes, which can push their roots down to great depths through cracks in the petrocalcic horizon. The soft calcic horizon is permeable and can store large quantities of water due to its relatively fine texture (Durand, 1959). Massoud (1973), however, found that calcareous soils tend to store considerably less water than non-calcareous soils of the same texture. This may be due to the influence of lime on the formation of soil aggregates or to the covering of clay particles by lime.

Availability of oxygen The availability of oxygen to the root systems of plants is negatively influenced by stagnating water on level petrocalcic horizons. Especially in Mediterranean climates, in which most of the precipitation falls in the cool season, this causes root damage. Soft calcic horizons are generally permeable and admit air. Abundant soft lime in surface horizons induces slaking of the soil upon wetting, thus blocking soil aeration.

Workability of the land (ease of cultivation) Petrocalcic horizons, within plowing depth, have a negative effect on the workability of the soil. No proper seedbed can be prepared for annuals, while dust mulching of perennials becomes ineffective. Where petrocalcic horizons occur at shallow depth, special measures have to be taken for the planting of perennials. Removal of the crust by subsoiling with heavy equipment is mentioned for newly planted vineyards in Algeria. For treecrops it is considered cheaper to resort to the blasting of plantholes, with special agricultural explosives (Durand, 1959).

Resistance to soil erosion If a thin soil cover is present on top of a petrocalcic horizon, this will be eroded very easily due to runoff provoked by the impermeability of the underlying horizon. Petrocalcic horizons proper are very resistant to erosion. This means that the sediment yield from exposed petrocalcic surfaces will be low. The slaking effect of lime on topsoils, as mentioned before, also has a detrimental effect on the resistance to erosion. Conservation measures such as the construction of terraces are hampered by the presence of shallow petrocalcic horizons.

Adequacy of foothold Shallow soils overlying petrocalcic horizons do not present an adequate foothold for plants. This is especially serious for perennials. As such the measures mentioned in foregoing paragraphs to destroy the petrocalcic horizon, are also essential to assure a foothold for newly planted perennials.

Conditions for germination Petrocalcic fragments, forming a rubble layer on the surface, adversely influence germination conditions for most annual crops. This is mainly due to the fact that fine seeds fall away too deeply between the coarse fragments. The surface crust, which forms on top of soils rich in soft powdery lime, due to slaking in wet conditions, is often a cause for poor germination.

It may be stated that petrocalcic horizons which normally occur at shallow depth, seriously affect the different land qualities. In many cases this means that the use of the lands has to be restricted to grazing or forestry. As far as the cultivation of crops is concerned, preference is given to perennials over annuals on lands underlain by these horizons.

Soft calcic horizons which occur deeper in the profile have a less detrimental effect. The main hazard is their rapid hardening due to exposure or other causes. In this context it is worth mentioning that Richter et al. (1978) found that an extremely rapid hardening of a soft calcic horizon took place after the introduction of irrigation in combination with heavy applications of organic manure.

3 Description of the study area

3.1 LOCATION

The area is situated in the central part of Badajoz province which forms part of the region called Extremadura in S.W. Spain. Mérida is the central town of the area. It is located roughly 70 km east of Badajoz and approximately 350 km south-west of Madrid. The area, as shown in Fig. 1, lies between 6°05' and 6°31' longitude west of Greenwich and between 38°47' and 38°57' latitude north.

The area is situated between the towns of Montijo (west of it), Mirandilla (north of it), Guarena (in the east) and Solana de los Barros (south of it). It encompasses the western extremity of the Sierra de San Servan.

3.2 CLIMATE

The climate of the study area is typically Mediterranean, being characterised

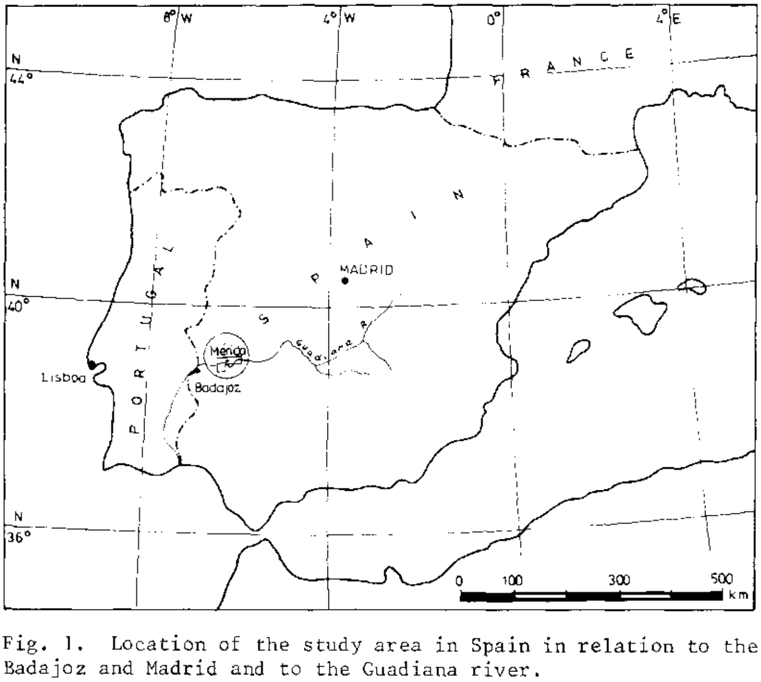


Fig. 1. Location of the study area in Spain in relation to the towns of Mérida, Badajoz and Madrid and to the Guadiana river.

mainly by warm dry summers and cool moist winters. According to Meigs (1962) this is due to the fact that most of the rainfall is associated with westerly storms that result from the southward movement of the polar front during the winter season. The summer drought is related to the approach of the dry side of the oceanic highs.

According to the classification of Köppen & Geiger (1932) the climate is Csa. In this system the symbols represent the following:

C: warm temperate (average temperature of the coldest month is between +18^{o}C and -3^{o}C)

s: dry season in the summer

a: average temperature of the warmest month exceeds 22^{o}C

According to the classification of Thornthwaite (1948), the climate of the study area is semi-arid. Thornthwaite defines a so-called moisture index as: Im = (100 s - 60 d)/n in which the symbols mean the following:

Im: moisture index

s: precipitation surplus over potential evapotranspiration

d: precipitation deficit from potential evapotranspiration

n: total water need or total potential evapotranspiration

On the basis of the data of Fig. 2 it can be calculated that the moisture index for the survey area is -20.8. This means that the climate classifies in the semi-arid class (between -20 and -40), very close to the border with the sub-humid class (between -20 and +20).

According to UNESCO-FAO (1963), the climate is meso-Mediterranean of the accentuated type. In this terminology, a Mediterranean climate is a climate with a dry period of 1-8 months, coinciding with the period of the longest daylight. The Mediterranean climate is further subdivided on the basis of the 'xerothermic index' (i.e. index of hot weather drought). The xerothermic index is the sum of the monthly indexes which are found by subtracting from the total number of days, the days with rain together with half the days of fog and dew. The resulting total is multiplied by a factor derived from the mean atmospheric humidity. The qualification of accentuated meso-Mediterranean corresponds with a xerothermic index that falls between 75 and 100. For the nearest major meteorological station, Badajoz, the attenuated thermo-Mediterranean climate with a xerothermic index of 100-125, applies.

The nearest major meteorological station with full coverage of data is for the survey area Badajoz. Its data are reported in Table 3 for the period 1934-1960. Castillo & Beltran (1973) report for this same station for the period 1931-1960 several agro-climatological data which are quoted in Table 4.

For two stations near the western and southern limits of the study area, precipitation, temperature and potential evapotranspiration data according to Thornthwaite (1948) are available for the period 1957-1966. The data are reported by the Instituto Nacional de Investigaciones Agrarias in Madrid and pertain to the stations Lobon (6^{o}41' west, 38^{o}51' north; altitude 232 m) and Almendralejo (6^{o}26' west, 38^{o}41' north; altitude 336 m). From the averages of these two stations a water balance dia-

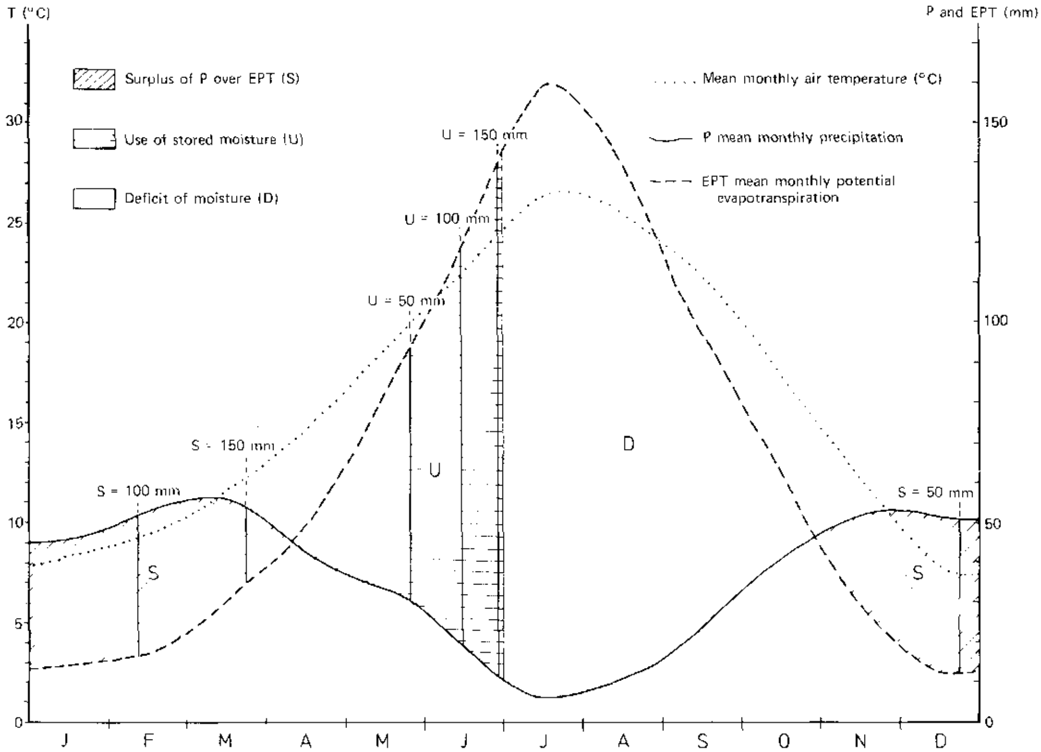


Fig. 2. Water balance diagram based on the average precipitation and evapotranspiration for the stations Lobon and Almendralejo, for the period 1957-1966. The average of the mean monthly air temperatures for these two stations has been indicated too. The potential evapotranspiration has been computed according to Thornthwaite (1948). In the graph it has been indicated, how much moisture surplus (S) results from the winter rains and during which period this moisture, if stored in the soil, can compensate for the excess of evapotranspiration over precipitation in the summer period. The total surplus of about 150 mm is used up (U) by the beginning of July.

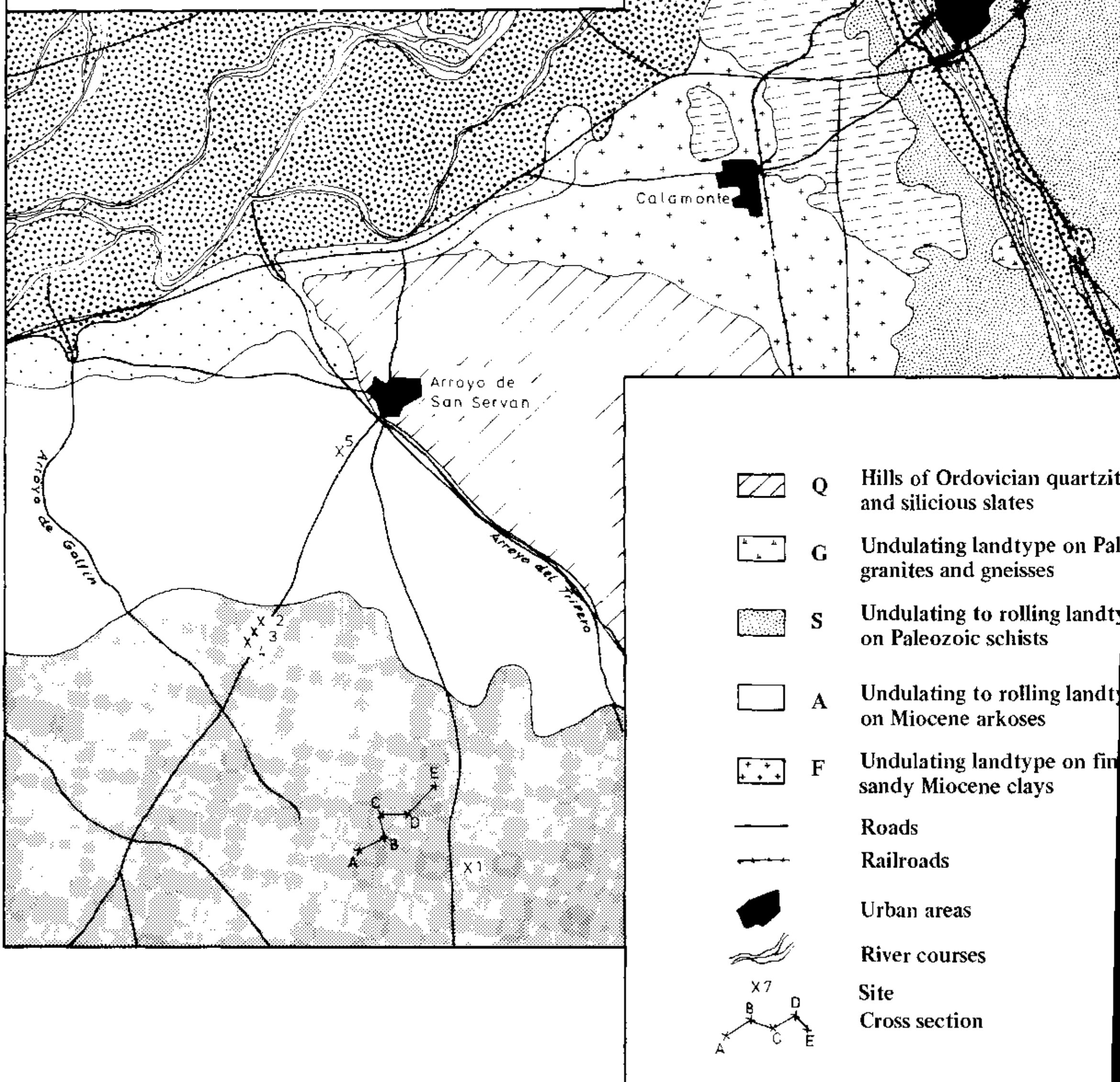
gram (Fig. 2) has been constructed. The average monthly temperatures are also indicated. The graph shows how much moisture surplus results from the winter rains and during which period this moisture, if stored in the soil, can compensate for the excess of evapotranspiration over precipitation in the summer period.

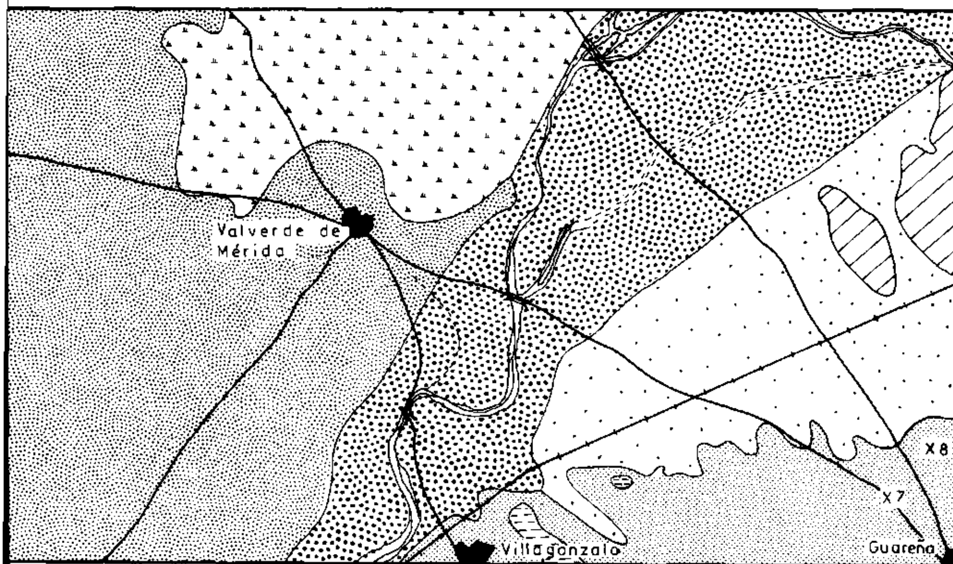
It can be concluded from the diagram that the moisture regime is xeric according to Soil Survey Staff (1975) for all soils that do not receive important amounts of runoff from adjacent areas. Fig. 2 shows that the total amount of surplus water for the winter months is about 150 mm. If this amount were stored in the soil it would not last longer than the end of June. At least three months follow this period, during which the potential evapotranspiration exceeds the precipitation and the soil moisture control section is consequently dry. During the winter at least $2\frac{1}{2}$ months of excess follow the point where 75 mm of rain has been stored and at which the soil moisture control section is supposed to be completely moist. The total period of ex-

Table 3. Climatological data for the station Badajoz (38°53' north, 6°58' west, 203 m) for the period 1934-1960.

	Temperature (°C)						Relative humidity (%)		Precipitation			Bright sunshine	
	average daily		average monthly		absolute		average of observations at:		average monthly fall (mm)	maximum fall in 24 h (mm)	average number of days with 0.1 mm or more (d)	average monthly duration (h)	average % of possible
	max.	min.	max.	min.	max.	min.	06.30 h	12.30 h					
January	13.1	4.4	18.1	-1.4	21.3	-4.6	91	71	61	47	10	153	51
February	15.2	5.1	20.7	0.8	28.6	-4.8	88	62	50	73	8	176	58
March	17.9	7.5	24.5	2.8	28.4	-1.0	87	58	64	61	11	188	51
April	21.1	9.6	27.8	5.3	33.9	2.6	83	50	46	34	8	263	66
May	24.3	11.9	32.0	7.2	39.2	4.6	80	46	43	67	8	297	67
June	30.2	15.7	37.5	10.9	41.4	7.1	72	38	18	63	3	351	79
July	34.1	17.8	41.1	13.5	45.0	11.4	67	31	3	13	1	395	87
August	33.3	17.9	39.3	13.7	42.4	11.0	69	33	5	24	1	361	85
September	29.7	16.2	36.7	11.8	42.0	9.0	76	41	25	49	4	274	73
October	23.5	12.3	30.4	6.5	35.8	2.8	83	51	52	48	7	220	63
November	17.5	8.0	22.7	2.5	26.8	-2.7	90	64	62	85	9	162	53
December	13.5	5.1	17.8	-0.6	20.5	-4.8	92	72	62	77	10	142	48
Year	22.8	11.0	41.6	-2.7	45.0	-4.8	81	51	491	85	80	2982	67
Number of years	27	27	27	27	27	27	21	21	27	27	27	11	11

Fig. 3. Landtypes of the survey area.





	M	Gently undulating to undulating landtype on Miocene clays
	R	Dissected plateau on Plio-Pleistocene "Raña" deposits
	T	Nearly level sand covered Pleistocene planation surface on mixed materials
	V	Nearly level landtype on Holocene deposits of the Guadiana valley

N

For a description of physiography, parent materials, soil and calcic horizons of these landtypes see Section 3.3 and 3.5

Observation site :
Site 1 = Riola 1
Site 2 = Arroyo 1
Site 3 = Arroyo 2
Site 4 = Arroyo 3

For the location of profiles P1, P2, P4 and P3 = E18 see cross section AE.

0 1 2 3 4 5 km

Table 4. Agroclimatological data for Badajoz (see Table 3) covering the period 1931-1960 as reported by Castillo & Beltran (1973)

Average absolute minimum temperature of the coldest month (January)	$-1.5^{o}C$
Average maximum temperature of the warmest 6 months (May-October)	$29.0^{o}C$
Entirely frost-free period	5.9 months
'Leaching rainfall' (excess of precipitation P over potential evapotranspiration E+ for the period that P > E)	160 mm
'P/E ratio' (average annual precipitation/ditto potential evapotranspiration)	0.46

+ Potential evapotranspiration according to Penman.

cess of precipitation over potential evapotranspiration, which corresponds more or less with the period during which part of the control section is moist, amounts to about 5 months. The mean monthly air temperature has been included in Fig. 2. This serves as the basis for estimates of the soil temperature at 50 cm depth according to Soil Survey Staff (1975). It can be concluded that the mean annual soil temperature is below $22^{O}C$ at 50 cm. Furthermore it can be deduced that mean summer and winter temperatures vary by more than $5^{O}C$ at this depth and that the mean annual temperature is over $8^{O}C$ at this depth. The conclusion that, on the basis of the above-mentioned data, the moisture regime is xeric, applies to all soils for which profile descriptions have been included in this text. The Vertisols amongst them have a xeric moisture regime on the basis of the period during which their cracks are open and closed which corresponds with the period during which their moisture control sections are dry and wet respectively. Shallow soils like those with petrocalcic horizons, that are not capable of storing 150 mm of rain, are dry in the summer for periods which exceed the one indicated with D in Fig. 2. They do not fulfil the requirements for an aridic moisture regime, however, due to the precipitation distribution pattern for the area. Consequently these soils have a xeric moisture regime too. Knibbe (1974a) comes to a similar conclusion for the soils of the adjacent Montijo area on the basis of the climatological data from this station.

Special management practices are in use in the area, in order to conserve moisture. As such the amount of moisture stored in soils with a good moisture-holding capacity, can be increased to values as high as 300 mm. The efficiency of these measures for various crops can be evaluated in a theoretical model. This will be treated in Section 3.6.

3.3 GEOLOGY AND GEOMORPHOLOGY

The geological history of the study area as described by Pannekoek (1968), IGME

(1970) and Van Dorsser (1974) is briefly summarised as follows.

In the Paleozoic era a large geosyncline existed in which several materials were deposited. The following formations of interest for the survey area date from this period: Cambrian limestones and Ordovician quartsites and slates. Later in the Paleozoic these materials were subjected to intense folding and faulting when they were influenced by the Hercynean orogenesis. Intrusion of mostly granitic magma occurred synchronously, leading to the formation of large batholiths and causing both regional and contact metamorphism of many rocks of the area.

During the Mesozoic downwearing prevailed, leading to the formation of an erosional surface, from which only some major mountain ranges protuded.

In the Tertiary period of the Cainozoic era, this plain was subject to transgressions and regressions which were separated by minor tectonic disturbances, followed by renewed base levelling. According to older literature, the sedimentation started in the Oligocene period. Finds of fossil remains of mammals have led to an updating of the onset of the sedimentation to the Vindobonian, which belongs to the Middle Miocene (IGME, 1970). In this period heavy marine clays were deposited, followed by terrestrial arkose which in turn was covered by sandy clays and heavy clays during the next transgression. The clays are separated from the arkose by discordances. Both may contain lime and as such are referred to in the literature as marls (IGME, 1954ab). The upper one of these clays contains very considerable amounts of lime in its top. This lime is generally considered by geologists to be of sedimentary origin. According to Pérez Mateos (1955), who investigated the mineralogy of the Tertiary deposits of the Guadiana basin in Extremadura, the arkose is autochtonous while the upper clays are allochtonous and have been transported to their present position by rivers. Gehrenkemper (1979) attributes the lime content of Miocene sediments near Talavera de la Reina (approximately 150 km N.E. of the survey area) to the weathering of plagioclase in granodiorites nearby. The total thickness of the Miocene sequence is variable but the following average thicknesses can be given:

- clays underlying the arkose 80 m,
- arkose grading from coarse to fine 60 m,
- clays overlying the arkose 30 m.

The end of the Tertiary period was marked by erosive processes which led to the formation of an erosional surface with a gradual slope towards the west. On this surface the coarse terrestrial deposits of the so-called 'Raña' were laid down during the Upper Pliocene. Gehrenkemper (1978) reports for this material thicknesses that vary from a few metres to 17 m in areas north of the Montes de Toledo near Talavera de la Reina and south of the same mountain range near Guadalupe. In his opinion the Raña was formed as an accumulation glacis in three phases towards the end of the Pliocene, due to a climatic change towards slightly more humid circumstances which caused destabilisation of the older weathering products of the mountain ranges. This caused the initiation of the Raña formation as mudflow-like mass movements close to the mountain fringe. This was followed by torrential dynamics mainly in the middle part of the glacis, while a more regular form of alluvial sedimentation ended the process and shaped the raña plain. This mode of genesis is reflected in the distribution pattern of the raña materials in the survey area which can be distinguished in so-called 'mountain raña', consisting of mainly angular stones along the mountain ranges and 'normal raña', which consists of mainly rounded stones and gravels which are extensive throughout the rest of the area. The 'mountain raña' has been called a 'fanglomerate' by Pannekoek (1968). Van Dorsser (1974) reports a thickness of up to 7 m for raña deposits of the survey area.

During the Quaternary, degradational processes accompanied by local deposition prevailed, the latter mainly in the Guadiana valley. Various processes contributed to the downwearing and incision of the Pliocene surface. It is quite probable that relief inversion due to the high resistance to erosion occurred, since most of the thickest and best conserved raña remnants now occupy high positions in the terrain although they were deposited in level or even slightly depressed positions (as valley deposits). Minor tectonic events have contributed to the shaping of the relief during the Quaternary. The present landscapes on Tertiary materials display several fault systems when viewed on air photos.

In the following paragraphs a description is given of the units represented on the landtype map of the study area (Fig. 3), that reflects the geological history as outlined in the foregoing part. This description is mainly based on the geological compilation (IGME, 1970), supplemented by some additional field information. A problem in the use of the compiled geological map is that the original sheets have not been updated prior to their matching. This leads to different interpretations of the same phenomena on this map. As such the legend shows arkoses, e.g., both in the Oligocene and in the Miocene, while the newer concepts restrict them to the Miocene. This was taken into account and corrected when extracting the geological equivalents of the landtypes of the survey area.

(Q) Hills of Ordovician quartzites and silicious slates They were formed by the Hercynean orogenesis. Near Guareña small hills consist of these materials while the major unit is formed by the Sierra de San Servan. This is an eroded open anticline. Associated debris slopes and even some minor areas of mountain raña have been included in this unit.

(G) Undulating landtype on Paleozoic granites and gneisses Under this heading the granites and gneisses of the study area are combined. Since they are relatively similar in chemical composition, they are treated as one parent material for the soils of the area. The large batholith N.W. of Mérida consists according to IGME (1954b) of calcic alkaline granite of the two mica type, with a dominance of biotite over muscovite. The rocks are rather coarse-grained, changing to microgranites locally within the limits of the batholith. Mahmood (1979) describes a representative sample as containing between 40 and 45 % felspars by volume, of which more than 2/3 are alkali-

felspars. A minor intrusion S.E. of Mérida on the left bank of the Guadiana river is of a fine-grained type of granite, according to IGME (1950). The gneissic unit lies north of Valverde de Mérida. On the geological map this unit is included in the granodiorites. According to Mahmood (1979) it consists mainly of medium-grained orthogneiss and some interlayered medium- and fine-grained gneiss for which he does not commit himself to a classification in ortho- or para-gneiss. He describes a sample which shows roughly equal felspar content, higher quartz content and lower mica content in comparison with the above-mentioned granite sample.

(S) Undulating to rolling landtype on Paleozoic schists This landtype consists of intermediate and basic metamorphic rocks and occurs as three units: a large one extending north and east from Mérida, on the geological map marked as granodiorite, and two smaller ones along the southern bank of the Guadiana river, on the geological map marked as Miocene and Pliocene. Mahmood (1979), who studied a cross section from Proserpina Lake (situated at 5 km north of Mérida) to Valverde de Mérida, found the large unit to consist of the following materials: fine-grained hornfelsic schist, medium-grained hornblende schist, medium- to coarse-grained amphibolite, the latter locally overlain by secondary carbonate rock and arkose. The units south of the river have lost much of their original Miocene and Pliocene covers and show schists at or near the surface.

(A) Undulating to rolling landtype on Miocene arkoses This unit, southwest of the Sierra de San Servan, encompasses the area where arkose forms the main parent material for the soils. On the geological map it is shown as undifferentiated Miocene. It consists mainly of medium- and coarse-grained arkose.

(F) Undulating landtype on fine sandy Miocene clays This unit covers the area north of the Sierra de San Servan, around the village of Calamonte. On the geological map it is shown as undifferentiated Miocene. The material is a fine sandy clay. The sand is similar in mineral composition to the sands of the arkose. The unit can be considered as intermediate between the M and the A units. It is distinguished from those because of its difference in relief, lime content and soil mantle. This fine sandy Miocene clay is frequently found underlying raña plateaus. The R unit just north-west of Calamonte is underlain by it. Dissection of this unit exposes the material in the slopes.

(M) Gently undulating to undulating landtype on Miocene clays Two units south of the Guadiana river are indicated by this symbol, shown as undifferentiated Miocene on the geological map. They belong to the deep clays of the Upper Miocene, which are characterised by the presence of large amounts of lime in the upper few metres. This material, which the geologists call 'caleño', is the main concern of this study. On this subject Van Dorsser (1974) quotes Coque (1962), who favours an aeolian source

for the lime in similar deposits from Tunesia.

(R) Dissected plateau on Plio-Pleistocene 'Raña' deposits In this unit, which is located along the southern side of the broad Guadiana valley, one finds the closed complexes of coarse materials called 'Raña' and generally dated as transitional between the Pliocene and the Pleistocene. Most of the stones and gravels, which are rounded, are embedded in a matrix of sand and clay and occur as lenses. According to Van Dorsser (1974) the mineralogy of the sands of this deposit is very similar to that of the sands of the arkose. The complexes now stand out as partially dissected plateaus which probably owe their formation to relief inversion. Goosen et al. (1973) describe similar relief inversions for Raña overlying Paleozoic rocks. On the geological map the units are shown as 'arcillas areniscosas' (clays with sandstone cobbles) of the Pliocene.

(T) Nearly level sand-covered Pleistocene planation surface on mixed materials This symbol refers to a gently sloping plain which is present over long stretches of the southern margin of the Guadiana valley. It is most probably an old, mainly erosional surface, formed in mostly redeposited materials from the Tertiary hinterland. The surface is covered by sand which varies in thickness from a few decimetres to over one metre. According to several authors (Goosen et al., 1973; Van Dorsser, 1974; Datiri, 1976; Nieuwenhuis & Trustrum, 1977) the sand is of aeolian origin. The geological map includes most of the T units under Pliocene 'arcillas areniscosas' while part is included in the undifferentiated Miocene.

(V) Nearly level landtype on Holocene deposits of the Guadiana valley This unit covers the materials that fill up the valley of the Guadiana river. The character of the materials suggests that a considerable part is not to be called Guadiana alluvium proper, since it is mostly of local origin. Pleistocene and Holocene degradation of the Tertiary landscapes along both sides of the river has supplied the bulk of these materials. They vary from heavy clays to sands and gravels. The geological map classifies this unit as Quaternary alluvium.

3.4 HYDROLOGY

The main river of the area is the Guadiana, which, with its major tributaries, normally carries water throughout the year. Most of the smaller watercourses are known to dry up during the summer. This applies to the streams of the igneous and metamorphic landscapes and to the Tertiary clays as well, except those streams that find their origin at the foot of the quartsite hills; they carry some water throughout the year (IGME, 1950).

The low permeability of most rocks and sediments of the area implies that the potential for the utilisation of groundwater is rather low. As such the city of

Mérida draws its water supply from two barrages which have been operative since Roman times. Irrigation water is drawn in large quantities from the Guadiana river which is regulated by an elaborate system of barrages in its upper course.

Before the Guadiana river was regulated by the aforementioned structures it had a very irregular regime, due to climatic factors and a poorly protected catchment. Discharges could vary from less that 0.20 m^3/s in a very dry summer to over 10 000 m^3/s as measured in the winter of 1947. The average discharge over the period 1936-1945 was 128 m^3/s. All these values were measured near Badajoz according to IGME (1950, 1954a). A peak discharge of 10 000 m^3/s is equivalent to a discharge of approximately 0.15 $m^3/s.km^{-2}$ catchment. If this tendency is displayed by a major river, its minor tributaries must show it in a more pronounced way, especially if the storage capacity of such catchments is low. As such, the streams on igneous and metamorphic rocks will discharge most of their water in the form of direct runoff and little or none in the form of delayed discharge or groundwater discharge. The same applies to the Miocene clays, which may store some water of the first rains in their cracks, but which show a high direct runoff later in the rainy winter season when the cracks are sealed and the impermeable character of the clay prevails. Petrocalcic horizons accentuate this behaviour. The arkose landscapes will probably show more delayed discharge and groundwater discharge since the infiltration and percolation in this material is expected to be somewhat higher. The inverse relationship between permeability of materials influencing the effectiveness of the storage, and peak flows measured is demonstrated by Halasi-Kun (1973) and Meijerink (1977). The density of the drainage nets is high on granite and gneiss; on the other materials of the survey area it is rather variable, since the time-dependent incision has not proceeded to all areas. In the Miocene clay area, most valleys show rather flat bottoms in part due to infill by sediments from the interfluves. Other landscapes generally show valley types with more pronounced forms. For more details reference is made to Section 3.5.

3.5 PHYSIOGRAPHY AND SOILS

In this section a description is given of the physiography and soils of each unit of the map (Fig. 3). Type and location of the calcic horizon in the soils of these units is given in the description of each landtype too.

The map of Fig. 3 was compiled from several photo interpretation and field studies carried out in the area in the period 1974-1980. It was locally completed by the author by the interpretation of aerial photographs (scale of 1 : 33 000, 1956). As a base map a blow-up of the 1 : 200 000 topographic map served.

(Q) Hills of Ordovician quartsites and silicious slates This unit includes the quartsitic ridges together with their debris slopes. Their relief is characterised as steeply dissected for the ridges, and hilly for the debris slopes. The units are

mostly devoid of any soil cover and as miscellaneous landtypes they would qualify as Rock land and Rubble land respectively. Lime is completely absent from these materials.

(G) Undulating landtype on Paleozoic granites and gneisses The gneissic landscape can be distinguished to some extent from the granitic one, in having wider and shallower valleys and in being less intensely dissected, resulting in a gently undulating topography. The soils of these landscapes are generally shallow, coarse textured and non-calcareous. Xerochrepts and Xeropsamments (typic and lithic subgroups for both) are common soils on the divides and slopes of this landscape. The valleys are occupied by the typic and aquic subgroups of these same soils. Occasionally in the granite and more commonly in the gneiss areas, these soils are associated with Haploxeralfs: aquic subgroups in the valley bottoms and the typic subgroups elsewhere. Mahmood (1979) reports the presence of some very limited areas of soil on both granite and gneiss which have a continuous soft calcic horizon, but which may be hardened locally. The lime either penetrates the underlying saprolite or lies on top of the saprolite. In the granite area this was observed near the transition of the M landtype and also close to a limestone outcrop, while the observation in the gneiss area was made in the centre of the unit.

(S) Undulating to rolling landtype on Paleozoic schists The fine-grained schists generally have a gently undulating topography while the coarse-grained ones show an undulating to rolling topography. The degree of dissection is less on the fine-grained ones than on the coarse-grained ones. The convex tops may have calcic horizons, some of which show induration. In this case Xerochrepts of the calcixerollic and occasionally petrocalcic subgroups are the soils. Chromoxererts and Haploxeralfs, mostly of the typic subgroups, are found in these positions too. In more strongly dissected landscapes most tops are non-calcareous. Xerochrepts and Haploxeralfs, often of the lithic subgroup, are found here. The slopes generally show relatively shallow soils which end in strongly calcareous saprolite in the higher reaches: Xerochrepts of the lithic vertic, paralithic vertic and lithic subgroups. Lower down on the same slopes, deeper non-calcareous Chromoxererts and Xerochrepts, both of the typic subgroup, occur in concave positions. Xerorthents of the typic and aquic subgroups have been found in the valley bottoms. They may contain lime but do not show calcic horizons.

(A) Undulating to rolling landtype on Miocene arkoses This unit comprises the relatively coarse-grained arkoses around Arroyo de San Servan. Their relief is generally undulating. Near arkose outcrops in the higher reaches it may be gently rolling and in the larger footslopes it may become nearly level. The soils of this landscape are generally moderately fine to fine textured and most of them are calcareous. Most arkose outcrops in the highest reaches of the landscape are crowned by petrocalcic hor-

izons. They carry the shallowest soils: Xerochrepts mainly of the petrocalcic subgroup. The slopes have mainly discontinuous soft calcic horizons which become continuous locally. Their soils are Xerochrepts, mainly of the calcixerollic subgroup. Fluventic Xerochrepts are found in footslopes and colluvial terraces. Chromoxererts of the typic subgroup occur in bottom positions.

(F) Undulating landtype on fine sandy Miocene clays This unit, which is to some extent similar to the M unit, differs from it in amount of lime present in the landtype and in the character of the soils. Lime is usually present as discontinuous soft calcic horizons or as concretions. There is no concentration of lime at shallow depths in the highest parts of the landscape. The soils are generally fine textured and may contain variable amounts of gravels and cobbles related to adjacent raña landscapes. The stones often show very characteristic distribution patterns which may owe their formation to a combination of gilgaï and slope processes. Similar phenomena were observed in the T and R units in the soils underlying a sand cover (Nieuwenhuis & Trustrum, 1977). The main soils are Xerochrepts of the calcixerollic, vertic and typic subgroups and Haploxeralfs of the calcic subgroup. In low positions Chromoxererts mainly of the typic subgroup are found.

(M) Gently undulating to undulating landtype on Miocene clays The landtype can be described as a dissected plateau. The valleys are mostly broad and gently sloping. The interfluves often have slightly elevated edges. Their central parts contain many closed depressions. In other places convex ridges form the remnant of the former plateau surface. The soils are mostly fine to moderately fine textured. The plateau edges and convex ridges are characterised by relatively shallow soils with petrocalcic horizons: Xerochrepts mostly of the petrocalcic subgroup. Most slopes show continuous soft calcic horizons: Xerochrepts mostly of the calcixerollic subgroup. Valley bottoms and depressions are characterised by Chromoxererts (mostly typic) and their intergrades towards the Inceptisols: vertic Xerochrepts. These soils generally have discontinuous soft calcic horizons at greater depths. This distribution pattern is illustrated in Fig. 10 by the cross section AE and by the air photo (Fig. 4).

(R) Dissected plateau on Plio-Pleistocene 'Raña' deposits This unit groups some weakly to moderately dissected remnants of a plateau upon which deposits of Raña of variable thickness cover arkose or sandy Miocene clay. Locally some aeolian sands form the top of this sequence. The topography is nearly level to gently undulating in the central parts and undulating to rolling along the dissected edges. Here outcropping raña gravel protects the surface against further erosion and causes the formation of the characteristic 'raña shoulder'. The soils of the central parts of this unit are mainly coarse over fine textured. They are mostly non-calcareous in their upper layers and may show discontinuous soft calcic horizons and/or discrete lime nodules at depth. The main soils of the nearly level surfaces are Vertisols or Alfi-

Fig. 4. Airphoto mosaic of the area south of Arroyo de San Servan in which most of the investigations were concentrated. The ridges and plateau edges which show up as light tones on the photo have petrocalcic horizons at or near the surface. The location of the three profiles of Section 4.3 and of the cross section AE has been indicated. Profile E11 of Fig. 41 is indicated too.

sols covered by sand which classify, according to the Soil Taxonomy system as Thapto-Xeralfic Xerorthents, Aquic Xerorthents and Typic Haploxeralfs. The valleys which have a sandfill have Xeropsamments mainly of the aquic subgroup. Near the edges very gravelly Haploxeralfs and Rhodoxeralfs occur mainly of the typic subgroup, while the slopes are characterised by very gravelly Typic Xerochrepts.

(T) Nearly level sand-covered Pleistocene planation surface on mixed materials This unit is found along the southern limit of the Guadiana valley, it shows a very gentle slope towards the river. The surfaces are covered by an aeolian sand cover of variable thickness. The texture of the cover varies from sand to sandy loam. The underlying materials which vary in texture from moderately fine to fine often show a characteristic microrelief which is blanketed by the sand cover. Consequently the soils vary from coarse to moderately coarse over fine textured. The deep coarse textured soils classify either as Xeropsamments or as Xerorthents, in both cases mainly of the aquic subgroup. The deep profiles in the slightly heavier aeolian mantle classify as Xerochrepts mainly of the typic subgroup. When the underlying terrace material is closer to the surface, Thapto-Xeralfic Xerorthents together with Haploxeralfs are found, which show the influence of the sandy cover in their tops. The aeolian cover is non-calcareous but the underlying terrace material contains lime. In soils developed mainly from this material at depths of about 1 m, either a discontinuous soft calcic horizon is present or discrete lime nodules are found. Combinations of these two features are also encountered.

(V) Nearly level landtype on Holocene deposits of the Guadiana valley The valley surface is interrupted by numerous abandoned channels most of which have been filled up in levelling operations for irrigation purposes. The valley can be divided into rather coarse recent alluvia along the present branches of the river, and the older valley fill which is heavier but locally shows an aeolian sand cover. Both units are crossed by numerous channels which anastomose irregularly in the older valley fill and meander parallel to the present streambeds in the recent alluvia. The soils of the recent part are mainly medium to coarse textured and weakly developed. No lime is present. The main soils belong to the typic and aquic subgroups of the Xerofluvents, Xerorthents and Quarzipsamments. Xerochrepts mainly of the fluventic subgroup are also present. The older valley fill shows Haploxeralfs and Chromoxererts, both mainly of the typic subgroups, together with typic Xerorthents where the sand cover is prominent. Locally the proportion of Vertisols to Alfisols increases towards the edges of the valley. The older valley-fill part of the landscape shows calcareous soil material at depth combined with different proportions of lime nodules which form a calcic horizon. According to Goosen et al. (1973) the nodules are of two types: autochtonous and allochtonous.

3.6 VEGETATION, LAND USE AND AGRICULTURE

According to UNESCO (1970) the area is mapped as 'formations of the Mediterranean evergreen oak stage'. This term refers to the 'potential vegetation', which means the vegetation as it would be without the intervention of man and animals. The holm oak forest *(Quercus ilex)* is an open forest with shrub undergrowth. Only some patches remain, and these have been turned into semi-natural vegetation locally called 'dehesa'. These dehesas formed from the original evergreen oak forest according to Spiers (1981) as a result of grazing and burning. Some oak trees were retained and periodically pruned to stimulate acorn production which served for the fattening of pigs. The cuttings were used for charcoal production. Most of these pastures were used in a 5-8 year rotation with one year of cereals. These dehesas are now progressively eliminated in order to give way to mechanised farming. Even on the poorer soils the dehesas are being cleared now in order to plant *Eucalyptus* species for wood production.

Dry farming is possible in this area only when special measures are taken to conserve moisture. The following rotations of annuals occur (Rural Survey Staff, 1973):

- Clean fallow or 'barbecho limpio'. This implies that wintergrain (wheat, barley, oats or rye) is grown every other year. As such the system is also called 'año y vez'. The crop is sown in October and harvested in June or July of the following year. The remaining stubble is grazed till the fall when the land is tilled to allow maximum penetration of winterrains. This tillage is practised regularly till the fall of the next year in order to conserve moisture by 'dust mulching'. Now a new grain crop is sown and the whole cycle repeats itself.
- The cultivated fallow or 'barbecho semillado'. This implies that the rotation of the aforementioned wintergrain crops is combined with drought-tolerant summercrops. In this case the grain stubble is plowed in autumn and left under tilled fallow till the spring of the next year, when horsebeans, vetches, maize, sunflower or melons are sown. The cultivation of these crops is accompanied by intensive interrow tillage in order to make optimal use of scarce moisture.

The main perennial crops which are also intensively intertilled are grapes and olives. Deep calcareous soils are preferred for this type of cultivation. These crops are, however, often found on soils which are too shallow to sustain annuals.

Huizing (1979) has made a study of the effect of the above-mentioned water conservation measures on yields of some common crops of the area. He used meteorological data from Mérida, supplemented with information from the station Talavera to construct a waterbalance diagram. Working with a theoretical model of Doorenbos & Kassam (1979) and Doorenbos & Pruitt (1977), he has computed the yield depression that will result due to moisture deficiency in the various stages of development of the crops. The yield reduction is expressed as a percentage of Ym which is defined by Doorenbos & Kassam (1979) as: 'Maximum harvested yield for a high producing variety adapted to

Table 5. Yield depression as a percentage of Ym (Doorenbos & Kassam, 1979), due to moisture deficiency for a number of crop/soil/management system combinations for the Mērida area according to Huizing (1979).

Crop	Storage capacity in the soil (mm)	Rotation	Yield depression (%)
wheat	300	clean fallow	0
wheat	300	cultivated fallow	40
wheat	150	clean fallow	35-40
wheat	150	cultivated fallow	40
barley, vetch and oats	300	clean fallow	0
barley, vetch and oats	300	cultivated fallow	0
barley, vetch and oats	150	clean fallow	0
barley, vetch and oats	150	cultivated fallow	0
grapes		-	55

the given environment with growth factors not limited'. For the computation of the reference evapotranspiration he used the radiation method. He considers two soils with a moisture storage capacity, in the root zone of the crops considered, of 150 and 300 mm respectively. Working with median monthly rainfall data (rainfall that is exceeded once every two years), he finds the result reported in Table 5. For wheat it turns out that the critical period falls in the interval March-June. The main conclusion is that, of the two moisture conservation methods considered, the clean fallow only makes sense on the soils with the larger water-holding capacities. For grapes no particular soil was considered since it was assumed that this crop used all precipitation. The result shows that the climate is not optimal for a maximum production of grapes. It must be remarked in this respect that the quality of the product was not taken into account.

The only area where irrigated farming is important is the Guadiana valley and its immediate surroundings. The main annual crops grown under this farming type are: sugarbeets, wheat, sorghum, rice, fodder crops and maize, as well as potatoes and other vegetables of many types and tobacco. The main annual crops are pears, peaches, apricots and apples.

The average yields of the major crops of the area vary, depending on the land qualities, from 1-2 ton/ha for dry-farmed wheat and from 1-2.5 ton/ha for dry-farmed barley. Sunflower yields approximately 1 ton/ha (dry-farmed), while the yield of grapes (unirrigated) varies from 3.5-10 ton/ha. Irrigated wheat and barley both yield approximately 4 ton/ha and irrigated maize brings approximately 9 ton/ha. These data are derived from Marsoedi (1981).

4 Observations

The area represented on the map (Fig. 3) forms part of a zone around the city of Mérida which has served for field studies of the Soils Department of the ITC since 1966. Several M.Sc. theses have been written on various aspects, and the area has been the subject of intensive soil mapping for training purposes. The material thus gathered has served as background information for this paper, particularly those data related to the Miocene clay landtype (M), where most of the investigations of this study have been carried out. The following approach has been chosen for the treatment of all these data from different sources.

In Section 4.1 a detailed account of the information used is given in tabular form. The methodology applied in all determinations and observations is treated in Section 4.2. In Section 4.3 profile descriptions and standard analytical data for 3 sites selected as representative are presented and discussed. Reference is made to the other profiles not reproduced in this text if aspects relevant to this study vary significantly. Section 4.4 contains a cross section of the Miocene clay landtype (M) showing the spatial relationship between the soils treated. In Section 4.5 the main features of the micromorphology from the material available are listed and discussed. In Section 4.6 special determinations on lime and clay nodule samples carried out for this study are listed in tabular form and discussed. In Section 4.7 data on stable isotope ratios of three lime samples from profile Riola 1 are reported. Micro-paleontological analyses of these same samples are found in Section 4.8. In Section 4.9 a number of conclusions are drawn from the information contained in the discussions of the various aspects. The experiments carried out with materials characterised in Section 4.6 are treated in Chapter 5.

4.1 SOURCES OF INFORMATION

Table 6 lists all material relating to the Miocene clay landtype (M). The analytical data for the profiles reported jointly by Roy (1974) and Jayaraman (1974) are based on analyses carried out at the Laboratory of Physical Geography and Soil Science of the University of Amsterdam, while their micromorphological studies were carried out at the Micromorphology Division of the Netherlands Soil Survey Institute in Wageningen (STIBOKA). The analytical data for the profiles reported jointly by Rao (1975) and Jung (1974) were carried out at the same laboratory in Amsterdam. Their micromorphological descriptions were made at the International Soil Museum (ISM) in Wageningen. Micromorphology of two additional samples drawn for this study was de-

Table 6. Sources of information. The table indicates the authors, number, classification and location of the profiles about which information was available. Information from the Profiles P1, P2, P3 and P4 includes descriptions of associated deep augerings. In the matrix a cross (x) indicates that information is present and a point (.) indicates that information is lacking.

	Jayaraman (1974) and Roy (1974)				Jung (1974) and Rao (1975)			
	Riola 1	Arroyo 1	Arroyo 2	Arroyo 3	P1	P2	P3 = ISM E18	P4
	Petrocalcic Xerochrept	Petrocalcic Xerochrept	Typic Chromoxerert	Calcixerollic Xerochrept	Typic Chromoxerert	Typic Chromoxerert	Typic Chromoxerert	Petrocalcic Xerochrept
Location site on the map (Fig. 3)	1	2	3	4	ABCDE			
Profile description	x	x	x	x	x	x	x	x
Analytical data								
Granulometric analysis	x	x	x	x	x	x	x	x
pH (H_2O and $CaCl_2$ or KCl)	x	x	x	x	x	x	x	x
Electrical conductivity	.	.	.	.	x	x	x	x
Organic carbon percentage	.	x	.	.	x	x	x	x
Calcium carbonate equivalent	x	x	x	x	x	x	x	x
Gypsum	.	.	.	.	.	.	x	.
Exchangeable cations	.	.	.	.	.	.	x	.
Cation exchange capacity (CEC)	.	.	.	.	.	.	x	.
Base saturation (BS)	.	.	.	.	.	.	x	.
X-ray diffraction of clay	x	x	.	.	x	x	x	x
Micromorphology	x	x	x	x	x	x	x	.

scribed at the ISM too.

Jung and Rao's profile, P3, is the equivalent of Profile E18 of the collection of soil monoliths of the ISM. Of the analyses reported for E18, granulometry and X-ray diffraction were carried out by the ISM while the remainder were done at the

Royal Tropical Institute (KIT) in Amsterdam. New samples were drawn up to a depth of 540 cm from profile Arroyo 1. These were subjected to X-ray diffraction by the ISM in order to study the clay mineralogy of the subsoil. In order to facilitate comparison of the X-ray diffraction data of the two laboratories, they are all rated according to a four point scale as indicated on the data sheets.

Special determinations on lime and clay samples as listed in Section 4.6 were carried out by the author in the ITC soils laboratory. In Section 4.7 there are stable isotope analyses of lime samples of the Riola 1 profile, which were carried out at the Physics Laboratory of the University of Groningen by W.G. Mook. Micropaleontological analyses of the same Riola samples (Section 4.8) were carried out by A.C. van Ginkel of the Institute for Geology and Mineralogy of Leiden University.

For the location of the profiles and sample sites of the area see the map (Fig. 3), the aerial photograph (Fig. 4) and the cross section (Fig. 10), which carry the corresponding site numbers and profile numbers.

4.2 METHODOLOGY

Under this heading the methodology for obtaining all determinations and other operations such as profile description, classification etc. is described briefly.

Classification of the soils. Profiles were classified according to the Soil Taxonomy System (Soil Survey Staff, 1975). The classifications were updated according to the approved amendments to this system of May 5, 1978.

Profile description. The profiles were described according to the Guidelines for Soil Profile Description (FAO, 1967). Certain terms introduced in Sections 2.1 and 2.3 have been added to clarify some features.

Granulometric analysis. Samples of the fine earth fraction were treated in order to remove soluble salts, organic matter and lime. The fraction coarser than 50 µm was split in two by means of sieving, while the fraction finer than 50 µm was dispersed with sodium carbonate/sodium pyrophosphate. By means of the pipette method two fractions, clay and silt, were determined. Weight losses that were due to the pre-treatment of the sample were proportionally divided over all the fractions in order to make up 100 %. The result is expressed as a weight % (mass fraction).

pH. The soil was shaken with H_2O at a ratio of 1 : 2.5 for two hours, after which the pH was determined by means of a glass electrode. The procedure was repeated with 0.01 mol/l $CaCl_2$.

Electrical conductivity (EC_e). This was measured in the saturation extract and expressed as mS/cm at 25^{o}C.

Organic carbon percentage (C %). This was determined according to Allisons's method (Black, 1965), except for Profile E18 which is equivalent to Profile P3. For this profile, the data from the Royal Tropical Institute are reported, which determines organic carbon according to the Walkley-Black method (Black, 1965). The result is expressed as a weight % (mass fraction).

Calcium carbonate equivalent ($CaCO_3$ %). This was determined according to the method of Scheibler (volumetrically). The data of Profiles P1, P2 and P4 of Jung (1974) and Rao (1975) were determined gravimetrically according to Wesemael (1955). The result is expressed as a weight % (mass fraction).

Gypsum. This was determined by precipitation with acetone and measured turbidimetrically.

Exchangeable cations. Cations were displaced by a solution of 1 mol/l NH_4OAc. For calcareous soils the ammonium acetate solution was brought to pH 8.2 prior to the extraction. Despite this precaution some Ca ions not derived from the complex were determined in the solution as analytical data show. As such the determination should rather be called 'extractable cations' when dealing with calcareous soils. The data are expressed in exchange equivalents as mmol/100 g soil.

Cation exchange capacity (CEC). The samples were saturated with Na^+ by treatment with sodium acetate. Subsequently the Na^+ was displaced by treatment with ammonium acetate (buffered at pH 8.2 in the case of calcareous samples). The displaced Na^+ was determined and expressed in exchange equivalents as mmol/100 g soil.

Base saturation (BS). This figure was computed by dividing the sum of the exchangeable bases by the CEC, expressing this ratio as a percentage. Figures exceeding 100 were rounded off to 100 %, assuming that the discrepancy between the figures was due to free calcium carbonate in the sample.

X-ray diffraction of the clay fraction. Wet samples were mounted on glass slides, dried and analysed by a Philips diffractometer. The samples were irradiated with Co radiation and scanned over an angle of $2\theta = 2^o$ to $2\theta = 32^o$. The contents of each mineral in the clay was estimated from relative peak intensities. The contents were expressed as - to xxxx for clay minerals and - to ++++ for other minerals. (x) and (+) refer to intermediate cases. Traces are indicated by tr. while a question mark indicates that the presence of a mineral is not certain.

Liquid limit (LL). Determinations were made on a number of lime samples according to the ASTM (1954) procedure. The liquid limits were ascertained by one determination in a range between 15 and 40 blows and corrected by means of a nomogram (Olmstead, 1949). Of each sample, moist consistency was determined according to the Guidelines for Soil Description (FAO, 1967).

Bulk density. Bulk density of lime samples has been determined by measuring weight and volume of undisturbed samples drawn by means of sample rings. Bulk density of clay nodules has been determined from the data acquired in the measurement of the coefficient of linear extensibility. The bulk densities are reported as BD (dry) for the values derived from weight and volume in an oven-dry condition. For the clay nodule samples, a bulk density in saturated condition was also calculated, by dividing the *weight in saturated condition* by the volume in this condition. This value is indicated as BD (sat.)$^+$. For the lime samples the same value was calculated, for two extreme cases, from BD (dry), assuming a certain specific weight for the solid phase (Section 4.6.1.2). The same applies for the bulk densities in moist condition taken from the lime at the end of Experiment II (Section 5.2.2 and Table 14) and reported as BD (moist)$^+$. *It must be stressed that BD (sat.)$^+$ and BD (moist)$^+$ do not refer to weight dry/volume saturated and weight dry/volume moist respectively, which are the meanings commonly attributed to these ratios in the literature.* In this study the need was felt for a bulk density of clay and lime that would be able to predict the behaviour of these two materials relative to each other in saturated and moist condition (see Chapter 5).

Grain size of calcite crystals. An estimation of the average grain size of the crystals in the lime samples was made by means of a petrographic microscope. For this purpose preparations were made of the dried material. The fraction smaller than 0.5 mm was sprinkled thinly on an object glass covered with heated Canada balsam. The estimations were based on the measurement of the long and the short axis of a limited number of crystals.

Coefficient of linear extensibility in saturated condition (COLE sat.). The coefficient of linear extensibility was measured for a number of clay nodules, which were coated in dry condition with SARAN resin according to Brasher et al. (1966). Weight and volume were determined in dry state, then the coating was scratched to allow moisture to penetrate after placing the objects on a wet sponge. When constant weight was reached, volume was determined again. Volume determinations were made on the basis of weight loss upon immersion in water. Volumes and weights were corrected by deducting the part corresponding to the SARAN coating which weighs 1.4 g/cm^3 (Bouma, 1977). COLE (sat.) was calculated as the cubic root of the ratio of the saturated over the dry volume, minus 1 (Grossman et al., 1968).

Percentage of water-stable aggregates of the lime. In order to evaluate the influence of the degree of aggregation of the lime on the liquid limit of the samples, wet sieving was applied. Samples were brought to the liquid limit, then put through a 50 µm sieve by means of vibration under the application of water. After a 20 minute treatment under standardised conditions, the residue was dried and weighed. The result is expressed as a weight % (mass fraction).

Micropaleontology. Samples of lime were desintegrated by treatment with H_2O_2 and studied under a binocular microscope.

Stable isotopes. The stable isotopes C^{13} and O^{18} were determined by means of a mass spectrograph. Their fractionation rates are expressed in ^{o}/oo in relation to the standard sample: the Pedee belemnite.

Micromorphology. Large size thin sections were prepared using the technique of Jongerius & Heintzberger (1972). They were studied under a petrographic microscope. Most of the terminology applied is according to Brewer (1976).

4.3 CHARACTERISATION OF THE SOILS

Of the materials listed in Table 6, three profiles have been selected for reproduction in this text. Riola 1 and Arroyo 1 are representative of the 'high soils' of

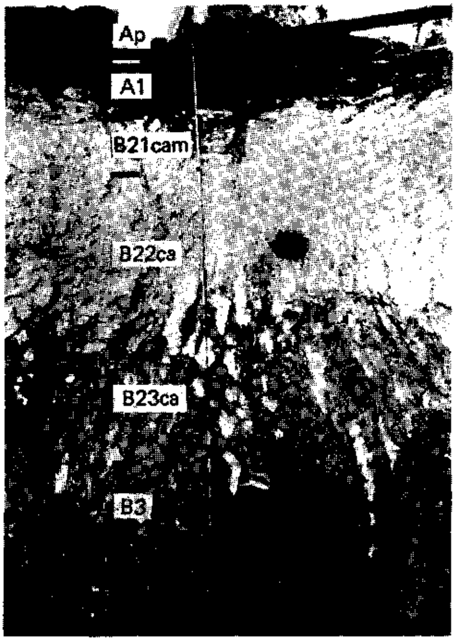


Fig. 5. Profile Riola 1. The photograph was taken in the northeastern corner of the pit. Some overburden is present on the surface which is visible just underneath the pole. The surface soil, laminated petrocalcic horizon, continuous soft calcic horizon and its transition via a 'striped zone' towards the underlying Miocene clay, have been indicated with their corresponding horizon symbols. (Photo courtesy of M. Knibbe.)

the plateau edges and from the tops of the ridges. Riola 1 was intensively studied by Jayaraman (1974) and Roy (1974). Unfortunately this exposure was no longer available for the investigations of the present study. Most samples had to be drawn from Arroyo 1 which resembles Riola 1 closely. Notwithstanding the fact that Profile Arroyo 3 classifies differently from Riola 1 and Arroyo 1 at subgroup level, this profile is not considered to be basically different in genesis from the other two. There is hardening of the calcic horizon in this profile too, but not to such an extent that a continuous petrocalcic horizon is present. Profile P3, which is equivalent to Profile E18 of the ISM, has been selected as a representative example of the 'low soils' of valleys and depressions.

4.3.1 Profile descriptions and analytical data

For the three profiles reference is made to photographs in which the corresponding horizon symbols have been indicated. Fig. 5 shows a general view of the Profile Riola 1. Fig. 6 shows details from this same soil. Fig. 7 is a general view of Profile Arroyo 1, details of which are shown in Fig. 8. Fig. 9 shows a photograph made

Fig. 6. Detail from the transition of the soft calcic horizon towards the 'striped zone', in Profile Riola 1. An arrow indicates the point where a 'clay pillar' has desintegrated into clay lumps and these in turn into clay nodules. Each section of the measuring tape represents 10 cm. (Photo courtesy of M. Knibbe.)

of the soil Monolith E18 which represents Profile P3.

All three soils have continuous soft calcic horizons of which the lower boundary towards the underlying clay is irregular or broken. The following terms are used to indicate the features related to this 'striped' transition zone:

- *Clay pillars* are large elongated clay bodies vertically oriented and connected to the underlying horizon.
- *Clay lumps* are smaller clay bodies separated from the clay pillars by cracks filled with lime.
- *Clay nodules* are still smaller, mainly spherical clay bodies, which occur isolated throughout the overlying calcic horizon and in the other overlying horizons.

Absolute size indications can be derived from the profile descriptions into which this nomenclature was introduced and from Figs. 6, 8, 39 and 41. Size classes for (clay) nodules are according to FAO (1967).

4.3.1.1 Profile Riola 1

Site information

Soil classification	: Petrocalcic Xerochrept.
Date of examination	: May 1973.
Authors of description	: M. Jayaraman and D.K. Roy.
Location	: App. 8 km south of Arroyo de San Servan on the Arroyo-Almendrajelo road (Riola wine factory pit). Site 1 on map (Fig. 3).
Elevation	: App. 305 m above sea level.
Landform	
i. Physiographic position	: Level to convex 'mesita' summit.
ii. Landform of the surrounding country	: Moderately undulating.
iii. Microtopography	: Nil.
Slope	: Less than 1 %.
Land use	: Arable land with olives and grapes.
Climate	: Semi-arid.

General soil information

Parent material	: Miocene clay.
Drainage	: Well drained.
Soil moisture condition	: Dry.
Depth of groundwater table	: More than 4 m.
Presence of surface stones or rock outcrops	: Many petrocalcic fragments; no rocks.
Erosion	: Moderate sheet erosion.
Presence of salt or alkali	: Nil.
Human influence	: Plowing.

Brief description of the soil

Moderately deep, well drained dark reddish brown surface soil with yellowish red, clay sub-soil of medium structural development; overlying a laminated petrocalcic horizon with many large sub-rounded to sub-angular, non-calcareous clay nodules, followed by a calcic horizon with large clay nodules. Below 250 cm the calcic horizon appears as alternate stripes, more or less vertically oriented with non-calcareous red clay lumps, as well as clay of reduced grey colours. Red heavy clay with manganese coatings appears below 325 cm, with well developed prismatic structure and prominent slickensides.

Description of soil horizons

0-25 cm Ap	Dark reddish brown (5YR 3/4) moist, yellowish red (5YR 3/6) dry, clay; moderate, fine, sub-angular blocky; common medium lime concretions; slightly sticky, slightly plastic, friable moist, slightly hard dry; common, fine, tubular pores; common medium roots; calcareous; gradual, wavy boundary.
25-40 cm A1	Yellowish red (5YR 3/6) moist, clay; strong, medium sub-angular blocky; few medium lime concretions; slightly sticky, slightly plastic, firm moist; common, fine to medium, tubular pores; few, fine roots; calcareous; clear, wavy boundary.
40-100 cm B21cam	Petrocalcic horizon, laminated; few, fine and medium roots; many, large, rounded to sub-rounded, non-calcareous clay nodules; gradual, wavy boundary.
100-250 cm B22ca	Calcic horizon; pinkish white (5YR 8/2) moist, many, large, non-calcareous clay nodules; abrupt, irregular boundary.
250-325 cm B23ca	Calcic horizon with clay pillars which break up into clay lumps; calcic material and clay appear as alternate stripes more or less vertically oriented; clay lumps non-calcareous; calcic material in soft powdery form; phenomenon of pseudo-gley with clay of reduced grey colours, alternating with soft calcic stripes; clay: moderate, coarse angular blocky; sticky, slightly plastic, very firm moist, hard dry; few coarse roots; clear, irregular boundary.
325-450 cm B3	Red (2.5YR 5/6) moist, heavy clay; strong, coarse, prismatic; stripes of soft lime along cracks; sticky, slightly plastic, very firm moist, hard dry; prominent slickensides; manganese coatings over clay; non-calcareous.

Horizon	Depth (cm)	Particle size distribution (μm) weight % (mass fraction) c. sand 2000–250	f. sand 250–50	silt 50–2	clay 2	Texture
Ap + A1	0–40	5.0	12.0	20.5	62.5	Clay
B21cam petrocalcic material	40–100	n.d.	n.d.	n.d.	n.d.	n.d.
B21cam clay nodules	40–100	1.2	10.0	23.0	66.5	Clay
B22ca calcic material	100–250	n.d.	n.d.	n.d.	n.d.	n.d.
B22ca clay nodules	100–250	2.9	22.5	33.5	41.0	Clay
B23ca calcic material	250–325	n.d.	n.d.	n.d.	n.d.	n.d.
B23ca clay lumps	250–325	0.5	4.0	13.5	82.0	Clay
B3	325–450	0.5	4.5	13.5	81.5	Clay

Horizon	pH H_2O	pH $CaCl_2$	EC_e mS/cm	C % (mass fraction)	$CaCO_3$ % (mass fraction)
0–40	8.1	7.1	n.d.	n.d.	19.5
40–100 (ca)	8.2	7.4	n.d.	n.d.	94.4
40–100 (cl)	7.4	7.3	n.d.	n.d.	5.7
100–250 (ca)	8.5	7.5	n.d.	n.d.	94.0
100–250 (cl)	8.0	7.5	n.d.	n.d.	0.2
250–325 (ca)	8.4	7.5	n.d.	n.d.	85.9
250–325 (cl)	8.2	7.5	n.d.	n.d.	5.7
325–450	8.2	7.4	n.d.	n.d.	0.5

Horizon	X-ray diffraction of the clay fraction smectite	palygorskite	kaolinite	vermiculite	quartz	tobermorite
0–40	x(x)	xx(x)	tr	-	(+)	-
40–100 (ca)	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
40–100 (cl)	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
100–250 (ca)	(x)	xx	?	-	(+)	+(+)
100–250 (cl)	xx	xxx	tr	-	++	-
250–325 (ca)	(x)	xxx	?	-	(+)	-
250–325 (cl)	x	xxx(x)	tr	-	(+)	(+)
325–450 (cl)	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.

Symbols:
xxxx abundant
xxx common
xx small
x very small
These terms apply to the relative quantities of clay minerals. The same range applies for non-clay minerals indicated by +. Brackets indicate intermediate cases while traces are indicated by tr. A ? indicates that the presence of a mineral is uncertain.
(ca) = calcitic material
(cl) = clayey material
n.d. = not determined
- = content 0

4.3.1.2 Profile Arroyo 1

Site information

Soil classification	: Petrocalcic Xerochrept.
Date of examination	: June 1973.
Authors of description	: Jayaraman and Roy (supplemented by Elbersen, 1981).
Location	: A road cut on the Arroyo-Solana de los Barros country road, 6 km southwest of Arroyo de San Servan. Site 2 on map (Fig. 3).
Elevation	: About 270 m above sea level.
Landform	
i. Physiographic position	: Level to convex 'mesita' summit.
ii. Landform of the surrounding country	: Moderately undulating.
iii. Microtopography	: Nil.
Slope	: Less than 1 %.
Land use	: Arable land with olives.
Climate	: Semi-arid.

General soil information

Parent material	: Miocene clay.
Drainage	: Well drained.
Soil moisture condition	: Slightly moist.
Depth of groundwater table	: More than 3 m.
Presence of surface stones or rock outcrops	: Many petrocalcic fragments.
Erosion	: Slight sheet erosion.
Presence of salt or alkali	: Nil.
Human influence	: Nil apart from routine cultivation.

Brief general description of the profile

Shallow, well drained, yellowish brown, silty clay loam surface soil overlying a hard, indurated and laminated petrocalcic horizon, which is underlain by a soft, powdery calcic horizon containing non-calcareous clay nodules. Stripes of soft calcic material alternating with clay 'pillars' form the transition towards the underlying Miocene clay. The Miocene clay contains lime pockets up to a depth of at least 5 m. As such it qualifies as a discontinuous soft calcic horizon.

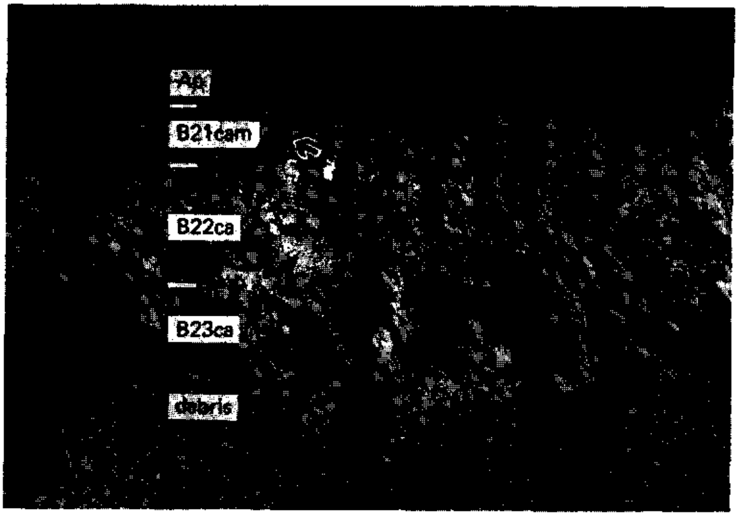


Fig. 7. Profile Arroyo I. A thin surface horizon overlies a laminated petrocalcic horizon in which several clay nodules are embedded (arrow). Underlying the petrocalcic horizon is a continuous soft calcic horizon which contains clay nodules. This horizon merges via a 'striped' transition zone into the underlying Miocene clay. In the photograph this horizon sequence is indicated by the correponding horizon symbols.

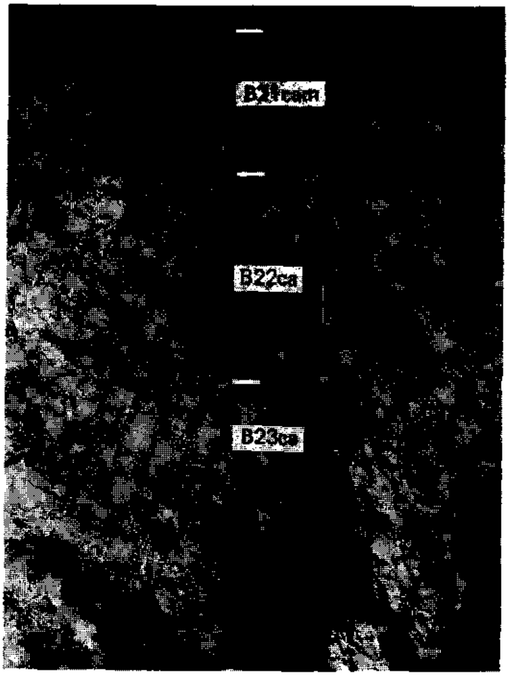


Fig. 8. Detail from Fig. 7 in which clay nodules are visible in the petrocalcic and calcic horizons. The hammer rests on a 'clay pillar' which protudes high into the ontinuous soft calcic horizon, breaking up into clay lumps. The corresponding horizon symbols of Fig. 7 are indicated in the photo.

Description of soil horizons

0-16 cm Ap	Yellowish brown (10YR 5/4) moist and dry, clay loam; weak, fine sub-angular blocky structure breaking into crumbs; slightly sticky, non-plastic, friable moist, slightly hard dry; common petrocalcic fragments; common very fine and few fine tubular pores; common fine and few very fine roots; calcareous; abrupt, smooth boundary.
16-55 cm B21cam	Pinkish white (7.5YR 8/2) moist, white (N 9/0) dry petrocalcic horizon consisting of various laminated sub-horizons; the degree of cementation deminishes with depth and varies from indurated in the top to strongly cemented at the bottom; the horizon contains few, large (1-5 cm), hard, massive, partially rounded and partially angular non-calcareous clay nodules of a yellowish red (5YR 5/6) moist, pink (5YR 7/3) dry colour; the nodules have a lime coating and show thin patchy black cutans of manganese compounds on some of their faces; few fine and medium roots; diffuse wavy boundary.
55-140 cm B22ca	Pink (5YR 8/3) moist, white (N 9/0) dry, calcic horizon consisting of soft powdery lime with many weakly cemented to strongly cemented partially broken lime fibres; the horizon contains many large clay nodules and at the tops of intruding clay pillars few clay lumps which vary in size from 2-7 cm. Both nodules and lumps are hard, massive, partially rounded and partially angular, non-calcareous and of a yellowish red (5YR 5/6) moist, pink (5YR 7/3) dry colour; they have a lime coating and show thin patchy to broken black cutans of manganese compounds on most of their faces; clear irregular boundary.
140-300 cm B23ca	Reddish yellow (7.5YR 7/6) moist, pink-pinkish white (7.5YR 8/3) dry, lime which forms a discontinuous soft calcic horizon in the form of 'stripes' alternating with 'pillars' which consist of red (2.5YR 5/6) moist, pink (5YR 7/4) dry clay, the clay pillars have a strong coarse angular to sub-angular blocky structure which breaks up into strong medium angular blocky elements; the structural elements of the clay pillars are massive and show thin broken white (7.5YR 8/1) moist and dry, cutans probably of bleached clay on their ped faces together with thin broken black cutans of manganese compounds, the elements are non-calcareous; very few very fine roots. In horizontal section the lime 'stripes' form a roughly hexagonal pattern between the clay 'pillars'; intersecting slickensides are abundant in the clay and common in the lime; locally, concentrations of reddish brown mottling occur in the lime often accompanied by cementation.
300-540+ cm B3	Dark red (2.5YR 3/6) moist, clay; mixed with some lime (auger sample).

Analytical data

Horizon		Depth (cm)	Particle size distribution (μm) weight % (mass fraction)				
			c. sand 2000-250	f. sand 250-50	silt 50-2	clay 2	Texture
Ap		0-16	5.5	27.5	31.5	35.5	Clay loam
B21cam		16-55	n.d.	n.d.	n.d.	n.d.	n.d.
B22ca		55-140	n.d.	n.d.	n.d.	n.d.	n.d.
B23ca	calcic material	140-220	n.d.	n.d.	n.d.	n.d.	n.d.
B23ca	clay	140-220	1.0	5.0	48.0	46.0	Silty clay

Horizon		pH		EC_e	C	$CaCO_3$
		H_2O	$CaCl_2$	mS/cm	% (mass fraction)	% (mass fraction)
0-16		7.8	7.2	n.d.	1.10	55.3
16-55		7.7	7.5	n.d.	0.29	82.6
55-140		7.7	7.6	n.d.	0.17	86.9
140-220	(ca)	7.8	7.4	n.d.	0.06	82.5
140-220	(cl)	8.3	7.6	n.d.	0.06	7.0

Horizon		X-ray diffraction of the clay fraction						
		smectite	palygorskite	kaolinite	vermiculite	quartz	chlorite	mixed layer
0-16		xx(x)	xx(x)	x(x)	-	-	tr.	-
16-55	(ca)	xx	xxx(x)	tr.	tr.	tr.	-	-
16-55	(cl)	xx	xxx(x)	x	x	-	-	tr.
55-140	(ca)	xx(x)	xx(x)	tr.	-	tr.	-	tr.
55-140	(cl)	xx	xxx(x)	tr.	x	-	-	-
140-260	(ca)	xx(x)	xxx(x)	tr.	-	-	-	tr.
140-260	(cl)	xx(x)	xxx(x)	x(x)	-	tr.	tr.	tr.
420-430		xxx(x)	xx(x)	x(x)	-	-	x	-
490-500		xxx(x)	xx(x)	x(x)	-	-	x	-
530-540		xxx(x)	xx(x)	x(x)	-	-	x	-

Symbols:
xxxx abundant
xxx common
xx small
x very small
These terms apply to the relative quantities of clay minerals. The same range applies for non-clay minerals indicated by +. Brackets indicate intermediate cases while traces are indicated by tr.
(ca) = calcitic material
(cl) = clayey material
n.d. = not determined
\- = content 0

4.3.1.3 Profile P3 equivalent to E18 (ISM)

Site information

Profile number	: E18 (ISM) equivalent to P3.
Soil classification	: Typic Chromoxerert.
Date of the examination	: June 1974.
Authors of the description	: Creutzberg and Van Baren/Rao and Jung (The upper 66 cm of the description of Creutzberg and Van Baren was used. To this the lower part of the description of Jung and Rao was attached. This part was checked and corrected against monolith E18 by Elbersen).
Location	: About 300 m north of farmhouse 'La Cora'. 6 km west of Torremegia, province of Badajoz, Spain (DE in cross section, Fig. 10).
Elevation	: 292 m above sea level.
Landform	
i. Physiographic position	: Broad valley bottom.
ii. Landform of the surrounding country	: Undulating.
iii. Microtopography	: Nil.
Slope	: Almost flat.
Land use	: Arable land with olives and grapes.
Climate	: Semi-arid.

General soil information

Parent material	: Miocene clay (colluvial material).
Drainage	: Moderately well drained.
Soil moisture condition	: Dry up to 15 cm; moist below.
Depth of groundwater table	: Not reached within 2 m (4 m in a well 500 m north of profile).
Presence of surface stones or rock outcrops	: No stones; no rocks.
Erosion	: Nil.
Presence of salt or alkali	: Nil.
Human influence	: Periodic harrowing.

Brief description of the soil

This profile consists of two parts: A colluvial upper part which merges via a transitional zone at a depth of 52 cm into a red clay that is similar to the clays of Profiles Riola 1 and Arroyo 1. The colluvial part of the profile shows a yellowish red fine textured surface soil, overlying a dark reddish brown fine textured sub-soil with moderate structure and showing many intersecting slickensides. A discontinuous soft calcic horizon which includes very many clay nodules and occasional slickensides forms the upper part of the red clay. The lime content of the soft calcic horizon increases with depth and the horizon turns into a continuous soft calcic horizon with many red clay nodules. At a depth of 115 cm the material changes to a heavy well-structured red clay with gley phenomena and prominent slickensides. Large pockets of soft lime make this a discontinuous soft calcic horizon.

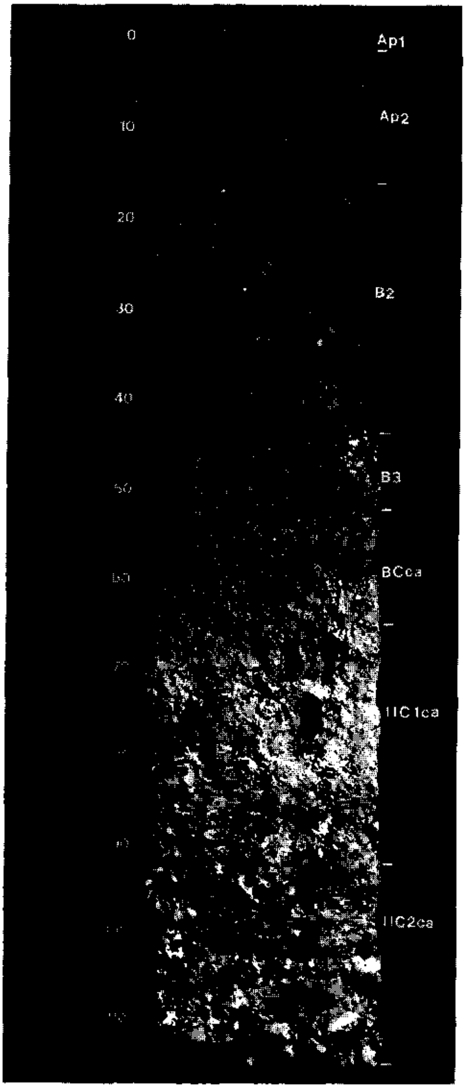


Fig. 9. Monolith E18 of Profile P3 showing a colluvial upper part with strong vertic properties overlying a continuous soft calcic horizon with red clay nodules developed in red Miocene clay. The horizon symbols of the profile description in Section 4.3.1.3 have been indicated in the photograph. (Photo courtesy of the ISM.)

Description of soil horizons

0-3 cm	Ap1	Yellowish red (5YR 3/6) moist and dry, clay; moderate to strong medium crumbs; very sticky, very plastic, very friable moist, slightly hard dry; very few small gravels of calcareous and quartz nature; slightly calcareous; common fine and few medium roots; abrupt wavy boundary.
3-15 cm	Ap2	Yellowish red (5YR 3/6) moist and dry, clay; massive to weak fine sub-angular blocky; very sticky, very plastic, very friable moist, slightly hard dry; very few very fine tubular pores; very few small gravels of calcareous and quartz nature; slightly calcareous; common fine and few medium roots; gradual smooth boundary.
15-42 cm	B2	Dark reddish brown (2.5YR 3/5) moist and reddish brown (2.5YR 3.5/5) dry clay; moderate fine blocky; very sticky, very plastic, firm moist, very hard dry; common intersecting slickensides; few very fine tubular pores; very few gravels of calcareous and quartz nature, less than in Ap; slightly calcareous; common fine and very few medium roots; gradual wavy boundary.
42-52 cm	B3	Dark reddish brown (2.5YR 3/5) moist and reddish brown (2.5YR 3.5/5) dry with many distinct coarse red mottles, clay; moderate fine blocky; very sticky, very plastic, firm moist, very hard dry; many intersecting slickensides; few very fine tubular pores; very few small gravels of calcareous and quartz nature, more than in B2; calcareous; few fine and few medium roots; clear wavy boundary.
52-66 cm	BCca	Red (2.5YR 4/7) moist and dry, with many medium distinct reddish yellow mottles, clay; strong fine blocky; sticky, very plastic, friable moist, hard dry; few very fine tubular pores; strongly calcareous; few medium roots; diffuse smooth boundary. (The overlying B3 material is tonguing into the BCca horizon.)
66-93 cm	IIC1ca	Light red to red (2.5YR 5.5/6) moist clay; few fine faint red (2.5YR 4/6) and (10R 4/6) mottles which exhibit weak fine sub-angular blocky structure; very sticky, very plastic, extremely firm moist, hard dry; few very fine and fine tubular pores; strongly calcareous; few very fine roots; few large crotovinas of a diameter of 1-2 cm filled up with B3 material; soft powdery lime in pockets and elongated patches; gradual smooth boundary.
93-115 cm	IIC2ca	Light red to red (2.5YR 5.5/6) moist, clay; dusky red (10R 3/4) clay occurs in nodules of 1-2.5 cm which exhibit a moderate to strong medium angular and sub-angular blocky structure set in a lime matrix; very sticky, very plastic, very firm moist; few very fine tubular pores; strongly calcareous; very few fine roots; dark ferro-manganese cutans on the clay nodules; few slickensides which do not intersect; abrupt smooth boundary.
115-200 cm	IIC3ca	Dusky red (10R 3/4) moist, clay; red clay alternating with large (4 x 25 cm) pockets of gleyed clay of light grey (10YR 7/1) moist colour; pockets of soft lime up to 10 x 15 cm occur; hard $CaCO_3$ pieces are also encountered; numerous slickensides intersecting at various angles are prominent; the cleavage faces are shining and coated with ferro-manganese cutans and with white lime.

Analytical data

Horizon	Depth (cm)	Particle size distribution (μm) weight % (mass fraction) c. sand 2000-250	f. sand 250-50	silt 50-2	clay 2	Texture
Ap1 + Ap2	0-15	11.4	13.5	19.9	55.1	Clay
B2	15-27	11.6	13.5	19.1	55.7	Clay
B2	27-42	11.7	12.4	19.0	56.9	Clay
B3	42-52	10.9	11.9	18.9	58.3	Clay
BCca	52-66	7.2	8.0	17.2	67.5	Clay
IIC1ca	66-82	3.8	4.9	14.4	76.9	Clay
IIC1ca + IIC2ca	82-102	2.7	5.5	16.2	75.6	Clay
IIC2ca + IIC3ca	102-118	2.0	3.6	15.8	78.6	Clay

Horizon	pH		EC_e	C	$CaCO_3$	$CaSO_4$	Exchange equivalents (mmol/100g soil) Exchangeable cations					CEC	BS
	H_2O	$CaCl_2$	mS/cm	% (mass fractions)	%	%	½ Ca	½ Mg	K	Na	Sum		%
0-15	8.2	6.7	0.23	0.41	0.2	-	44.0	6.9	0.9	-	51.8	46.3	100
15-27	8.0	6.1	0.14	0.38	-	-	36.8	6.5	0.4	-	43.7	41.3	100
27-42	8.0	6.3	0.22	0.32	0.3	-	36.9	6.7	0.3	-	43.9	43.8	100
42-52	8.3	6.8	0.23	0.29	6.2	-	36.8	6.5	0.2	-	43.5	41.3	100
52-66	8.4	6.9	0.26	0.25	30.0	-	31.1	5.5	0.2	-	36.8	31.7	100
66-82	8.7	7.2	0.23	0.16	56.6	-	25.4	4.1	0.2	-	29.7	24.0	100
82-102	8.7	7.2	0.28	0.06	50.8	-	24.0	4.7	0.2	-	28.9	24.5	100
102-118	8.7	7.4	0.22	0.03	69.8	-	18.5	3.2	0.1	-	21.8	17.0	100

Horizon	X-ray diffraction of the clay fraction smectite	palygorskite	kaolinite	vermiculite	illite	quartz
0-15	xxx	tr.	x	-	tr.	(+)
15-27	xxxx	tr.	x	-	tr.	(+)
27-42	xxxx	tr.	x	-	-	(+)
42-52	xxx	x	x	-	-	tr.
52-66	xx	x(x)	tr.	-	-	tr.
66-82	xx	xx	tr.	-	-	+
82-102	xx	xx	tr.	tr.	-	+(+)
102-118	xx	xx	tr.	tr.	-	+

Symbols:
xxxx abundant
xxx common
xx small
x very small
These terms apply to the relative quantities of clay minerals. The same range applies for non-clay minerals indicated by +. Brackets indicate intermediate cases while traces are indicated by tr.
n.d. = not determined
- = content 0

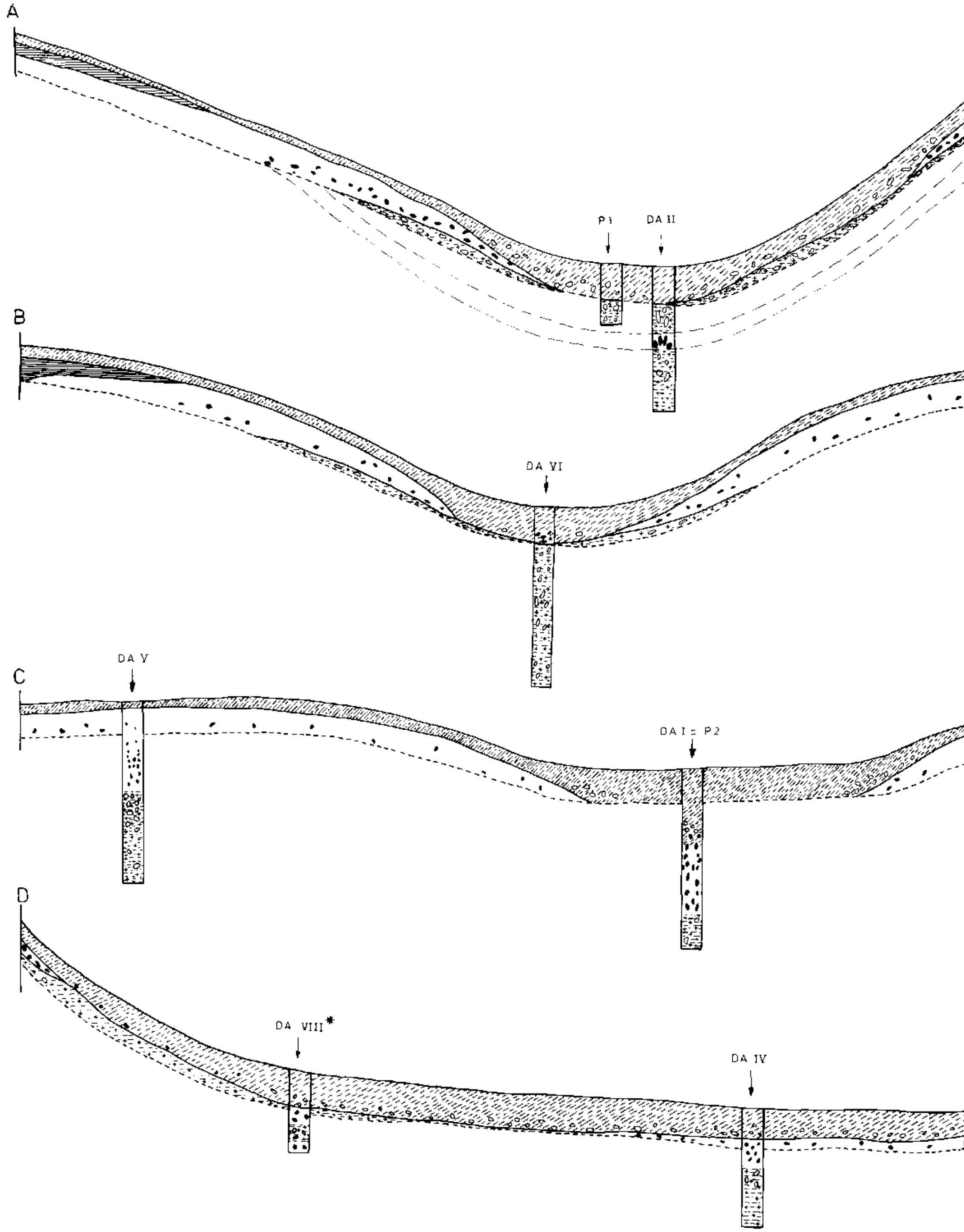
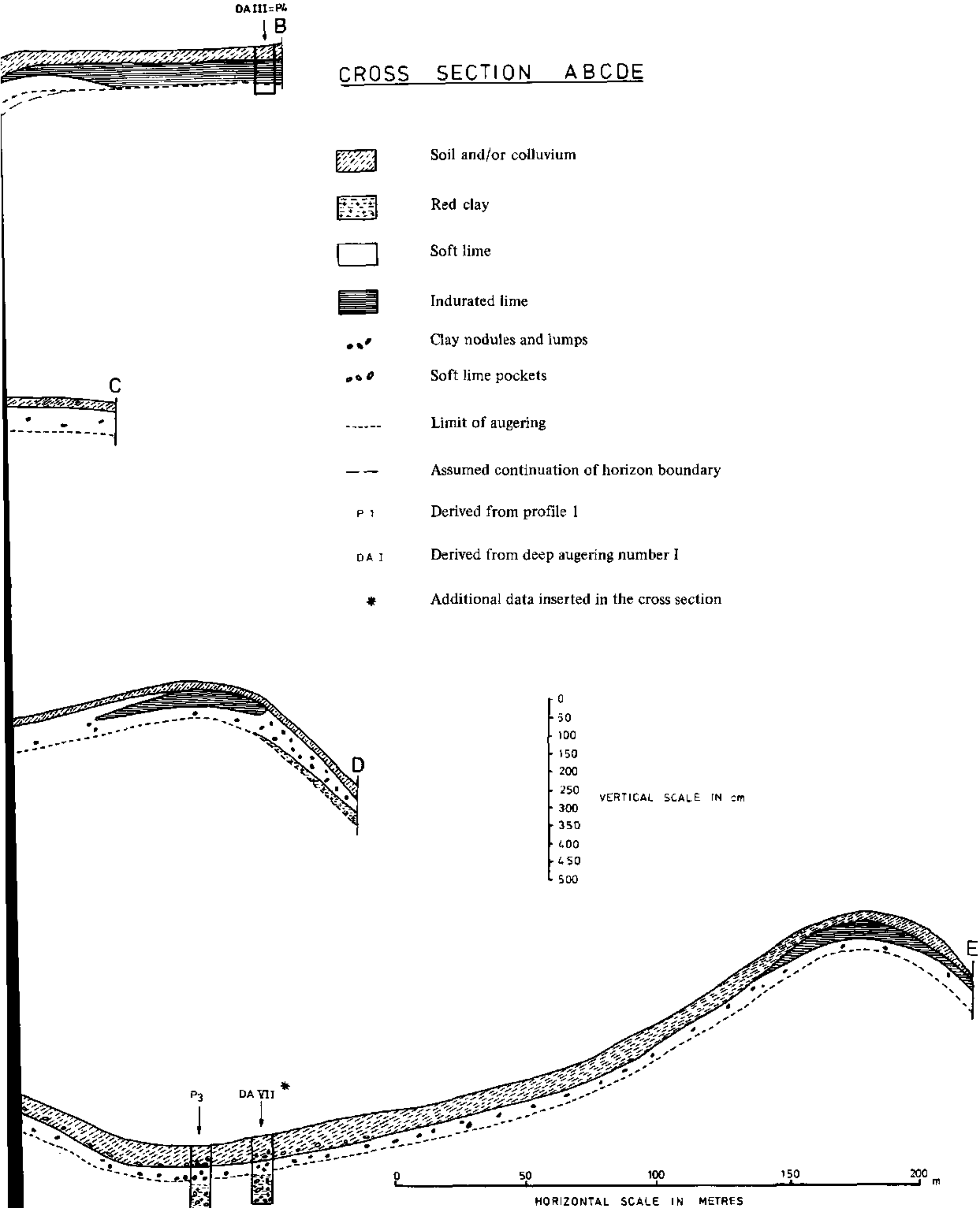


Fig. 10. Cross section AE of the Miocene clay landtype. The location is indicated in Fig. 3 and Fig. 4. The cross section was redrawn after an original published by Jung (1974) and Rao (1975) at a modified scale. Additional information was inserted. Further explanation is found in the text.



DA III=P4
B
CROSS SECTION ABCDE
Soil and/or colluvium
Red clay
Soft lime
Indurated lime
Clay nodules and lumps
Soft lime pockets
Limit of augering
Assumed continuation of horizon boundary
P 1 Derived from profile 1
DA I Derived from deep augering number I
* Additional data inserted in the cross section
C
D
0
50
100
150
200
250
300
350
400
450
500
VERTICAL SCALE IN cm
E
P3
DA VII *
0
50
100
150
200 m
HORIZONTAL SCALE IN METRES

4.3.2 Discussion

4.3.2.1 The 'high soils'

The profiles Riola 1 and Arroyo 1 of which the descriptions are reported here, are discussed in detail. Similar profiles (Arroyo 3 and P4) were studied to check the validity of the conclusions on Riola 1 and Arroyo 1.

The horizon nomenclature of these profiles should reflect the genetic history of the soils. As such the nomenclature is different from the one used by the original authors. The main process of the B horizon is considered to be the carbonate accumulation, while clay illuviation, as evident from the micromorphology (Section 4.5.1.2) is considered important in its lower part.

Texture. All samples are relatively fine textured, but some variations in silt and clay content do occur. Since dispersion problems cannot be ruled out in these highly calcareous soils, it is not clear how much importance should be given to these differences. The lowest samples of the profiles are either clay or silty clay. Variations in texture of the original Miocene clay are also reported for deep auger samples in which even silty and fine sandy layers occur. The various kinds of clay bodies encased in the calcic and petrocalcic horizons show a similar variation in silt and clay content. Sand content is low in all samples. The content of both fine and coarse sand shows a tendency to increase towards the surface. Surface soils are somewhat coarser textured than the underlying Miocene clay for both profiles reported.

Calcium carbonate equivalent. The lime content of the profiles is high. Calcic and petrocalcic horizons have a content of over 80 %. The underlying Miocene clay is non-calcareous in the interior of its structural elements. The same holds true for the clay nodules and lumps encased in the calcic and petrocalcic horizons. Whatever calcium carbonate is found in these samples is probably derived from a filling of small cracks. Surface soils do have a rather high lime content.

pH. The pH (H_2O) measured in most samples is most likely related to the high lime contents reported. The pH of a solution open to the atmosphere in equilibrium with a solid phase of $CaCO_3$ is 8.3. Higher values probably indicate that insufficient time was allowed to reach this equilibrium. Lower pH values could be due to buffering by organic matter. The lower pH of some clay nodules is probably related to their lack of lime.

Organic carbon percentage. The organic carbon content of the horizons of profile Arroyo 1 shows rather high values in the surface soil. The values decrease regularly with depth being less than 0.2 % below 55 cm.

X-ray diffraction of the clay fraction. The profiles are very similar in clay mineralogy. Smectite and palygorskite both are present in important quantities throughout the profiles. Palygorskite seems to have its maximum concentration in the calcic horizon, and smectite in the deep sub-soil. This can indicate that palygorskite forms in the calcic horizon possibly at the expense of smectite. The palygorskite (named attapulgite in Jayaraman's data) is commonly reported as a neoformation in calcic horizons (Ruellan, 1970; Scholz, 1972; Nahon & Ruellan, 1975; Redondo, 1975; Gras, 1975; Mathieu et al., 1975; Watts, 1980). The fact that a small decrease in palygorskite in the surface soils is evident could mean that this mineral is unstable in environments with a lower lime content. (This matter will be discussed in more detail in the paragraph on clay mineralogy of the 'low profiles', in Section 4.3.2.2.) Whether all the palygorskite is a neoformation in the calcic horizons or is at least partially inherited from the parent material is not established. The deepest samples of Profile Arroyo 1 still show considerable amounts of lime derived from crack fills, admixed so that the palygorskite present in these samples could just as well be formed under the influence of the lime, or be inherited from the parent material. The swell and shrink behaviour of the soil materials can probably be attributed entirely to the smectite present. Kaolinite is present in small to very small amounts in Profile Arroyo 1 and as traces only in Profile Riola 1. Vermiculite, chlorite and mixed layer minerals are reported as very small amounts or traces in some samples of Profile Arroyo 1 only. These differences can be indicative of minor variations in the Miocene parent materials. Taking into account, however, that data are compared from two different laboratories about concentrations close to the limit of detectability, not much weight should be given to this. The same applies to the minor differences in the amount of quartz reported. Tobermorite reported for some layers of Profile Riola 1 refers to a calcium silicate that could have formed locally in the calcic horizon. The peaks from which this was concluded, 0.115 nm and 0.610 nm, could well be indicative, however, of mixed layer minerals similar to those identified in Profile Arroyo 1.

4.3.2.2 The 'low soils'

Profile P3 = E18 of which the description is reported here is discussed in detail. Similar profiles (P1, P2 and Arroyo 2) were studied to check the validity of the conclusions.

The soils of the depressions and valley bottoms have the following properties in common: They are heavy textured and show vertic characteristics. All are colluvial in nature in the surface soil. In the closed depressions the colluvial layer is over 1 m thick, while this material measures around 70 cm in the valleys. The darker colluvium overlies red clays similar to the ones underlying the 'high soils' of the plateau. Locally, sandy arkose-like layers are encountered at a depth of some metres. All soils have calcic horizons mostly of the discontinuous soft type.

Texture. The colluvial materials are all fine textured. The underlying red clay shows clay contents which are somewhat higher. There is a clear difference in both fine and coarse sand content between the colluvial layers and the underlying clay.

Calcium carbonate equivalent. The colluvial materials are calcareous but their

$CaCO_3$ contents are rather low. The transition towards the red clay shows higher carbonate contents and qualifies generally as a discontinuous soft calcic horizon. The colluvial layers show some small petrocalcic fragments which do not show up in the lime content, since they do not form part of the fine earth fraction.

pH. The values measured in H_2O generally have a tendency to increase with depth. Nowhere do they reach the pH of 8.3, however. As such they remain lower than those measured in the 'high soils'. The values depend on the $CaCO_3$ content and organic matter content. They can be shown to have a strong positive correlation with the lime content and a strong negative correlation with the C %. As such the high organic matter content and the low $CaCO_3$ content of the colluvial layers probably account for their lower pH values.

Organic carbon percentage. This is relatively high in the colluvial materials, considering the climate of the area. It decreases with depth and reaches levels generally below 0.2 % in the red clay. Profile P2 forms an exception. It shows an unexpectedly high C % in the sub-soil which does not match with its other characteristics such as colour, pH etc. It is considered to be accidental.

Electrical conductivity of the saturation extract of these soils shows values which indicate non-saline soils.

Gypsum was tested in Profile E18 and was shown to be absent in all horizons.

Exchange capacity and bases on the complex. The cation exchange capacity is expressed per 100 g soil; as such the low values for the samples of the lower horizons can be attributed to the high lime content of these samples. If the CEC is computed per 100 g clay, correcting for lime content and deducting the contribution of the organic matter at a rate of 4.5 mmol exchange equivalents per g C, only a small variation is found between the different horizons of the profile. The values vary in this case from a maximum of 81 mmol/100 g clay for the top soil to 65 mmol/100 g clay for some of the calcic horizons. These values seem to be in good agreement with the clay mineral suite of the material. The main cation on the complex is Ca, while a small percentage is taken up by Mg. Monovalent cations occur in negligible quantities. The total of the exchangeable cations is slightly in excess of the values found for the CEC. This is probably due to the dissolution of free lime despite the fact that the extractions were carried out with a solution buffered at pH 8.2. The base saturation is consequently reported as 100 %.

X-ray diffraction of the clay fraction. The profile shows a clear distinction between the colluvial top with smectite as the dominant clay mineral and the red clay present in the underlying calcic horizons in which palygorskite and smectite are about equally important. This is also reflected in the swell and shrink behaviour and the CEC of the corresponding profile parts. Small quantities or traces of kaolinite are present throughout the profile. Quartz varies from traces to clearly identifiable quantities. In the surface soil some traces of 'illite' were identified possibly related to K-fertilisation which caused collapse of 2 : 1 minerals. The same relationship observed in the 'high soils' seems to apply here too: Palygorskite accompanies the presence of large quantities of lime. It either forms the weathering product of the parent material in the presence of lime or is inherited from it. Bigham et al. (1980) state that palygorskite can be expected to precipitate together with calcite in an environment relatively low in Mg while sepiolite will be the precipitate in the presence of dolomite at higher Mg levels. Watts (1980) treats the formation of palygorskite in calcretes in detail. He mentions, for calcretes from South Africa, two modes of formation: neoformation after or during calcite precipitation and transformation from montmorillonite under uptake of Mg. The smectite that dominates in the upper colluvial layers seems to be, at least partially, a product of pedogenesis at or near the surface. Its formation probably continued during the transport phase and after the deposition of the colluvium, since it is present in quantities higher than those observed in the upper part of the 'high soils' which are presumed to have been the source of the colluvial materials. Palygorskite is present as traces only in the colluvial materials. It probably did not resist the weathering conditions that persisted in these materials. Bigham et al. (1980) consider palygorskite a metastable mineral which is degraded and ultimately destroyed by sufficiently intense pedogenesis. In one case they found evidence that discrete smectite is forming from the weathering products of palygorskite. Considering the qualitative character of the X-ray diffraction analyses, the Miocene parent materials in the sub-soils of both 'high' and 'low' profiles could well be identical.

4.4 CROSS SECTION

The cross section (Fig. 10) was redrawn after an original published by Jung (1974) and Rao (1975). Additional field information was inserted, which led to slight modifications. Both horizontal and vertical scales were changed by means of an HP 9845B desk top computer to which a plotter was attached. The original cross section was based on augerings to depths of 100-120 cm at 6 m intervals between A and B and at 12 m intervals between B and E. Some deep augerings were inserted too. The surface configuration of the cross section was based on measurements with a tacheometer.

The cross section represents the materials encountered in four classes:

- soil and/or colluvium (with or without soft lime pockets and clay nodules),
- red clay (with or without soft lime pockets),
- soft lime (with or without clay nodules and lumps),
- indurated lime.

The red clay of the parent material is distinguished from the soil materials and colluvia on the basis of colour. The soil materials and colluvia vary in moist colour from yellowish brown and dark yellowish brown to yellowish red. The moist colours of the clay vary from light red to red, dark red and dusky red.

In the transition zone between soil or colluvium and the underlying materials, red clay nodules may be found embedded in the soil matrix. They seem to form the parent material from which the overlying soils weather. When encountered in a relatively fresh and easily recognisable state they are indicated in the cross section. In the cross section no indication is made of clay nodules embedded in the petrocalcic horizon, nor of loose petrocalcic fragments present in the colluvial material. The lime in the cross section was distinguished in the augerings on the basis of its colour, reaction and consistency.

The distinctions made in the cross section are for the larger part based on visual estimates of the proportion of the different constituents in the auger samples. Especially the estimates on the relative proportions of lime and clay or soil are important since the distinction between soft lime (with clay nodules) and clay or soil (with lime pockets) depends on it, the former implying that lime forms a continuous phase and the latter implying that soil or clay forms a continuous phase. Auger observations have certain limitations for this determination, since apart from the volume ratio, the distribution pattern must also be known before one can decide which of the two components forms a continuous phase.

By studying the data contained in the descriptions of the profiles and deep augerings, it can be concluded that Jung (1974) and Rao (1975) fixed their limit somewhat arbitrarily at approximately 50 % by volume. If the bulk density data of lime and clay (Section 4.6) are taken into consideration, this coincides with 50 % lime by weight up to a depth of about 120 cm and with about 65 % lime by weight at a depth of 250 cm (due to compaction).

Horizons with considerably less than 50 % lime by volume can still be considered as continuous soft calcic horizons provided the lime occupies the void system. It is indeed frequently found in samples that lime from the void system dusts all non-calcitic constituents. Taking this into account it seems that the criterion of 50 % lime by volume could be lowered to 30 or 40 % by volume for those cases where the lime occupies the void system. Nevertheless, in order to maintain uniformity of criteria, the 50% norm was used when inserting the additional deep augerings DA VII and DA VIII and the corrected Profile P5 (= B18). Additionally it may be mentioned that this norm coincides reasonably well with lime contents reported as common by Ruellan (1970) for 'encroûtements' which according to Table 2 are the equivalent of continuous soft calcic horizons in this publication.

To sum up, it is stated that the layers identified in the cross section as lime correspond to continuous soft calcic horizons while the soil and clay layers with lime pockets generally correspond with discontinuous soft calcic horizons.

The following general conclusions are drawn with regard to calcic horizons (Fig. 10):

1. The continuous soft calcic horizon seems to extend laterally across almost the whole area.

2. Gradual transitions occur laterally between the different types of calcic horizons.

3. In all places where the lower boundary of the continuous soft calcic horizon is

observed, the transition towards the underlying clay occurs via a discontinuous soft calcic horizon.

4. In the depressions the continuous soft calcic horizon lies deeper below the surface than in the rest of the landscape.

5. In the depressions the continuous soft calcic horizon is overlain by a discontinuous soft calcic horizon.

6. In the depressions the continuous soft calcic horizon contains more clay nodules than elsewhere.

7. In the high positions the upper part of the continuous soft calcic horizon merges into a petrocalcic horizon only where a relatively steep slope is nearby. This takes place along the rims of the plateaus next to the deeper dissections and on isolated high ridges.

The only exceptions to these rules are formed by the depression of DA VI, the small hummock between DA IV and P3 and by the area around DA VIII. For DA VI lime pockets occupying between 30 and 40 % of the volume of the horizon are reported between 190 cm and 320 cm. As such there is only a gradual and no principle difference between the calcic horizon of this depression and those of the surrounding area. The small hummock between DA IV and P3 has much more in common with the bottom of the surrounding depression than with the higher plateaus, since no petrocalcic horizon is present and since its continuous soft calcic horizon is overlain by a discontinuous soft calcic horizon. Deep augering DA VIII shows that the apparent lack of a continuous soft calcic horizon in this part of the cross section indicated by Jung (1974) and Rao (1975) is incorrect. In reality Profile DA VIII shows that even two layers (100-140 cm and 190-210 cm) qualify for continuous soft calcic horizons, if the 50 % lime by volume criterion is applied.

Comparing the aforementioned conclusions 1-7 with those mentioned in Section 2.3 taken from the literature, the following is evident: For the whole cross section with the exception of the valley bottoms, the horizon sequence is a normal one. To all these cases one can apply the rule: *'When in a profile the lime content increases with depth, the boundaries are abrupt or clear. When in a profile the lime content decreases with depth, the boundaries are normally gradual or diffuse.'*

The valley bottoms seem to be an exception, since here the lime accumulations first increase and then decrease gradually with increasing depth. The profile of the valley bottom in Section AB suggests a splitting up of the continuous soft calcic horizon into two such horizons, in the lower slope. The upper one changes into a discontinuous soft calcic horizon towards the middle of the depression while the lower one remains continuous under the whole depression. This interpretation of the available data is shown by the dashed lines in Fig. 10. A similar tendency to split up is also evident in DA VII and DA VIII. In other valley profiles such a split up into two continuous soft calcic horizons is not evident. It is probably more correct in those cases to assume that towards most valley bottoms the thick continuous soft calcic horizon splits up into a discontinuous upper one and a continuous lower one.

4.5 MICROMORPHOLOGY

4.5.1 Description of the 'high soils' with petrocalcic horizons

Micromorphological data are available for three profiles of these soils from Jayaraman (1974) and Roy (1974): Riola 1 and Arroyo 1 (both Petrocalcic Xerochrepts) and Arroyo 3 (Calcixerollic Xerochrept), indicated as Sites 1, 2 and 4 respectively on the landscape map (Fig. 3). Additional samples of the petrocalcic and calcic horizons of Arroyo 1 have been collected for this particular study. Data obtained from these samples are indicated by 'o.s.' (own sample). Of the calcic horizon both undisturbed and disturbed samples were collected; see also Section 4.6.1.1 and Figs. 15 and 16. The data are presented separately for:

- Petrocalcic horizon.
- Calcic horizon with clay nodules including its lower transition: the 'striped zone'.
- The underlying red Miocene clay.

The phenomena observed are treated in groups according to processes and morphology.

4.5.1.1 Petrocalcic horizon

The thin sections show a great variety of calcitic materials. Zones with a monotonous crystic fabric (pseudospar as defined by Bathurst, 1971) alternate with zones of a crypto-crystalline nature (clotted micrite), brecciated zones of apparently recemented fragments and concentric features. Occasionally clay nodules are enclosed.

Dissolution phenomena of the lime. Calcite crystals with diffuse edges are reported. Zones of uniform coarse crystic fabric showed dissolution phenomena along voids in the form of crystals with frayed edges (o.s.). The frayed edges can be distinguished from growths on the crystal by the fact that they show extinction in polarised light parallel to the rest of the crystal (Fig. 11).

Recrystallisation phenomena of lime. Clay nodules are reported to show a calcite coating. Voids with extensive lublinite (calcite needle fibres) formations are indicative of in situ formation (o.s.). Cracks filled in by more recent carbonates are reported. It is not clear, however, whether local recrystallisation or mechanical redistribution prior to the hardening of the petrocalcic horizon is the cause.

Brecciation. Zones are found which consist of angular fragments of microcrystalline calcite, which have a fabric different from that of the surrounding calcite (o.s.).

Non-calcitic components (clasts and clay bodies). Few quartz grains are found dispersed or 'floating' in the calcite matrix of the brecciated fragments. More commonly they are found in the clay nodules. Some of the quartz grains show an etched and pitted surface which could be indicative of chemical dissolution (o.s.). The clay of the clay nodules may be locally subject to dissolution too. The calcite crystals

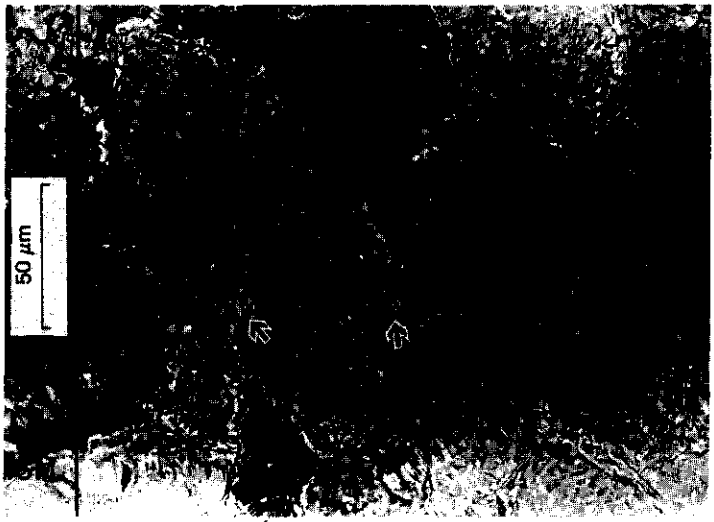


Fig. 11. Dissolution phenomena in the coarse crystic fabric of the calcite that makes up an important part of the petrocalcic horizon of Profile Arroyo 1 at a depth of approximately 10 cm below the top of this horizon. The arrows indicate frayed edges of the calcite crystals along the voids. Photograph taken with crossed polarisers. (Pseudospar in the terminology of Bathurst, 1971.) (Photo courtesy of ISM.)

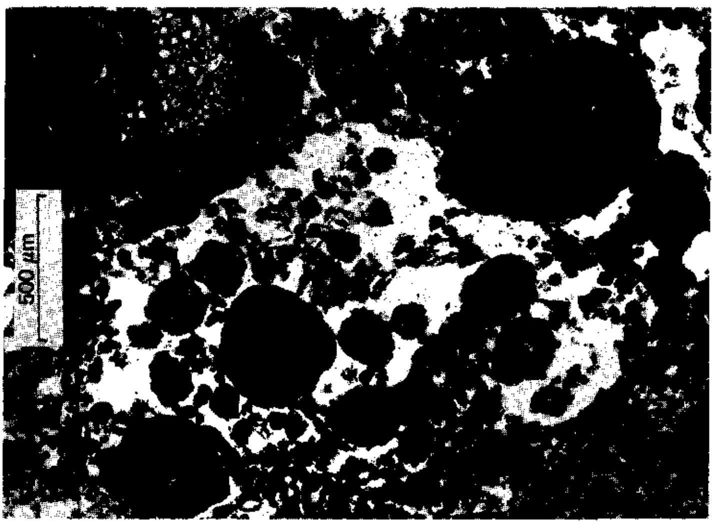


Fig. 12. Diagenetic oöids from the upper part of the petrocalcic horizon of Profile Arroyo 1. The concentric structure is clearly visible in some of them. They consist of calcite and clay. Photograph made in normal light. Photo courtesy ISM.

surrounding the clay nodules, however, do not show any preferred orientation relative to the nodules and boundaries are razor-sharp.

Cutans of non-calcitic materials. Mangans are reported to occur in the pores encountered in the encased clay nodules. A few voids in the laminated top of the horizon show chalcedans (o.s.).

Laminar features. Several layers which can be differentiated on the basis of the grain size of the enclosed clasts and clay nodules are reported. Bands differing in type of calcic fabric and colour were seen (o.s.).

Concentric features. Layers of sub-spherical sand-size carbonate particles consisting of concentric laminae of $CaCO_3$ surrounding a nucleus of different material are reported as oölithic layers. Similar phenomena, which included clay in the concentric laminae (o.s.), were seen (Fig. 12). Spherulites as defined by Brewer (1976) can also be observed locally in the laminae (o.s.).

Pores. 'Worm burrows' which confine themselves to bands in the upper part of the horizon are reported. Similar features were found in the angular fragments of the brecciated layer (o.s.).

4.5.1.2 The calcic horizon with clay nodules including its lower transition: the 'striped zone'

The material consists mainly of uniform, well developed, silt-sized, calcite crystals (pseudospar as defined by Bathurst, 1971), randomly oriented and forming a course crystic fabric. The material encases clay nodules of various sizes. There is evidence of dislocation in the form of shear planes, especially in the 'striped zone'. Locally the calcite grains are bound together into sand-sized elements (o.s.).

Recrystallisation phenomena of lime. Recrystallised lime, finely dispersed in the matrix having accumulated in pores, cracks and root channels is reported for the upper part of the horizon. Lublinite (calcite needle fibres) is present especially in Profile Arroyo 1. In disturbed samples of the calcite sprinkled in Canada balsam (Fig. 16) it is found that the silt-sized calcite crystals are commonly covered by micrite (o.s.). These growths confine themselves to the upper reaches of the soft calcic horizon directly underlying the petrocalcic horizon (o.s.). Similar phenomena are also reported by Jayaraman (1974). A secondary calcite coating along the walls of cracks in clay nodules is reported. Impregnation of the edges of these clay bodies is also mentioned.

Evidence of mechanical disturbance. Along the edges of clay lumps different orientation of clay is observed. Dislocation and uneven distribution of different types of calcite is reported. Linear features which locally show evidence of shearing in the form of crushed crystals (Figs. 13 and 14) are indicative of mechanical disturbance (o.s.). Orientation of the main axis of calcite crystals along slickensides was seen locally.

Non-calcitic components. Most of the quartz grains which occur are found in the

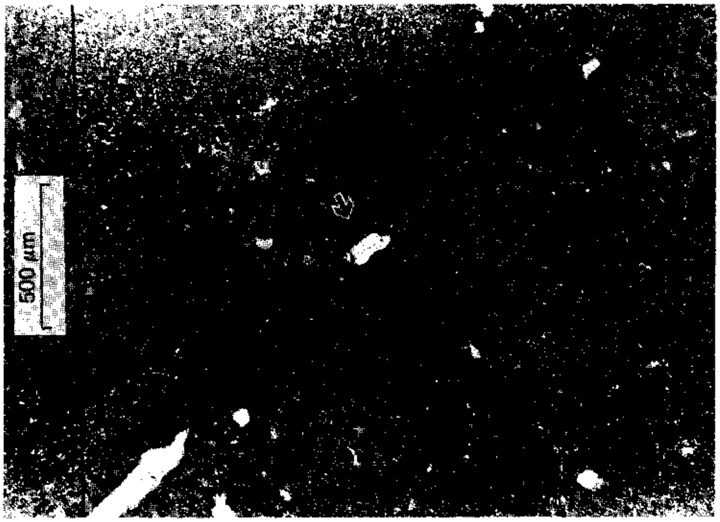


Fig. 13. Shear plane or slickenside in the soft calcic material of the 'striped' transition zone of Profile Arroyo 1 at a depth of 260 cm. The slickenside is visible as a dark line that connects several voids. The arrow indicates a quartz grain trapped in the shear plane. The photograph was taken in normal light. Photo courtesy ISM.

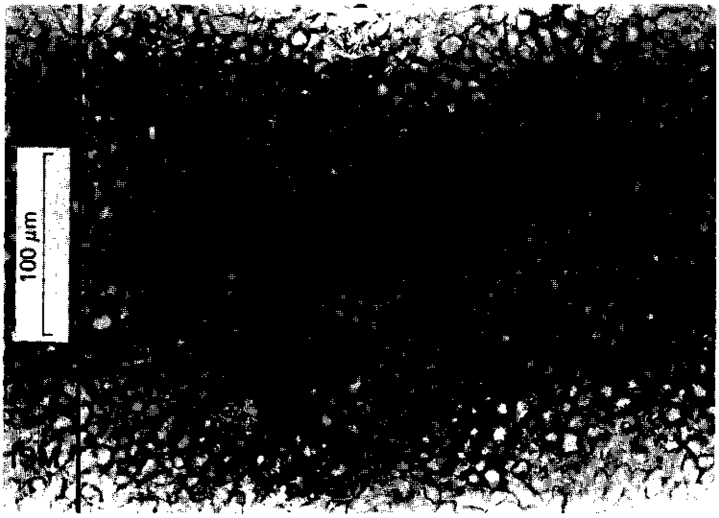


Fig. 14. Detail from Fig. 13, showing a quartz grain (white arrow in Fig. 13) trapped in a shear plane. Several calcite crystals appear to have been crushed against the quartz grain due to differential movement along the plane. Photograph taken in normal light. Photo courtesy ISM.

clay nodules, while only a few are contained in the lime. They do not show clear signs of pitting. Dissolution can not be excluded, but if present it is much weaker than in the petrocalcic horizon.

Cutans. Flecked striated ferri-argillans which are medium thick and sometimes disrupted are reported to occur in cracks and root channels of the calcitic matrix. The clay nodules and lumps show mangans along root channels and pores and ferri-argillans along cracks, while remnants of ferri-argillans, ferrans and mangans are found integrated in their matrix.

Animal activity. 'Animal burrows' are found in the calcic horizon of Profile Arroyo 3 only.

Other features. Brown impregnations, probably of iron, are found locally in the calcic horizon (o.s.). Limited amounts of clay appear as streaks pressed into the slickensides of the lime.

4.5.1.3 The underlying red Miocene clay

The main part of the material is made up of dense clayey substances.

Evidence of mechanical disturbance. Isolated calcite crystal concentrations are reported along ped boundaries. A large number of cracks is found. The matrix is reported to consist of compacted clayey material.

Non-calcitic components. Abundant quartz grains are present in the clay matrix.

Cutans. Yellowish red ferri-argillans are reported as common along the cracks in combination with mangans and clay cutans at the ped boundaries.

4.5.2 Description of the 'low soils' with colluvial influence

Of the 'low soils' representative of the valleys and depressions data are available from four profiles: Arroyo 2, P1, P2 and P3 (identical to E18), all of which classify as Typic Chromoxererts. They are all situated in cross section AE with the exception of Profile Arroyo 2 which occupies Site 3 on the map (Fig. 3). All four profiles, which consist of a colluvial upper layer and an apparently local lower layer, are subdivided for the description into three zones:

- The surface soil.
- The B horizon of the colluvial zone together with its transition towards the underlying in situ horizon.
- The IIC horizon in local weathering products of Miocene sediments.

4.5.2.1 The surface soil

The thin sections of the surface soil have a uniform appearance. Finely divided organic matter is distributed throughout the mineral material. This homogeneous distribution is probably due to animal activity while churning may also have played a role. Stress induced plasmic fabrics are common, especially around embedded quartz grains.

4.5.2.2 The B horizon of the colluvial zone together with its transition towards the underlying residual horizon

This horizon has a very heterogeneous aspect. The colluvial material shows a variety of contrasting enclosures: petrocalcic fragments (pedorelicts), pockets of soft lime many of which are superficially hardened due to lime redistribution and, especially in the transition zone, red clay masses of various sizes and shapes.

Organic matter is present, mostly in finely divided form throughout the matrix, locally it is confined to animal burrows.

Stress features. Features related to pressure vary from moderately developed birefringent plasmic fabrics to clear stress features along cleavage lines, drag phenomena and intersecting slickensides.

Evidence of clay illuviation. Few clay skins occur along large cracks. Part of them seem to have been destroyed, since some papules are present too. Most cutans observed in these horizons may be due to local clay redistribution and not to illuviation sensu stricto.

Animal activity. Clear signs of animal activity are present in the form of channels in some of which lublinite (calcite needle fibres) is present.

Petrocalcic fragments of both rounded and sub-angular form and of different sizes are always coated by laminae of apparently recrystallised lime. Some of the fragments are entirely laminated and some enclose discoloured clay masses. In one case 'oölithic grains' are seen in a fragment.

Pockets of soft lime occur in all profiles. They are mostly ringed by layers of fine, probably recrystallised, lime which may also penetrate in channels. As enclosures, specks and small bodies of red clay are encountered.

Red clay bodies, often more or less rounded in shape, occur varying in size from 100 μm to 5 mm. They are especially common in the lower part of the B horizon. Some carry concentric rings of $CaCO_3$. They are partially discoloured and some show neomangans.

Evidence of mechanical disturbance. The lower part of the B horizon of Profile P3 (= E18) shows evidence of mechanical disturbance, probably the result of swelling and shrinking of the clay. A very contrasting mixture of red and discoloured clay with calcite is found. The materials, though intricately mixed, show sharp boundaries.

4.5.2.3 The IIC horizon in local weathering products of Miocene sediments

The material is a compact non-porous red clay with enclosures of calcite, some discolouration and stress features. Petrocalcic fragments (pedorelicts according to

Brewer's 1976 terminology) are absent.

Stress features are common in the IIC of all three profiles. Pressure features, locally striated extinction patterns of the clay, shear planes and 'micro-tectonics' are reported. Extensive cracking occurs. Along the cracks redistribution of calcite and gley phenomena in the form of discoloured clay are evident. 'Flow' of calcite around stable lumps of red clay and of red clay in calcite is reported.

Evidence if clay illuviation. In two profiles some evidence of clay illuviation is found in the form of cutans in large cracks. Papules are not present.

Animal activity. Indications are found in P3 only.

Lime pockets are present in the form of masses consisting of crystalline lime which alternate with red clay. Specks of red clay are found as inclusions in these lime masses.

Red clay bodies occur which can be distinguished from the surrounding red clay matrix by the fact that they are surrounded by calcite (clay lumps).

Gley phenomena are common. Discoloured clay with sharp boundaries along cracks has been mentioned already. Redistribution of iron and manganese is evident. Impregnations in the form of neomangans are common.

4.5.3 Discussion

4.5.3.1 The 'high soils' with petrocalcic horizons

Dissolution and recrystallisation processes of lime are apparently still active in the upper part of the soil. This indicates that the petrocalcic horizon is formed by chemical redistribution of lime in the originally soft calcic horizon. Additional evidence for this is found in the gradual transition of the petrocalcic horizon to the underlying soft calcic horizon. This gradual transition is consistent with the fact that the chemical redistribution processes decrease in intensity with depth. This last fact fits with the expected distribution pattern of H_2O and CO_2 in the profile in relation to the surface; both of which substances that are essential for the chemical redistribution of lime.

The following features present in the petrocalcic horizon are mentioned by Jayaraman (1974) as proof of this layer's sedimentary origin: laminar features, concentric features and worm burrows. All these forms, however, are described in the literature (Sections 2.2.1 and 2.2.2) as common to petrocalcic horizons in general and as products of pedogenetic processes.

Laminar features The laminae can be seen with the naked eye in polished sections of the upper petrocalcic horizon. They do not show the habitus of sedimentary layers since they undulate and since they often surround objects. Lower down in the petrocalcic horizons, the laminae have the character of fibres which interweave and anastomose.

Concentric features The 'oölithic grains' are strikingly similar to phenomena that both Siesser (1973) and James (1972) describe as formations that originate in the petrocalcic horizon by pedogenetic processes. Siesser in particular takes great pains to prove that any other origin must be excluded. Hay & Wiggins (1980) report for a petrocalcic horizon near Wickieup, Arizona, the following: 'Most of the laminar layers are overlain by a layer of oöids between 1 and 5 cm thick. The laminar and overlying oölithic layers parallel the hillslopes, cutting across the near horizontal bedding in the alluvium.' They claim that the rounding of the oölithes which contain some opal and occasionally some sepiolite, is due to surface tensions of gels from these materials, which caused a thinning of the coating over the angular corners of the enclosed nuclei when the concentric layers were deposited. Hay & Reeder (1978) claim that oölithic textures can be formed due to replacement of clay coatings around sand grains by micrite. From the aforementioned data the conclusion can be drawn that the phenomena described in the petrocalcic horizons of the Mérida region would rather qualify for diagenetic oöids as defined by Siesser (1973).

'Worm' burrows James (1972) has published microphotographs of a pattern of circular tubes in a petrocalcic horizon that is very similar to the one described as worm burrows by Jayaraman (1974). Only a difference in size is noticeable. James's data are derived from a sample taken at exactly the same position: a few centimetres below the top of a petrocalcic horizon. He offers proof that these tubes are the product of the activity of boring algae.

Drawing on the abovementioned evidence it must be concluded that the features are more likely to be proof of a pedogenetic origin of the petrocalcic horizon than of a geogenetic origin. It is admitted that the subject of marine oöids versus diagenetic oöids is a controversial one in the literature and one could possibly quote other publications that proclaim these features as exclusively sedimentary. The latter conclusion would not, however, mean that the present petrocalcic horizon has to be considered a geogenetic feature. Rather the oölithes would in that case be considered as lithorelicts (as defined by Brewer, 1976).

Dissolution of non-calcitic constituents occurs, but only on a limited scale. It seems to be restricted to the petrocalcic horizon, where solution phenomena of quartz grains together with probable products of this process, chalcedans, are found.

Dissolution, in the sense of destruction of clay, cannot be ruled out but is difficult to prove. Boundaries between clay and lime are always razor-sharp. In the case of replacement of clay by lime one would expect transition zones and specific orientation of lime along the contact. None of these are observed, however.

In the horizon that forms the transition between soft lime and the underlying red clay, the 'smearing out' of small clay nodules trapped in shear planes is evident. It is conceivable that the clay, spread out thinly in the lime matrix, tends to disperse. As such it may form the source of clay for the argillans in the underlying horizon.

The fact that the clay nodules contained in the petrocalcic horizon have lack of lime and presence of remnants of mangans in common with the underlying clay indicates that they descend from this clay.

It must be stressed that the petrocalcic horizon seems to be too impermeable to allow large amounts of water to percolate into the deeper calcic horizons and the underlying clay, while the groundwater table is too low to moisten these zones from below. As such, gley phenomena, stress features due to swell and shrink of clay and clay illuviation, are considered as fossil in the layers underlying the petrocalcic horizon. The fact that they have been well preserved can be proof that the hardening of the petrocalcic horizon is a relatively recent phenomenon.

4.5.3.2 The 'low soils' with colluvial influence

That colluvial material originates from the 'high soils' can be derived from the fact that it contains petrocalcic fragments which are very similar to the petrocalcic horizon described for the 'high soils' (lamination and in one case an 'oölithic structure'). These are different from the hard rounded lime fragments lower down in the profile which have probably formed locally by concentric hardening of soft lime pockets subjected to some pedoturbation (disorthic nodules as defined by Wieder & Yaalon, 1974).

Clay illuviation is very weak in the colluvial layer. It is probably counteracted by the vertic processes which are evident in all three profiles studied of the 'low soils'.

Recrystallisation phenomena of lime, such as rings of lime around objects, are better expressed at greater depths in these soils than in the 'high soils'. This is probably due to the higher organic matter content of the colluvial material which is the source for CO_2. The drainage condition undoubtedly also plays a role, since these soils are subject to seasonal variations in moisture content.

4.5.3.3 Comparison of 'high' and 'low' soils

The red clay underlying the valley bottoms is similar to the red clay underlying the 'high soils'. They have the following features in common: stress features, gley phenomena (manganese impregnations), lime distribution, clay nodules in the formative stage and to a lesser extent argillans.

Similar to these in the 'high soils', clay nodules found in the transition zone between the colluvial material and the Miocene materials, have several features in common with the red clay deeper in the C horizon.

A difference between the red clay of the 'low' and the 'high' soils is found in the fact that most processes are still active in the 'low' soils whereas they are no longer active in the lower horizons of the 'high' soils.

4.6 ADDITIONAL DETERMINATIONS ON LIME AND CLAY SAMPLES DRAWN

The object of these determinations was to collect more detailed information on the properties of materials that make up the soft calcic horizons: the lime and the clay nodules. For this purpose the investigations were mainly concentrated on the site of Profile Arroyo 1. Here both lime and clay nodules were sampled at various depths. Undisturbed ring samples were taken of the lime, while the clay nodules could be sampled in undisturbed form without such precautions.

Undisturbed ring samples of lime were also taken from other sites indicated on the map (Fig. 3). The purpose of this sampling was to establish whether extrapolation of the findings of the Arroyo 1 site was justified.

In the sampling of the lime, care was taken to select pure lime samples avoiding concentrations of clay nodules. This was successful in the Arroyo 1 soil but in the other soils contamination with clay could not be avoided. Strong contamination of the lime by finely divided clay aggregates made extrapolation of the data measured for pure lime difficult.

The following properties were measured (methodology in Section 4.2) on the ring samples of the lime:

- $CaCO_3$ percentage,
- liquid limit: LL,
- bulk density: BD (dry),
- percentage of water-stable aggregates of a diameter of less than 50 μm,
- average equivalent size of the calcite crystals.

For the clay nodules the following properties were measured:

- bulk density: BD (dry) and BD (sat.)$^{+}$,
- coefficient of linear extensibility: COLE (sat.).

4.6.1 The lime samples

4.6.1.1 Results

In Table 7 the results are given of the aforementioned determinations. All experiments were carried out on the same ring samples. Bulk density was measured from the ring samples after drying. The content of the rings was then divided into one sample for $CaCO_3$ determination, one sample for calcite crystal-size and one sample for the determination of the liquid limit. Of the last sample, the part not used for the experiment was wet-sieved for stable aggregates, while wet consistency was determined on the portion from which the moisture percentage at liquid limit was determined.

Table 7. Properties of samples from soft calcic horizons. Ring samples were drawn at various depths at Site 2 and at Sites 5, 6 and 7. The following properties were determined: $CaCO_3$ %, liquid limit (LL), bulk density in dry condition (BD dry), percentage stable aggregates larger than 50 μm (st. agg. % > 50 μm), equivalent size of the calcite crystals (eq. size c.cr.) and wet consistency (wet cons.). The latter property is expressed in terms of plasticity and stickyness by the letters: N for Non, S for Sticky and P for Plastic. The methodology of these determinations is given in Section 4.2. The location of the sample sites is indicated in Fig. 3.

Sample number	Origin	Depth cm	$CaCO_3$ %	LL	BD (dry) g/cm^3	St. agg. % (> 50 μm)	Eq. size c.cr. (μm)	Wet cons.
107	Site 2, Arroyo 1	80	93.2	45	1.18	62.4	45	NS, NP
114		80	92.1	33	1.32	83.0	45	NS, NP
115		80	90.1	36	1.19	71.0	40	NS, NP
106	Site 2, Arroyo 1	120	93.6	26	1.40	25.0	30	NS, NP
98		120	92.8	36	1.40	17.9	45	NS, SP
99		120	87.6	37	1.18	34.4	40	NS, NP
100	Site 2, Arroyo 1	180	94.1	27	1.38	41.8	40	NS, NP
116		180	96.7	23	1.65	12.4	30	NS, NP
101		180	86.5	26	1.42	21.5	40	NS, NP
108		180	88.8	30	1.39	43.2	40	NS, NP
109	Site 2, Arroyo 1	260	95.6	23	1.56	11.9	25	NS, NP
118		260	97.7	17	1.70	29.9	25	NS, NP
117		260	95.8	24	1.69	10.2	20	NS, SP
110		260	96.6	25	1.86	29.0	25	NS, NP
103	Site 6 (Fig. 42) both at		77.0	35	1.36	36.3	5	S, P
111	130 cm		75.2	36	1.33	41.0	5	S, P
105	20 cm over stone line of		59.8	30	1.38	n.d.	15	SS, SP
97	20 cm under small gully of		63.0	42	1.47	n.d.	40	SS, SP
113	10 cm under Site nr. 7 (Fig. 44)		89.7	23	1.53	17.1	40	NS, SP
120	120 cm below surface of a		82.0	47	1.00	37.9	20	NS, SP
112	80 cm petrocalcic horizon of Site 7		70.3	55	1.06	57.6	25	NS, SP
104	10 cm under the top of cal-		46.4	44	1.39	40.1	n.d.	NS, SP-P
119	cic horizon of Site 5 (Fig. 35)		42.7	42	1.31	62.3	n.d.	SS, SP

4.6.1.2 Discussion

$CaCO_3$ percentage All the measured contents are high and all samples with the possible exception of those from Site 5 are drawn from horizons that qualify for continuous soft calcic horizons. The data from Arroyo 1 show the highest percentages which increase slightly with depth. This increase does not signify that clay nodules are more rare deeper in the profile, since the samples were drawn in such a way that clay nodules were avoided. In the samples from Guareña (Site 7) this was not possible. The lower lime contents of these samples are due to the inclusion of clay nodules. The samples from the other sites owe their low lime contents to small clay aggregates which occur dispersed throughout the lime mass.

Liquid limit (LL) The liquid limits determined are generally low. They decrease with depth in the Arroyo 1 profile and become remarkably low in the deepest horizon. The materials of the lowest horizons qualify in terms of the Bureau of Reclamation (1974) as 'quicksilt', a highly unstable material. It was found during the determinations that the pure lime samples changed rather abruptly from the solid to the liquid state, while samples contaminated by finely divided clay did not show such an abrupt change. A strong decrease in the volume of the dry lime powder was noted upon wetting.

These observations indicate that the crystalline character of the lime is the main cause for this behaviour. Upon wetting the calcite crystals tend to adhere to each other by means of very thin films of water between their crystal facets. The films are very thin if the crystals are clean and perfect in shape (Fig. 15). This explains why the deepest samples of Profile Arroyo 1 showed liquid limits as low as 17. Apparently that water content was sufficient to lubricate the crystals in order to allow them to move relative to each other when subjected to shocks. Strong deformations of objects formed from the lime at this water content are not possible, however, without breaking them, as is evident from the non-plastic consistency of the samples. The non-sticky consistency indicates that the lime grains adhere strongly to each other.

Higher liquid limits were measured for samples from the upper part of the calcic horizon of Profile Arroyo 1. This is probably due to the fact that the calcite crystals here are coated with small growths of micrite (Fig. 16), which prevent a perfect fit of the crystal facets. Higher liquid limits for clay contaminated samples are probably due to the same phenomenon: the clay particles prevent a perfect fit of the crystal facets. These liquid limits are to be considered as non-representative of the lime in its natural state, in which pure lime contains relatively large fragments of clay. The mixing of the material prior to the determination of the liquid limit caused the contamination of the calcite crystals by clay particles.

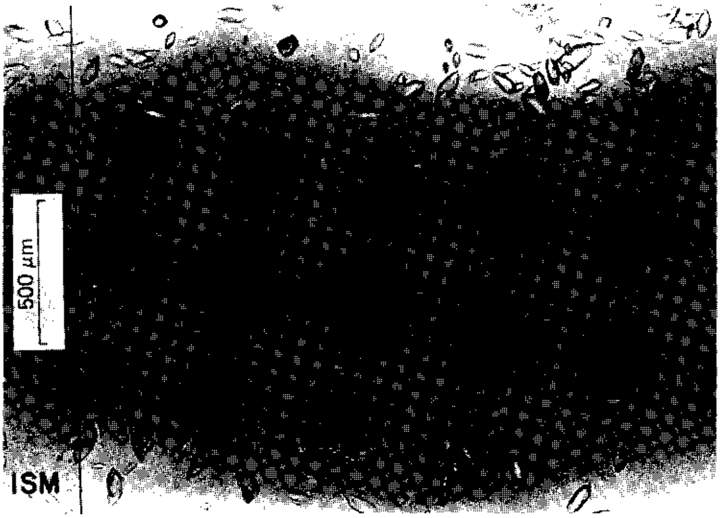


Fig. 15. Uniform silt-sized calcite crystals make up the material of the lime 'stripes' of Profile Arroyo 1 at a depth of 180 cm. The lime was loosely sprinkled into Canada balsam. The photograph was taken in normal light. Photo courtesy ISM.

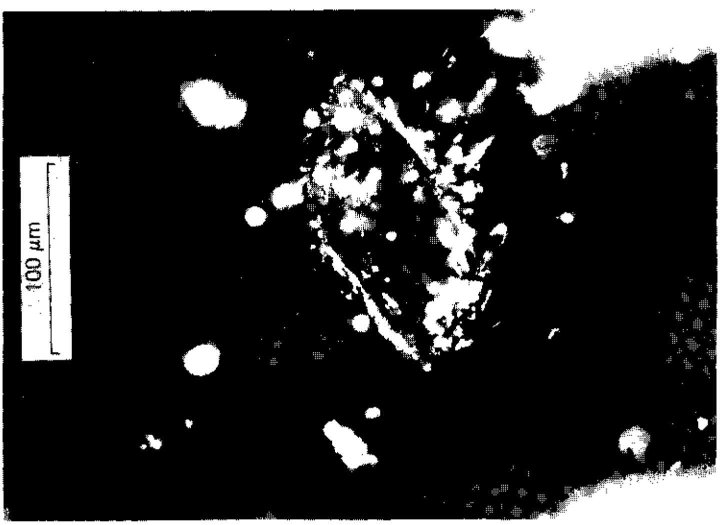


Fig. 16. Silt-sized calcite crystal from the soft calcic horizon of Profile Arroyo 1 at a depth of 80 cm. The crystal is covered by growths of secondary calcite. The photograph was taken from a sample of lime that was loosely sprinkled in Canada balsam. Polarised light shows the calcite grain half extinguished while the micrite growths light up. Photo courtesy ISM.

Bulk density [BD (dry)] The bulk densities increase with depth in Profile Arroyo 1. They vary from 1.18 g/cm^3 to 1.86 g/cm^3. If the non-calcitic minerals are considered to have the same specific weight as lime, pore volumes of 56 % and 31 % respectively are computed for these samples on the basis of a specific weight of calcite of 2.710 g/cm^3 (Weast, 1974). If this pore space is filled entirely with water, bulk densities of 1.74 g/cm^3 and 2.17 g/cm^3 respectively result for BD (sat.)$^+$. These correspond with moisture contents of 47 % and 17% by weight respectively. The generally lower values of the bulk density for the samples from the other profiles are at least partially due to inclusion of clay.

Percentage of water-stable aggregates Of the samples used for the determination of the liquid limit, which according to ASTM (1954) norms had been sieved over a 420 µm sieve, the remains were wet-sieved over a 50 µm sieve in order to separate the single calcite crystals from the lime aggregates. This limit was chosen on the basis of the dimension of the components derived from microscopic observation. The procedure adopted (20 minutes wet-sieving under moderately intense vibration) led in most cases to a clear effluent. Only clay-rich samples with dispersion problems may not have been separated completely (the samples which are sticky and plastic). The content of water-stable lime aggregates shows a clear decrease with depth in Profile Arroyo 1. This squares with the microscopic observation that aggregates consisting of silt-sized calcite crystals bound by small (micrite) crystals decrease in number with depth in the Arroyo 1 profile.

Average equivalent size of the calcite crystals In the loosely sprinkled samples measurements were made on a number of discrete calcite crystals. The aggregates were observed but not counted. Since the lime was rather uniform a range for a limited number of crystals was established. The long and short axes of each crystal were measured. The ratio of the long and the short axis varies from 1.7 to 2.6. No relation is found between this property and any other property of the lime. On average a ratio of 2.25 is found for the Arroyo 1 profile. This implies that these are 'bladed crystals' in the terminology of Folk (1965) (Fig. 15).

All crystals are assumed to consist of low Mg-calcite. No staining tests were done since X-ray diffraction of samples 98, 101, 103, 104, 112, 114 and 117 showed a total absence of dolomite.

For the computation of the equivalent average size of the calcite crystals the average of the mean of the long and short axis was calculated for a limited number of crystals. This means that crystals with an equivalent diameter of 50 µm will pass through a 50 µm sieve if vibration puts their long axis perpendicular to this sieve.

The data show that all crystals fit in the silt fraction and that their size tends to decrease with depth in Profile Arroyo 1. The silt fraction seems to be a common size category for lime in the soil. Meester (1971 and 1973) reports the size fraction of the lime of a number of profiles from Konya, Turkey as fine silt (mainly

2-8 μm). Abedi & Talibudeen (1974) found that silt-sized carbonate was more common in the upper horizon of the older soils of a catena that they studied in Azerbaijan-Iran, while clay-sized carbonate was more common in the upper horizon of younger soils. Massoud (1973) reports large amounts of lime in the silt fraction of sandy clay loam surface soils of the Nile delta in Egypt. Netterberg (1980) publishes data on the particle-size distributions of some 'powder calcretes' of South and South-West Africa. The majority of his samples consist for the major part of the silt and fine sand fraction. This material is normally indicated by the term sparite in carbonate petrology. In undisturbed samples the grains form a (mostly coarse) crystic fabric in the terminology of Brewer (1976). The grain size coincides with the one for vadose silt as mentioned by Blatt et al. (1972). Micrite growths (Fig. 16) are observed on crystals from the upper horizons of the profile only, as reported in Section 4.5.1.2.

4.6.1.3 Correlation

Table 8 shows the product moment correlation coefficients calculated between the different properties of the samples of Profile Arroyo 1 and their relation with depth. Computation of a correlation coefficient for the properties of all the lime samples reported in Table 8 is considered to be superfluous due to the fact that the sampling was not accomplished according to uniform criteria. Moreover the parameters measured are expected to be influenced by different factors in the different profiles, which makes correlation tests meaningless. The significance was verified by performing a two-sided t test on the correlation coefficient.

With the exception of the relation between $CaCO_3$ % and the liquid limit and $CaCO_3$ % and % stable aggregates, all combinations produce correlation coefficients that either qualify as probably significant ($P < 5$ %) or significant ($P < 1$ %). This does not mean, however, that these 'correlations' indicate direct causal relationships.

It is remarkable that all five properties relate to depth. Depth cannot be considered a characteristic of the samples proper, as such no direct causal relationship between depth and any of the properties can exist. A 'correlation' between a property and depth means that a relation exists between that property and one or more pedogenetic processes which increase or decrease in intensity with depth. The following relationships can be indicated:

- Increase of bulk density with depth is mainly due to increase in compaction proportional to the increase in overburden.
- A decrease in the percentage of water-stable aggregates with depth reflects a decrease in intensity of the chemical redistribution of lime which depends in turn on the distribution of CO_2 and H_2O relative to the surface of the profile.
- The crystal size of the lime is also related either to past or present distribution patterns of these two substances, or to other pedogenetic processes that have depth-dependent intensities.

Table 8. Correlation between five properties of 14 lime samples from Profile Arroyo 1 and their correlation with depth. The properties are listed in Table 7. The symbols in the matrix have the following meaning: n = number of observations, r = correlation coefficient, t = Student's t value, P = probability level of error when concluding that the correlation is significant, expressed as a percentage (two-sided distribution).

	$CaCO_3$ %	LL	BD (dry)	St. agg. % > 50 µm	Eq. size c. cr.	Depth
$CaCO_3$ %		n = 14 r = -0.52 t = 2.09 not sign.	n = 14 r = 0.71 t = 3.53 P < 1%	n = 14 r = -0.32 t = 1.17 not sign.	n = 14 r = -0.67 t = 3.13 P < 1%	n = 14 r = 0.54 t = 2.21 P < 5%
LL			n = 14 r = -0.81 t = 4.79 P < 1%	n = 14 r = 0.59 t = 2.56 P < 5%	n = 14 r = 0.79 t = 4.42 P < 1%	n = 14 r = -0.82 t = 4.94 P < 1%
BD (dry)				n = 14 r = -0.62 t = 2.72 P < 2%	n = 14 r = -0.83 t = 5.09 P < 1%	n = 14 r = 0.87 t = 6.13 P < 1%
St. agg. % > 50 µm					n = 14 r = 0.63 t = 2.83 P < 2%	n = 14 r = -0.68 t = 3.19 P < 1%
Eq. size c. cr.						n = 14 r = -0.83 t = 5.23 P < 1%

- It is amazing that the correlation coefficient found for the relation between $CaCO_3$ content and depth is not higher. It is also unclear why the highest lime contents are not found in the top instead of the bottom of the soft calcic horizon. This is strange since micromorphological evidence suggests that the aggregation c.q. the receipt of lime is strongest in the top of the horizon.
- The liquid limit reflects the effect of the aforementioned properties, all of which relate to depth. As such it is normal to find a relation between liquid limit and depth.

The mutual relationships found between the 5 properties reflect in part the relation which each of them has individually with depth. If the data had been acquired in an experiment in which each could be varied under controlled conditions, to measure its effect on the others, analysis of variance would have been the tool to unravel their mutual relationships. In the present set-up this is not indicated due to the 'design of the experiment' as performed by nature. Under the present conditions in which no variables can be specified as dependent or independent, partial correlation methods which measure interdependence only, are indicated (Snedecor &

Cochran, 1974). This approach is justified if the assumption holds true that any variable has a linear regression on the other variables or on any sub-set of them, with deviations that are normally distributed.

The partial correlation coefficient between two variables, each of which is correlated with a third variable, can be computed if the simple correlation coefficients between all three are known. The partial correlation coefficient measures that part of the correlation between the two variables that is not simply a reflection of their relation with the third variable.

When the mutual relations between the five properties of the lime are thus purified of the 'depth effect', we find that only one significant correlation is left, namely the one between bulk density and $CaCO_3$ content! For all other 'correlations' it is concluded that, for the present number of samples, no significant correlation can be proven.

4.6.2 The clay nodule samples

4.6.2.1 Results

For a batch of clay nodules from different depths of the Arroyo 1 profile (Site 2), bulk density, BD (dry) and BD (sat.)$^+$, and coefficient of linear extensibility in

Table 9. Properties of clay nodules from Profile Arroyo 1. Batches of samples were drawn from three different depths. The following properties were determined: bulk density in dry condition - BD (dry), bulk density in saturated condition - BD (sat.)$^+$, and coefficient of linear extensibility in saturated condition - COLE (sat.). The methodology of these determinations is given in Section 4.2.

Sample number	Depth	BD (dry) g/cm^3	BD (sat.)$^+$ g/cm^3	COLE (sat.)
1	100-120 cm	1.33	1.70	0.02
2		1.26	1.62	0.05
3		1.28	1.64	0.05
4		1.29	1.66	0.04
5		1.29	1.66	0.05
1	120-140 cm	1.27	1.65	0.03
2		1.24	1.66	0.03
3		1.28	1.72	0.02
4		1.29	1.67	0.04
1	260 cm	1.37	1.69	0.04
2		1.33	1.66	0.05
3		1.40	1.69	0.05
4		1.37	1.61	0.08

saturated condition, COLE (sat.), were determined (Methodology in Section 4.2). Table 9 summarises the results.

4.6.2.2 Discussion

The range of values of BD (dry) is rather limited. There seems to be a tendency for this property to increase with depth. No such tendency is apparent for the BD (sat.)$^+$ values, which have a narrow range also. For the COLE (sat.) values a larger range is evident. This range extends on either side of the value 0.03 which according to Franzmeier & Ross (1968) separates soils with dominance of smectite from soils in which this clay mineral is not dominant.

4.6.2.3 Correlation

Product moment correlation coefficients were computed in the same way as described for the lime samples. Correlation coefficients were computed for the three properties, mutually, and for all three properties with depth. The t test was performed on the results in order to check the significance of the relationships found. Table 10 summarises the results. A significant positive correlation is found between BD (dry) and depth. As discussed for the lime samples this signifies that this property shows the influence of one or more depth-dependent pedogenetic processes. It is most likely that the increase of bulk density with depth is caused by the proportional increase in overburden with depth. There is a significant negative correlation between BD (sat.)$^+$ and COLE (sat.). This is to be expected since the swelling diminishes the bulk density.

Table 10. Correlation between three properties of clay nodules of Profile Arroyo 1 and their correlation with depth. For the meaning of the symbols see Table 8 and Table 9.

	BD (dry)	BS (sat.)$^+$	COLE (sat.)	Depth
BD (dry)		n = 13 r = 0.19 t = 0.64 not sign.	n = 13 r = 0.42 t = 1.53 not sign.	n = 13 r = 0.83 t = 4.92 P < 1%
BD (sat.)$^+$			n = 13 r = -0.73 t = 3.55 P < 1%	n = 13 r = 0.003 t = 0.011 not sign.
COLE (sat.)				n = 13 r = 0.51 t = 1.96 not sign.

All other correlations turn out to be non-significant. The clue to this lack of correlation may be the wide range in COLE (sat.) values between the different clay nodules regardless of depth. The following factors could be responsible for this (Franzmeier & Ross, 1968): *amount of clay, soil fabric, absorbed cations* and *kind of clay*. Differences in *amount of clay* between individual clay nodules, so large as to account for differences in COLE of up to 400 %, can confidently be excluded. The lack of correlation between BD (dry) and COLE (sat.) indicates that it is improbable that differences in *soil fabric* are to be held responsible either. This leaves differences in *absorbed cations* and in *kind of clay* as possible factors responsible for the difference in swelling behaviour of the clay nodules. A subsequent check on the clay mineralogy of some of the nodules used to determine the properties listed in Table 9 has shown, however, the following. The nodules from a depth of 260 cm are all very similar in clay mineralogy despite the fact that they range in COLE (sat.) from 0.04-0.08. The clay nodules from a depth of 100-120 cm had in general lower smectite and somewhat lower palygorskite contents in comparison to the nodules from 260 cm. The variations in smectite content between the individual clay nodules from a depth of 100-120 cm did not show any relation with the COLE (sat.) values measured either. These findings do not support the claim that clay mineralogy is the cause of the differences in COLE (sat.). This leaves absorbed cations as a last option. Differences in the relative amount of Mg ions present can possibly account for the differences in COLE (sat.) measured. They could also account for some of the differences in clay mineralogy since Mg ions play a role in the transformations of smectite into palygorskite as mentioned in Section 4.3.2.2. No data are available, however, to verify this assumption.

4.7 STABLE ISOTOPE RATIOS FOR THE LIME OF RIOLA 1

Jayaraman (1974) reports on stable isotope analyses carried out on three samples of lime drawn at 80, 200 and 450 cm depth in the Riola 1 profile (Site 1). The results of the determinations (letter from W.G. Mook dated 21-12-1973) are indicated in Table 11.

The results are expressed as the relative difference between the isotope ratio measured and the one of a standard sample: The Peedee belemnite (PDB standard) which

Table 11. Stable isotope ratios for three lime samples from Profile Riola 1.

Sample number	Depth	δ^{13}PDB ($^o/oo$)	δ^{18}PDB ($^o/oo$)
Riola 7372	80 cm	- 8.86	- 3.19
Riola 7373	200 cm	- 8.27	- 2.57
Riola 7374	450 cm	- 9.20	- 3.62

is supposed to represent average marine carbonates. The relative difference is expressed as a $^{0}/oo$. This is done for both the ratios C^{13} (versus C^{12}) and O^{18} (versus O^{16}).

Salomons (1975) and Salomons & Mook (1976) have published a diagram in which they indicate which δ13-δ18 combinations are typical for soil carbonates of the temperate zone. If the values of Riola are plotted in this diagram they fall rather close to the perimeter indicated as typical for soil carbonates. For the Riola samples the δ13 values are about $2^{0}/oo$ higher and the δ18 values are about $5^{0}/oo$ higher.

The δ13 values of CO_2 in soil air upon which the aforementioned diagram is based are not representative, however, for arid areas. The CO_2 of the soil air of arid areas is not depleted in C13, relative to atmospheric CO_2, to such a high degree as the soil CO_2 of the humid temperate zone. The cause of this lies mainly in a different type of photosynthetic cycle of the plants in these areas. This is explained by Salomons et al. (1978). Data on this phenomenon are supplied by Magaritz & Amiel (1980) for CO_2 of Israeli soils. Lower organic matter contents of arid soils must also be taken into account, since this presumably allows for a larger component of atmospheric CO_2 in the soil air of these regions. Considering these facts it can be expected that the δ13 values of the Riola samples are within the range common to soil carbonates in these areas.

Indeed in the literature several δ13 values are found for calcic horizons of dry regions which are similar to those of the Riola samples: Manze & Brunnacker (1977) report about calcic horizons from Algeria which have δ13 values of the same range as the Riola samples. This similarity applies to calcic horizons for which they claim Pliocene age and also for horizons for which they claim old Quaternary age. The authors state that the data refer to soil carbonate and not to groundwater carbonate. Salomons et al. (1978) report on a number of calcrete samples from different parts of the world. From amongst their samples, those from Italy and France show δ13 values very close to those of the Riola samples.

The δ18 values of the Riola samples are, as has been mentioned, relatively high for soil carbonates in general. Manze & Brunnacker (1977) state that the δ18 values of Mediterranean soil carbonates are in general higher than those of Mid-European soil carbonates. The Riola values are still too high, however, if compared to the average isotopic composition of Spanish rainwater as reported by Salomons et al. (1978). This latter value for δ18 is $-4.5^{0}/oo$ which leads to an expected δ18 for soil carbonates of $-4.8^{0}/oo$. Higher values than those expected for soil carbonates indicate in the opinion of Salomons et al. (1978) that the carbonates have not been formed by precipitation from a bicarbonate solution due to loss of CO_2, as is commonly the case, but due to evaporation of this solution. They supply data on another profile in Spain which shows higher δ18 values than are to be expected on the basis of the average rainwater composition and attribute this deviation to the evaporitive genesis of the soil carbonates. They find an argument for this hypothesis in the strong correlation between the δ18 and δ13 values of these carbonates. It is interesting to note that those same values for the Riola samples show a highly significant correlation too. (Product moment correlation coefficient of 0.999!) It should be taken into account, however, that only 3 samples were measured.

If the δ13 values of the carbonate of the parent material are known and the δ13 value of the soil CO_2 is also known, the δ13 of the newly formed carbonates can be computed. On the basis of these data an estimate can be made of the percentage of soil carbonate that has been recrystallised, using a formula published by Salomons & Mook (1976). Unfortunately for the Riola profile, a number of data are lacking. It is interesting, however, to make an estimate of the percentage of recrystallised carbonates in this profile, on the basis of the following assumptions:

- δ13 of the carbonate of the parent material (p.m.) is 0^{o}/oo (ancient marine carbonate).
- δ13 of the CO_2 of the soil is -21^{o}/oo (the value measured as an average for soil CO_2 in Israel by Magaritz & Amiel, 1980).

On the basis of these data it can be computed that for Riola the newly formed soil carbonates will have a δ13 value of approximately -9^{o}/oo. When one introduces these data into the formula of Salomons & Mook (1976), $P = \frac{(\delta 13 \text{ soil} - \delta 13 \text{ p.m.})}{(\delta 13 \text{ new} - \delta 13 \text{ p.m.})} \times 100$, in combination with the δ13 values actually measured, one obtains values for P which vary from 92 % to 102 %.

This means that if the Riola carbonates would originate from ancient marine carbonates in the Miocene clay, they must have been subject to complete recrystallisation.

4.8 MICROPALEONTOLOGY OF THE LIME OF RIOLA 1

Jayaraman (1974) reports on micropaleontological determinations carried out on three samples drawn in the Riola 1 profile pit at depths of 80, 200 and 450 cm respectively. The samples which were studied under a binocular microscope turned out to be entirely sterile. This result makes a sedimentary origin of the lime rather improbable. Marine carbonates without any trace of microfossils are particularly unusual. Complete recrystallisation of a former sediment could possibly also account for the absence of fossils.

4.9 CONCLUSIONS

1. The 'high soils' show a horizon sequence which is entirely pedogenetic in origin since:

a. The chemical and physical characteristics of the materials over and under the calcic horizons are very similar.

b. The calcic horizons are laterally continuous and show gradual transitions of the different types. They bear a distinct relation to the land surface with which they run parallel.

c. The calcic horizon has a stable isotope composition which closely resembles the one of soil carbonates.

d. No fossils were found in the samples studied.

e. The micromorphology of the profiles does not render any evidence for an origin different from pedogenesis.

2. The 'low soils' are very similar to the 'high soils', except for the following:

a. Their upper part consists of a colluvial layer derived from material of the surface of the 'high soils'.

b. The pedogenetic processes which are evident in the 'low soils' are largely active while the same processes are fossile in the 'high soils', with the exception of the redistribution of lime in solution, which is still active in - and directly under - the petrocalcic horizon.

3. On the basis of the material contained in this chapter no conclusion on the origin of the lime is drawn yet.

5 Experiments

The observations on the unusual distribution patterns of lime and clay in the calcic horizons of, e.g., profile Arroyo 1 and Riola 1 as illustrated in the foregoing chapter, have aroused interest in the behaviour of the materials when brought into close contact under natural conditions. Experiments were designed to verify possible movements of clay nodules and other objects, embedded in a soft lime matrix which is subject to periodic wetting and drying. Experiments of a similar nature carried out by Springer (1958) with stones embedded in so-called vesicular desert soil materials have demonstrated such movements. Since displacements, if detectable at all, were supposed to be of a rather low order of magnitude, accurate measurements had to be devised.

Lime samples mainly from profile Arroyo 1 were drawn from different depths, together with clay nodule samples. These clay nodules were embedded together with lead pellets, gravels and petrocalcic fragments in different combinations in the soft lime materials and subjected to cyclic wetting and drying.

Apart from the variation in origin of the lime and the nature of the objects, the following treatments were introduced in the experiments, as summarized in Table 13.

- Grainsize of the lime samples: Various fractions of the lime samples were prepared, by means of dry sieving. The size classes used in the different experiments are mentioned in Table 13.
- Packing of the lime at the initiation of the experiments: In most cases, the lime was given a dense packing by pouring it into water in order to avoid consolidation during the experiment. In one case the lime was inserted in dry state.
- Confining pressure: In one experiment, a pressure was exerted by means of a lead weight on the lime surface during the wetting and drying, in order to simulate the effect of the overburden pressure in the soil.
- Moistening: In most cases the moistening of the material was effected by means of an ascending flow, under slight pressure. In one case the moistening was effected by means of a descending unsaturated flow. The purpose of the ascending form of moistening was to reduce air enclosure, which occurs when moistening is attempted, in a descending mode, by pouring the water on top of the lime surface. For a description of the form of moistening under natural circumstances see Section 5.3.5.

For the registration of the movements, transmittant X-ray techniques were used. (Attempts to record the movements of the objects in a mechanical way, by means of small rods attached to them, failed.) Stereo radiography and photogrammetric techniques were applied to reconstruct the position of the centre of gravity of the various objects with sufficient accuracy. For this purpose the objects had to be marked with small lead cylinders.

The position of the objects was recorded relative to a reference frame, at various stages during the different moist-dry cycles, to which the set-up was subjected. In most experiments, displacements were measured and plotted in graphs against time. The general pattern wat that the objects rose upon wetting and fell upon drying. In several cases this led to a small net gain in height for each cycle and in some other cases to a small net loss. Cases in which the object oscillated around its points of departure were also encountered. Lateral movements of the objects were also evident.

Some additional determinations were made. In one experiment the heave of the lime surface, which became evident during several experiments, was registered by means of a lever. Bulk density of the lime after the termination of this experiment was also determined.

Analyses of the movement pattern, represented in the graphs of the different objects under various conditons, gave an insight into the processes responsible for the movements. Study of the X-ray images, in combination with the bulk density data and the surface-heave data, made more specific conclusions possible.

5.1 SET UP AND EXECUTION OF THE EXPERIMENTS AND MEASUREMENTS

5.1.1 Set up of the experiments

Plexiglass containers about 13 cm x 7 cm x 15 cm in dimension were constructed (Fig. 17). Four cylindrical lead markers were inserted in the front and in the back windows of the containers, such that the square formed by these markers on the back coincided exactly with the projection of the square formed by them on the front. The bottom of the container was covered with a layer of about 5 cm of clean coarse sand, into which a perforated tube was placed, to allow for even moistening during the experiment. Lime was deposited over the sand in a layer of about 9 cm. In most experiments a uniform and dense packing of the lime was attained by first pouring this material into water.

Clay nodules were marked in the following way. Two holes, with a diameter of 2 mm, were drilled approximately perpendicular to each other, intersecting close to the centre of gravity of the clay nodule (Fig. 27). Two small lead cylinders were inserted into each hole. Petrocalcic fragments and stones were marked similarly, by glueing lead markers to their surface according to two perpendicular axes through their centre of gravity.

While the container was being filled with lime, the marked objects were placed in this layer of material, together with some lead pellets.

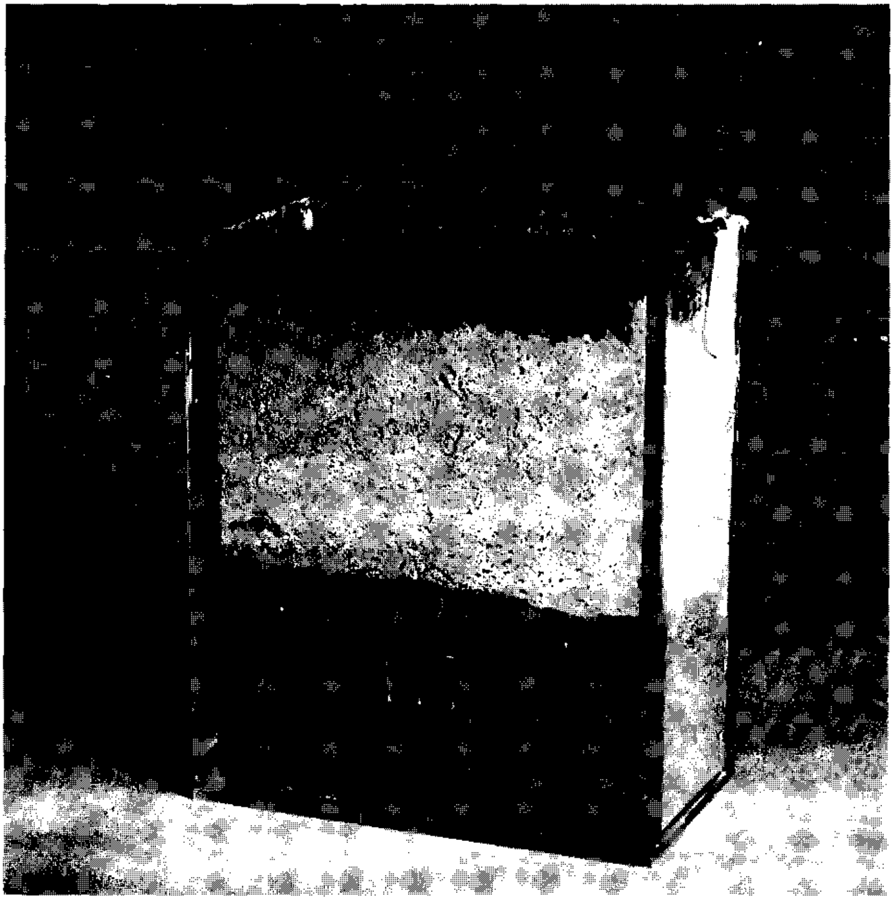


Fig. 17. Rectangular plexiglass container in use for Experiment IIIb. The container is filled with a layer of clean coarse quartz sand into which a perforated tube is stuck. On top of this sand, lime has been poured into which various marked objects are embedded. The lime surface is covered by porous material (ground brick). An arrow indicates a lead marker in the front window reference frame.

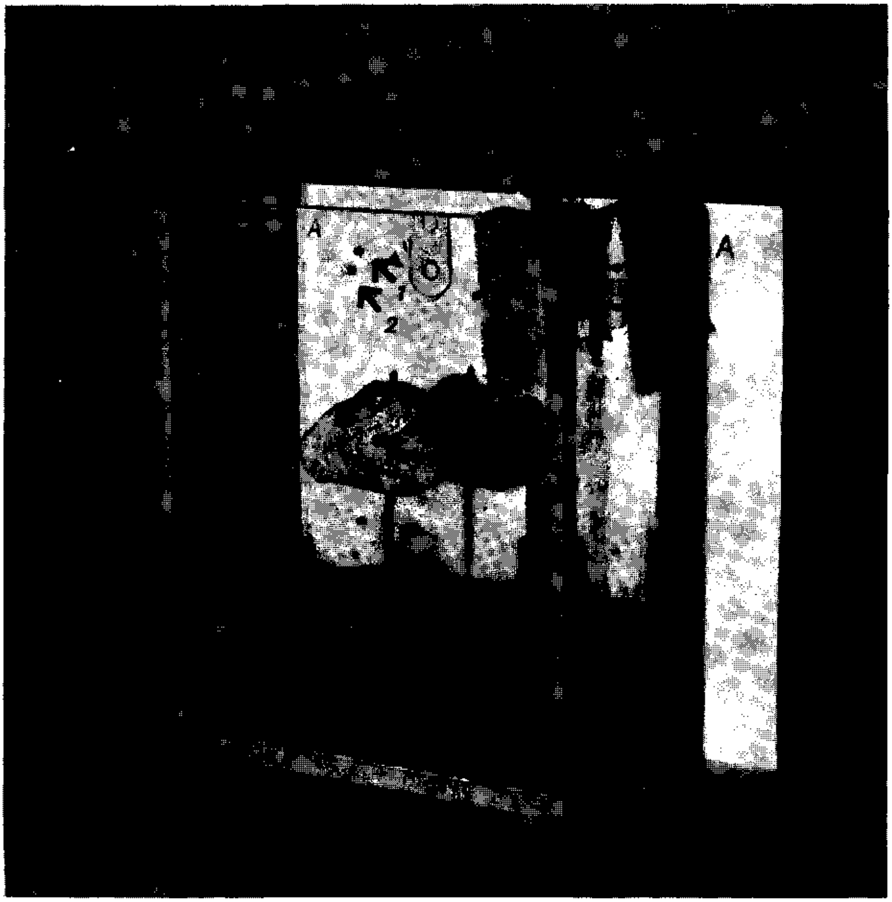


Fig. 18. Mock-up of image formation during radiography, simulated with normal light. For this purpose the lime has been removed and a clay nodule which was embedded in it has been placed on a rod. The film (A) was placed against the back window of the container. The lead markers of the back window are in contact with the film plane (Arrow 1). The shadows of the lead markers of the front window are projected away from the back window markers, due to the divergent character of the X-ray beam (Arrow 2). Fig. 20ab shows how these data are used to reconstruct the true projected positions of the objects.

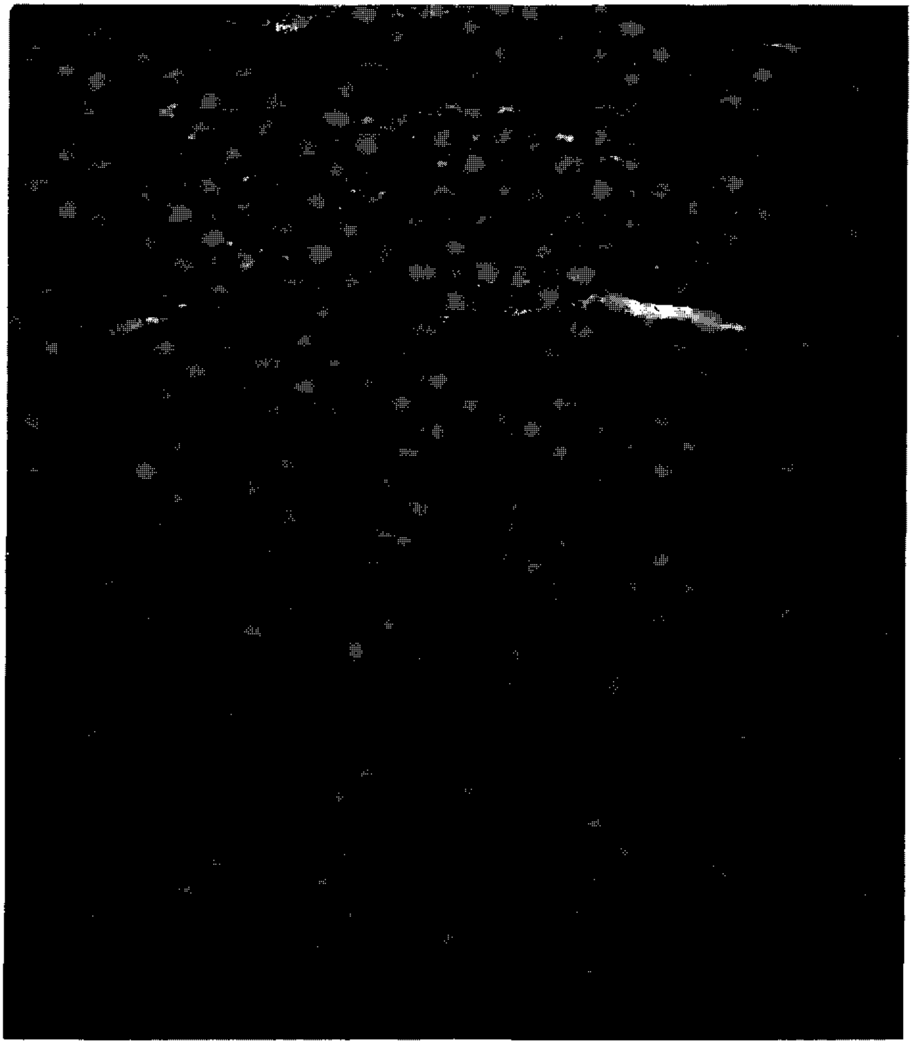


Fig. 19. Dodged print of X-ray image Nr. 577L (left hand photograph of the stereo-pair), representing Experiment II in dry condition at the end of the 11th cycle. The shadows of the back window markers (a, b, c, d) and front window markers (a', b', c', d') allow the construction of the isocentre (Fig. 20ab). The following objects have been marked: CNR = clay nodule right, CNL = clay nodule left, LR = lead pellet right, LL = lead pellet left. The lead markers encrusted in two channels bored through the centres of gravity of the clay nodules are clearly visible and allow the construction of the position of the centre of gravity. The voids around and mainly above the clay nodules, which have shrunken in dry state, are clearly visible. A crack has developed in clay nodule CNL into which lime has penetrated (Fig. 27). A concentration of round air vesicles is visible mainly in the upper part of the lime. Few voids can be seen underneath the clay nodules; they are all planed off in a horizontal direction. The sand surface can be distinguished in the image just underneath the line d'c'.

5.1.2 Registration of the position of the objects

The position of the enclosed objects was recorded during the different stages of the experiments, by means of stereo X-ray photographs. These were made by placing the X-ray film against the back window of the container and exposing the object from the front to radiation (Fig. 18). Table 12 supplies the technical data on the radiography.

The object was encased in lead slabs in order to diminish backscatter. In order to obtain a stereo-effect, the container was moved between exposures over a distance of 10 cm perpendicular to the axis of the cone-shaped X-ray beam. The resulting photos, of which a positive copy is reproduced in Fig. 19, show the lead markers as dark spots due to the absorption of the X-rays by the lead (transparent spots in the original photos and dark spots in the positive copies).

The markers of the back window of the container were in direct contact with the film and as such show no displacement. The markers from the front window and those from the encased objects are displaced due to the divergent character of the X-ray beam (Fig. 18). The displacement would be radial from the centre of the reference square if the photo was taken by aiming the axis of the X-ray beam on this centre. In order to obtain a stereo-effect, however, two photographs were made, a left and a right one. The left hand photograph was taken by exposing the container to the X-rays from a point left of the centre of the reference frame, resulting in a displacement of the shadows of the front window markers and object markers towards the right. This is evident in Fig. 19. The reverse holds true for the right hand photograph.

5.1.3 Reconstruction of the position of the objects

By means of a construction, the true projected position of the objects relative to the markers of the back window could be determined. Fig. 20a shows the construc-

Table 12. Technical data on radiography.

Equipment	Philips-Rotalix
Focal spot	0.3 mm
Potential	100 kV
Current	15 mA
Time	Variable; generally 2 seconds
Distance	50 cm (from focus to film)
Filmtypes	Kodirex and Kodak Definix (both envelope packed)
Dimension of objects	6 cm of lime packed between two walls of perspex 0.5 cm thick

tion of the true projected position of the centre of gravity of a lead pellet (LL), made for X-rays 577 R and L (Photo 577 L is shown in Fig. 19). Fig. 20b shows the construction applied to a clay nodule (CNL) of the same photo-pair.

The following is the description of the construction shown in Fig. 20a: First the intersection i(L) of the centre of the X-ray beam with the film was constructed for the left hand photograph (L). For this purpose, a sheet of transparent material was placed over the photograph, upon which all the markers of front and back windows and of the object were transferred. Intermittent lines were drawn through the markers of the front window a'(L), b'(L), c'(L) and d'(L) and their counterparts of the back window a, b, c and d. The extension of these lines coincided in one point, which is the intersection of the centre of the X-ray beam with the film plane. This point functioned as the isocentre i(L) of the left hand photograph. All displacements in this photograph are radial to this isocentre. Now a line was drawn from this isocentre through the centre of gravity Z1'(L) of lead pellet LL. The tracing was then transferred to the right hand photograph and oriented according to the identical contact points of the back window markers a, b, c and d. Next, the procedure was repeated in an identical way, tracing intermittent lines a'(R)a, b'(R)b, c'(R)c and d'(R)d to find isocentre i(R) from which a line was drawn to the centre of gravity Z1'(R). The projected position of Z1 was found at the intersection of the lines drawn from the isocentres i(L) and i(R) to Z1'(L) and Z1'(R) respectively.

Fig. 20b shows a similar construction, now applied in order to find the true projected position of the centre of gravity (Z2), of clay nodule CNL, of X-ray stereopair 577 RL. Two transparencies with the data copied from the photos were superimposed in order to pool the information. The construction of the isocentres, i(L) and i(R), was identical to that described for Fig. 20a. For the clay nodule, the centre of gravity had to be constructed from the images of the four lead markers (two in each of the two holes drilled through the clay nodule) on both films. For this purpose crosses were drawn through the smaller squares which form the projection of the cylindrical markers. These crosses were connected by lines, which intersect in the points Z2'(R) and Z2'(L), which represent the position of Z2 in the right and left hand image respectively. The true projected position of Z2 was now found at the intersection of the line that connects i(L) and Z2'(L) with the line that connects i(R) and Z2'(R).

This construction is an adaption of a technique called radial triangulation, commonly used in the rectification of aerial photography, see Visser (1968). Stereo radiography applied to soils is described by Bouma (1969), Krinitzky (1970), Rogaar & Boswinkel (1978) and Rogaar (1980).

The construction method employed has a high degree of accuracy for those points that were determined from four other points (centres of gravity of the larger objects), minor discrepancies tended to cancel each other out. From the excellent coincidence of the four lines determining the isocentre and the fact that upon repetition, the construction turned out to be well reproducible, it could be con-

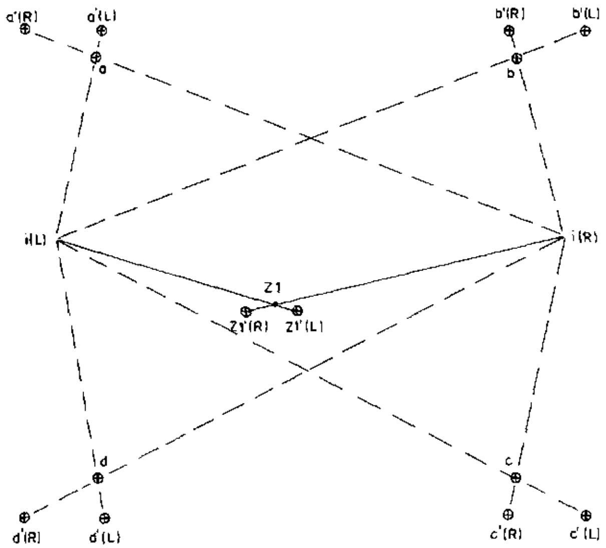


Fig. 20a. Construction of the projected position of Lead pellet LL (Z1) of Stereo-pair 577 LR, of Experiment II, in dry condition at the end of the 11th cycle (see Fig. 19). The explanation of the radial triangulation procedure is in the text.

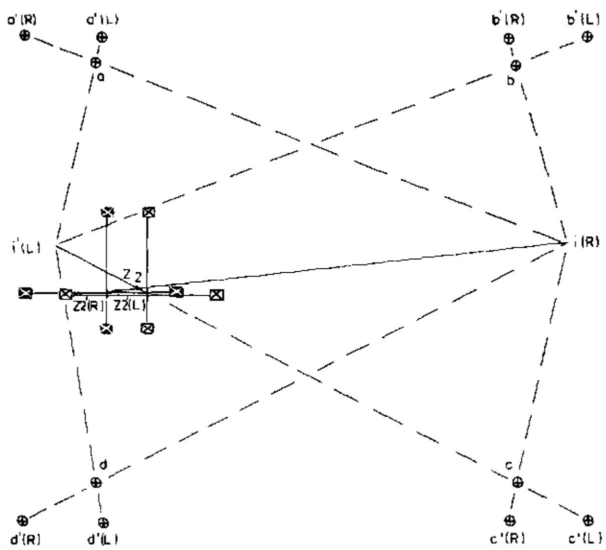


Fig. 20b. Construction of the projected position of Clay nodule CNL (Z2) of Stereo-pair 577 LR, of Experiment II, in dry condition at the end of the 11th cycle (see Fig. 19). The explanation of the radial triangulation procedure is in the text. Solid squares represent the shadows of the markers of the clay nodule in the right hand photo and open squares those in the left hand photo.

Table 13. Summary of experiments and their results. For details of the properties of the material used in this experiment see Table 7, Table 9 and Fig. 15.

Experiment number	Lime fraction	Source	State of the lime at the start	No.	Objects (type)	Upward displacement of object (mm)	Number of cycles	Remarks
Ia	< 2 mm	Arroyo 1 at 260 cm	The lime was inserted in dry state in the container and then wetted	CNR	Clay nodule Arroyo 1, 260 cm	- 2	7	The materials were moistened from the bottom upwards.
				CNL	Clay nodule Arroyo 1, 260 cm	- 1.6		
				LR	Lead pellets	- 2		
				LL		- 2		
II	< 0.5 mm	Arroyo 1 at 60-80 cm	The lime was poured into water in the container on top of the sand	CNR	Clay nodule Arroyo 1, 260 cm	+ 8.2	11	The materials were moistened from the bottom upwards
				CNL	Clay nodule Arroyo 1, 60-80 cm	+ 7		
				LR	Lead pellets	+ 7.2		
				LL		+ 7.1		
IIIa	Total	La Cora 140-175 cm	The lime was poured into water in the container on top of the sand	CNR	Clay nodule Arroyo 1, 260 cm	0	1	The materials were moistened from the bottom upwards. The lime sample was a mixed auger sample drawn 50 m S. from C in cross section AE. It contained a large amount of clay aggregates. The upward displacement has been marked ± since moistening in the second cycle brought the objects back to 0-level.
				CNL	Clay nodule Arroyo 1, 60-80 cm	± 0.4		
				LR	Lead pellets	± 0.5		
				LL		± 0.6		
Ib	< 0.5 mm	Arroyo 1 at 260 cm	The lime was poured into water in the container on top of the sand	CNR	Clay nodule Arroyo 1, 260 cm	0	2	Moistening was carried out by supplying water in unsaturated flow from the top down through a gypsum crust.
				CNL	Clay nodule Arroyo 1, 260 cm	0		
				SM	Raña gravel	0		

IIIb1	< 0.5 mm	Arroyo 1 at 260 cm	The lime was poured into water in the container on top of the sand	CNR	Clay nodule Arroyo 1, 260 cm	+ 4.2	5	The materials were moistened from the bottom upwards.
				SL	Raña gravel	+ 3		
				PM	Petrocalcic fragment Arroyo 1 at 80 cm	+ 5		
IIIb2	< 0.5 mm	Arroyo 1 at 260 cm	The lime was poured into water in the container on top of the sand	CNR	Clay nodule Arroyo 1, 260 cm	- 2.5	4	This was a continuation of Experiment IIIb1, to which a heavy weight was applied on the top.
				SL	Clay nodule Arroyo 1, 260 cm	- 2.5		
				PM	Petrocalcic fragment Arroyo 1 at 80 cm	- 2.5		

cluded, that errors were less than 0.2 mm for recorded movements in a vertical direction. Errors in a horizontal direction were sometimes greater, if the two isocentres fell both close to the line through the objects to be measured. Poor intersections resulted in such cases, which affected the accuracy in a horizontal direction but which did not affect the accuracy of measurement of the rise and fall of the objects in a vertical direction

5.1.4 Execution of the experiments

The experimental set ups were carried through a number of cycles of wetting and drying and photographed intermittently at the different stages. A cycle in these experiments signifies the time interval between the moment of wetting the contents of the container and the moment at which drying of these contents is complete.

Wetting was mostly carried out from the bottom up. Water was added to the sand layer at the bottom of the container. The flow was controlled, in order to avoid an upwelling of water along the tube. In practice this resulted in maintenance of a head that fluctuated between 0 and 10 cm above the sand surface. This resulted in a flow of about 100 cm^3/h. An exception to this treatment was Experiment Ib, which was moistened from the top down by unsaturated flow, through a gypsum crust on the surface. Most containers received about 800 g of dry lime and 400 g of dry sand, to which in total approximately 300 cm^3 water was added in each cycle.

After moistening, the containers were left approximately 1 day. This was followed by a drying period of about 3 weeks in a stove at 50°C. The drying was monitored by means of weighing. In all experiments the containers were handled with care, especially those of which the contents were in a moist state, in order to avoid shocks that could disturb the arrangement of the constituents.

In total 98 X-ray photographs were taken and 48 triangulations were made.

5.2 RESULTS OF THE EXPERIMENTS

Table 13 summarises the experimental conditions and the results in the form of movement registered for the different objects. Additional particulars will be given for those experiments only that deviate from the standard set-up treated in the foregoing section.

5.2.1 Experiment Ia

This experiment, which was carried out with a lime sample from which only the fraction coarser than 2 mm was removed, showed a net downward movement of all the enclosed objects. The experiment deviated from all the others in the fact that no consolidation of lime was undertaken prior to the experiment, by pouring this material into water. The results are shown in graph form in Figs. 21a and 21b.

Fig. 21a was drawn to explain the mode of representation used in Fig. 21b, 22, 23 and 28. It shows the movements of one clay nodule only. The movements of the centre of gravity of clay nodule (CNR) of Experiment Ia are plotted against time, during the first two cycles of this experiment. On the y-axis, the movement in mm is shown on an amplified scale. The x-axis shows the time in days. It can be seen, that the object rose rapidly upon the moistening that initiated the first cycle. It was found at approximately the same level after some drying had taken place and ten days had passed. When drying was complete, after 35 days, at the end of the first cycle, the object had gone down again and was approximately level with the position in which it started. At the moistening that initiated the second cycle, it rose rapidly to about the same height as attained in the first cycle. After ten days of drying of the second cycle had passed, it had lost about half of the height gained at the moistening stage. At the end of the second cycle when drying was complete, the centre of gravity of the clay nodule had fallen below the level occupied at the beginning of the experiment.

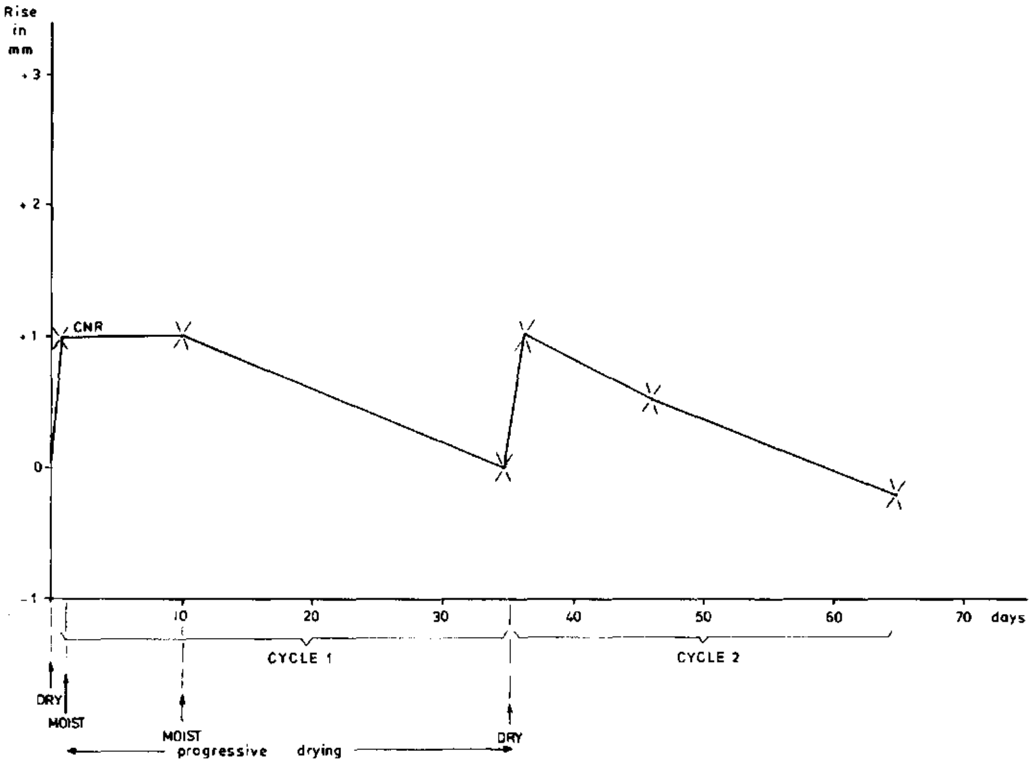


Fig. 21a. The vertical movements of Clay nodule (CNR) of Experiment Ia plotted against time, during the first two cycles of the experiment. As indicated in the figure, a cycle in this case signifies the time interval between the moment at which the moistening of the container starts and the moment at which drying is complete.

In Fig. 21b the movements of all the objects of Experiment Ia are plotted against time. It can be seen that all objects rose upon wetting and fell upon drying. The total extent of this movement was 1-1.5 mm for the clay nodules and about 0.5 mm for the lead pellets. Every cycle showed a small net downward movement. At the end of the second cycle, the right hand clay nodule (CNR), had fallen below its original level. Both lead pellets (LL and LR) were back at zero and the left hand clay nodule (CNL) was still situated at 0.4 mm over its level of departure. After seven cycles, all four objects had fallen below their zero levels, as indicated in Table 13, Column 7.

The X-ray photographs of the dry condition show a narrow void around and especially above the clay nodules. Some cracks in the lime mass show up too. These features disappeared almost completely from the image upon moistening. Vesicles formed during the experiment in the upper part of the lime. These vesicles remained visible in the X-ray photographs taken in a moist condition. It was noted that during this experiment, moistening was somewhat slower than in the other experiments. This

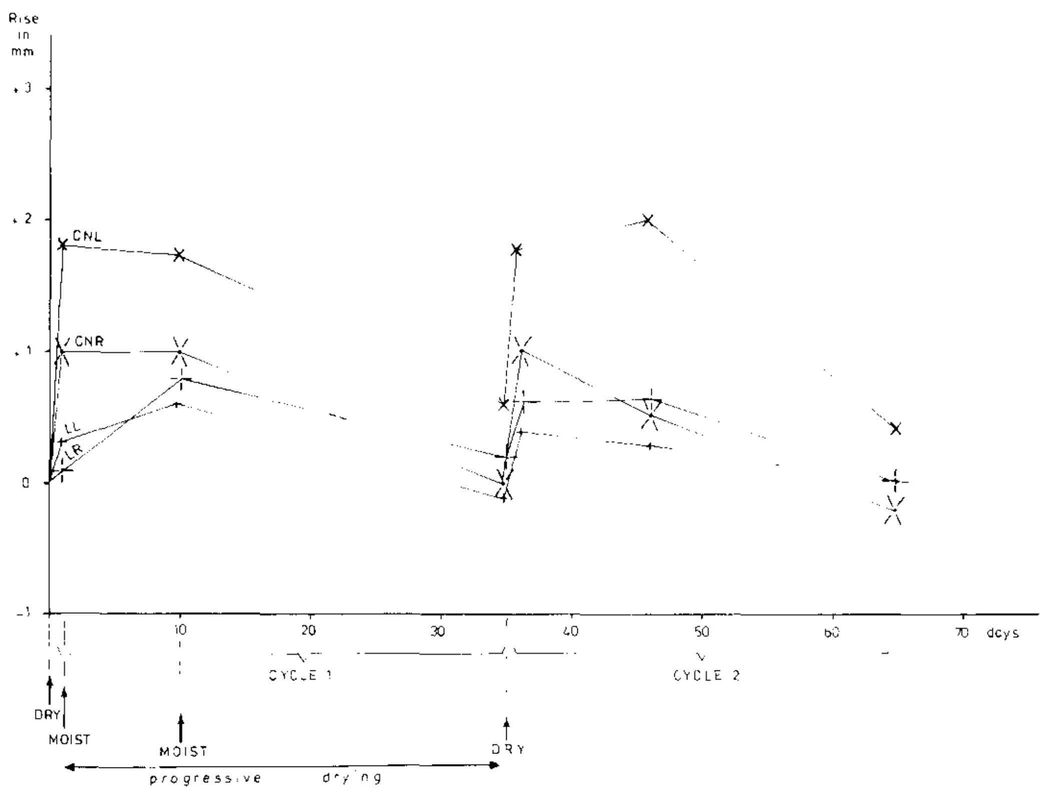


Fig. 21b. The vertical movements of Clay nodules (CNR) and (CNL) and Lead pellets (LL) and (LR) of Experiment Ia, plotted against time, during the first two cycles of the experiment.

was due to the fact that the set-up of Experiment Ia did not include a perforated tube to distribute the water throughout the sand layer. This made the infiltration from the feeder tube directly into the sand, much slower.

5.2.2 Experiment II

In the course of this experiment a net rise of all objects was noted. Fig. 22 shows the positions of all objects in dry condition, at various moments during the experiment, plotted against time. It can be seen that after an initial fast rise, the process stabilized and the average curve becomes almost a straight line. No sign of decline of speed of rise can be observed in the last of the eleven cycles. The effect per cycle seems to vary considerably. Cycle 7 was very effective, whereas Cycle 8 was an ineffective one, but this was followed by some very effective cycles. Differences between objects are present. The performance of clay nodule (CNR) was clearly higher than that of the other objects.

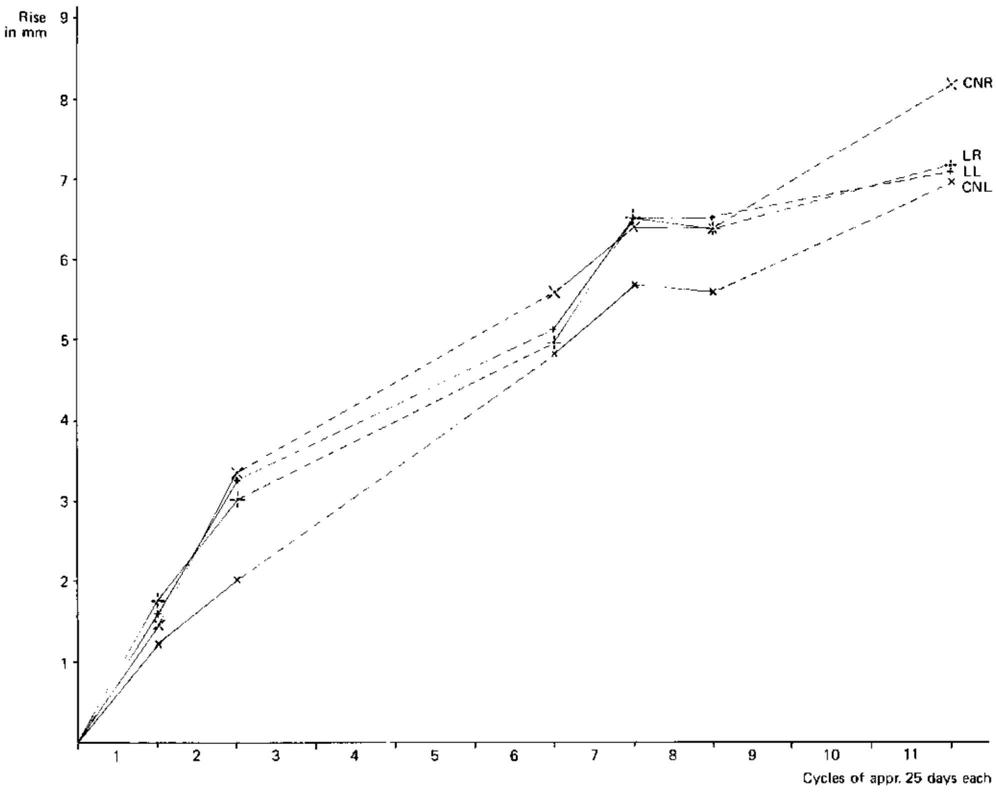


Fig. 22. The vertical movements of the objects of Experiment II, plotted against time during 11 cycles. The observation points are taken in a dry condition. Dotted lines indicate interpolations since X-rays were not taken for each cycle. CNL = clay nodule left, CNR = clay nodule right, LL = lead pellet left, LR = lead pellet right.

In Fig. 23 several observations of the first two cycles in dry, moist and intermediate stages have been plotted against time. The general pattern shows that after moistening, there was a rapid rise of all objects. After this there were minor movements upwards or downwards during the first ten days of the drying cycle. When the drying continued, all objects generally fell, The only difference in the behaviour of clay nodules and lead pellets was, that the amplitude of the movements of the former, was greater.

In comparing the first two cycles of Experiment II (Fig. 23) with those of Experiment Ia (Fig. 21b), it can be seen that apart from the similarity in the general pattern of movements, as mentioned above, an important difference in the behaviour of the objects is evident. The objects of Experiment II show a small net gain in height in each cycle, while the objects of Experiment Ia show a small net loss. The total amplitude of the movements of the objects of II is considerably greater than that of the objects of Ia.

The trajectory of the objects of Experiment II is shown ten times enlarged in

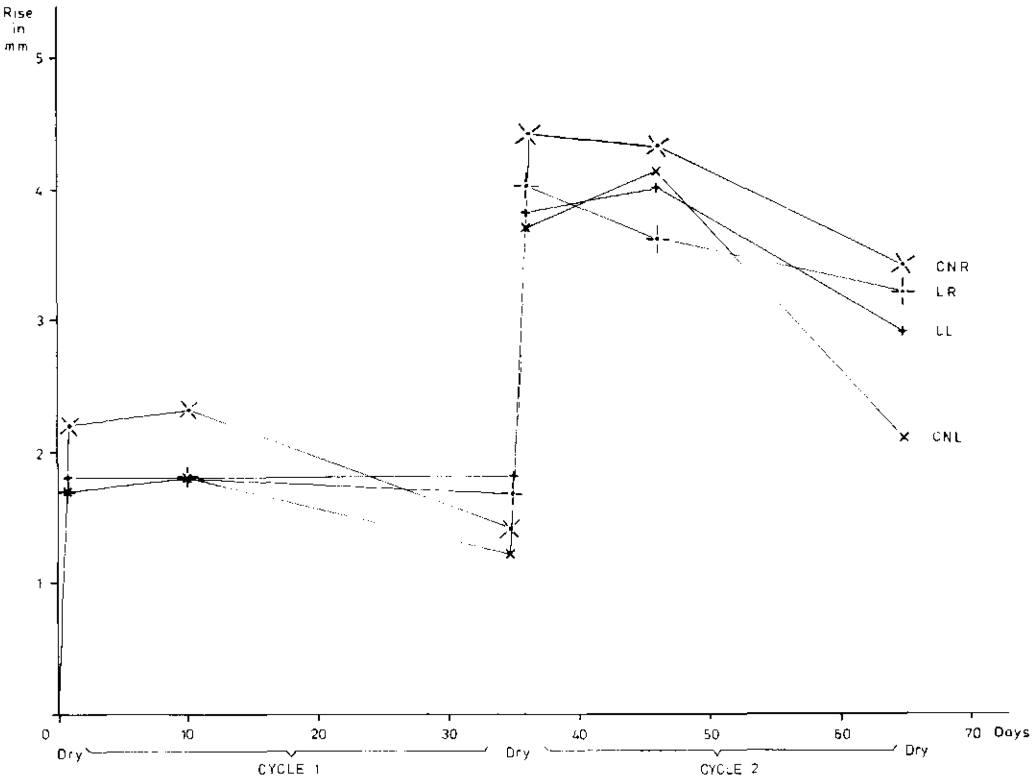


Fig. 23. The vertical movements of the objects of Experiment II plotted against time, during the first two cycles. The conditions represented in chronological order are: dry-moist-moist-dry-moist-moist-dry. CNL = clay nodule left, CNR = clay nodule right, LL = lead pellet left, LR = lead pellet right.

Fig. 24. As already mentioned the accuracy of the construction for measurements in vertical direction is higher, than that for measurements in a horizontal direction. Part of the observed movements in a horizontal direction may be due to this effect. It is, however, beyond doubt that horizontal movements of the objects did occur since the registration errors in a horizontal direction, are not larger than 0.5 mm.

In the course of Experiment II, it was noted that a considerable amount of vesicles became trapped in the lime, which caused this material to increase in volume. Consequently a device was installed, to measure the heave of the surface of the lime mass, by amplifying the movement by means of a lever. Fig. 25 shows the movements of the lime surface during the last four cycles of the experiment, plotted against time. For each cycle the horizontal time scale has been subdivided into two parts, the first one into hours to represent the rapid rise that occurs upon moistening, and the second one, of a much smaller scale, to represent the movements of the surface during the remaining period of the cycle. Irrelevant differences in length of the cycles, (due to the fact that the containers, once dry, were not always remoistened immediately), are not shown here. Each cycle is represented by a standard block. It can be seen that the initial heave varied from cycle to cycle and that small downward movements often followed. In all cases part of the heave was produced, apparently by the rise of the temperature, just after placing the set-up in the stove for drying.

Study of the X-ray images (Fig. 19), shows the formation of prominent voids

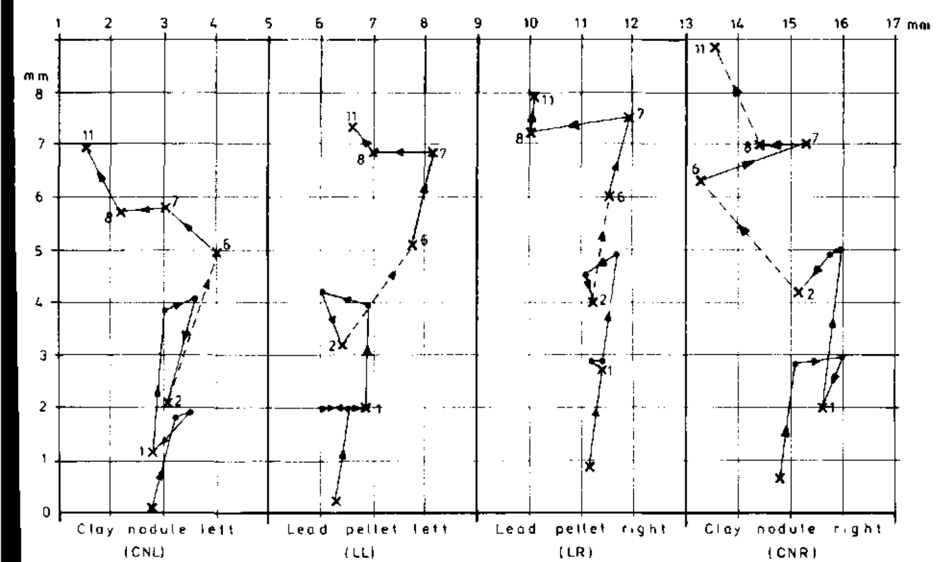


Fig. 24. Trajectory of the centres of gravity of clay nodules and lead pellets of Experiment II enlarged. The position of the objects in moist condition is indicated by a point (.); the position of objects in dry condition is indicated by a cross (x). Numbers indicate the number of cycles passed for each position. Intermittent lines are interpolations of intervals for which no X-rays were taken. Arrows indicate the direction of movement.

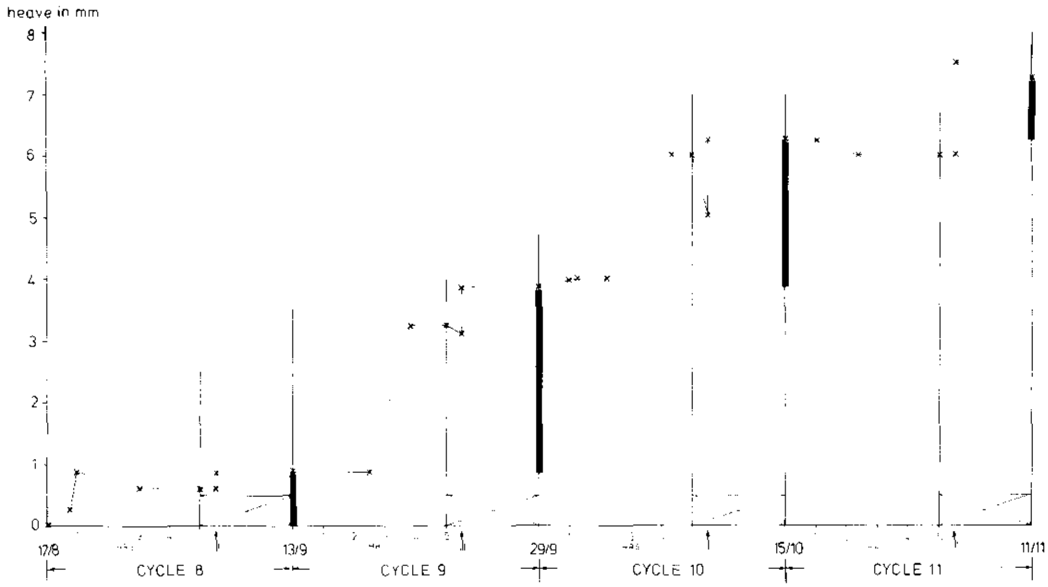


Fig. 25. The heave of the surface of the lime of Experiment II, during the last four cycles of the experiment. Each cycle has been subdivided into two parts with different scales: The first part is divided into hours, the second part (crossed) represents the remainder of the cycle (see dates). Arrows indicate the moment at which the sample was introduced into a stove for drying, which led to some heave immediately, due to expansion of the entrapped air. The solid bars indicate the net heave per cycle. It is clear that most of the heave occurs shortly after the moistening. Downward movements of the surface of the lime occur in each cycle.

above the clay nodules in dry state. In the course of the experiment, some of these voids seemed to 'disintegrate' into numerous small vesicles which also developed in abundance, independently of these voids. The vesicles appeared in increasing quantity during the course of the experiment. They restrict themselves as Fig. 19 shows almost exclusively to the lime overlying the clay nodules. Under the clay nodules hardly any voids are visible. The vesicles increase in size from the surface downward. They are round near the surface and become increasingly horizontally planed off with depth.

For this experiment, some measurements were made of the position of the lead markers in the clay nodules, in order to ascertain the amount of swelling during the experiment. Values for COLE (sat.) were found which are similar to those reported in Section 4.6.2.1. Differences, however, were found between different cycles and also between different axes of the same clay nodule in the same cycle. Since some lead markers shifted somewhat in their borings, and since some clay nodules tended to develop concentric cracks during the experiment, the measured values cannot be qualified as accurate. It could, however, be ascertained that most of the swelling of the clay nodules took place, almost instantaneously upon wetting.

At the end of Experiment II, undisturbed ring samples were taken from the lime

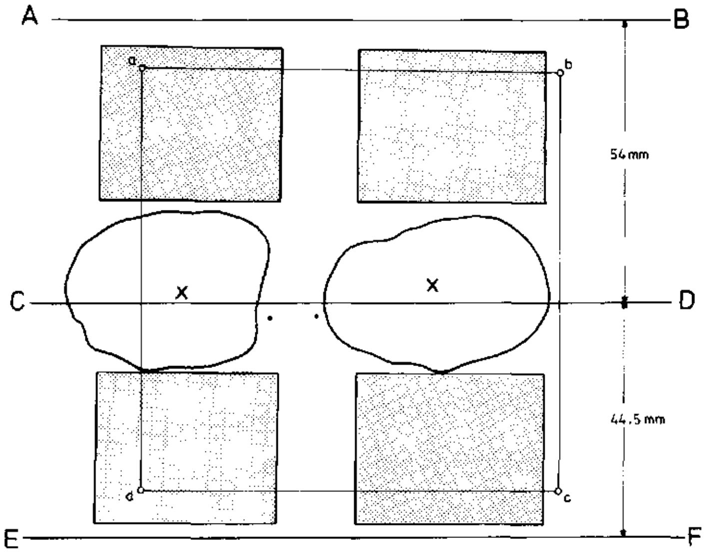


Fig. 26. Reconstructed position of the centres of gravity of two clay nodules indicated by a cross (x) and of two lead pellets indicated by a point (.), of the plate of the heave indicator (AB), and of the average level of the sand surface (EF) in relation to the reference frame of the back window markers (a, b, c, d) at the end of Experiment II, when samples were drawn for bulk density. The average level of the embedded objects is represented by CD. The approximate circumference of the clay nodules is given. The bulk density samples have been indicated by their true size as dotted squares. Compare with Fig. 19.

over and under the clay nodules, in order to check for changes in bulk density during the experiment. The samples were taken after the container had been remoisted in the same way as had been done during the experiment. (For the position of these samples see Fig. 26.)

In order to determine the bulk density at the start of the experiment, lime from the same fraction of the same sample as used for Experiment II was poured into water. From this, ring samples were drawn. Table 14 shows bulk densities, moisture contents and pore volume of the lime samples. For the determination of the latter value, the specific weight of lime, 2.71, was taken as representative of the whole solid fraction. These figures are discussed in Section 5.3.3.

Upon removal, the clay nodules showed a number of mainly concentric cracks, probably the result of fast moistening. In some cracks, lime with a vesicular structure had penetrated (Fig. 27).

5.2.3 Experiment IIIa

This experiment which was carried out with a lime sample that had been obtained by augering and which was not sieved, did not yield a significant net rise for clay nodules or for lead pellets. The experiment was abandoned in the second cycle, when it was seen that movements caused by the second moistening, brought all the objects back to the same height that they had reached in moist condition during the first cycle. The amplitude of the movement was small compared with that of Experiments II and IIIbI.

It should be stated that the sample can hardly be qualified as 'natural' since

Table 14. Bulk density (BD, see Section 4.2), moisture content and pore volume of the lime of Experiment II at the end of the 11th cycle.

Source	Sample no.	BD (moist)+	BD (dry)	Pore volume	Moisture content (v/v)	(w/w)
Lime poured in water	1		1.42	47 %		
	2		1.45	46 %		
Over the clay nodules	1	1.20	0.92	66 %	28 %	30 %
	2	1.20	0.92	66 %	28 %	30 %
Under the clay nodules	1	1.70	1.35	50 %	35 %	26 %
	2	1.69	1.34	49 %	35 %	26 %

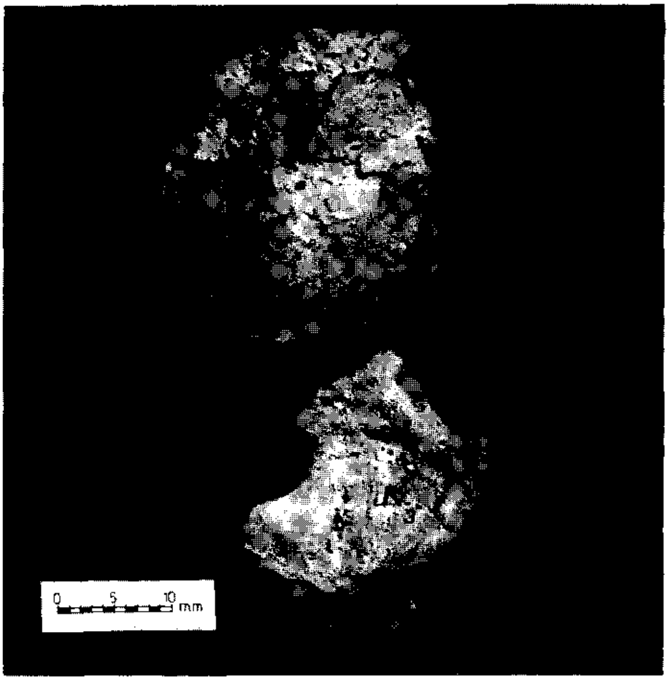


Fig. 27. Detail from a clay nodule of Experiment II that fractured during the experiment. The fracture shows the two channels bored through the centre of gravity (Arrow 1) into which the lead markers were inserted. Lime has penetrated into the crack (Arrow 2). Vesicles are visible in the lime that penetrated (Arrow 3).

the auger that took it ground up several clay nodules, which caused the admixture of rather large quantities of clay to the lime. This probably influenced the properties of the lime in moist condition, as shown, e.g., by the deviating liquid limits of clay-rich lime samples, reported in Section 4.6.1.1.

On X-ray photographs it can be seen that during the experiment, voids formed around and especially above the clay nodules in dry condition, and disappeared in moist condition. The overall cloudy appearance of the images indicates that from the start the heterogeneous mixture enclosed more air, than in the other experiments.

5.2.4 Experiment Ib

This experiment involving moistening from the top down by means of unsaturated flow, was carried out to evaluate the effect of this process on the behaviour of various objects encased in lime. The objects in this case were two clay nodules and a rounded piece of quartzite gravel from the raña deposits (Unit R), which are common in the survey area, as indicated in the map (Fig. 3). For this purpose, the set-up was identical to Experiment II, except that the moistening took place through a gypsum crust on the surface, over which a constant head of approximately 1 cm water was maintained (see Bouma, 1977). In order to avoid local saturation of the sample, the bottom of the container was perforated, covered by porous material and placed in dry sand during the moistening.

During the two cycles that the experiment was run, no movement could be detected, in the centres of gravity of the clay nodules, nor in that of the raña gravel. Comparison was made between the dry state at the start and the dry state at the end of the second cycle. Intermediate images were not available. Since no effect was seen, the experiment was discontinued after the second cycle.

5.2.5 Experiment IIIb1

The set-up for this experiment was identical to that of Experiment II, except for the source of the lime and the nature of the embedded objects (see Table 13).

A net rise was noted for all objects enclosed, which measured 4.2 mm for a clay nodule, 3 mm for a raña gravel and 5 mm for a petrocalcic fragment placed in the middle. These results were obtained in five cycles (movements shown in Fig. 28). From the positions recorded in a moist state at the initiation of the fifth cycle, it can be seen that, just as in Experiments Ia and II, all objects show a downward movement upon drying. This measures about 1 mm for the clay nodule and the petrocalcic fragment and only 1/4 mm for the raña gravel.

At the end of the fifth cycle, a modification was made in the experiment which was then continued under the number IIIb2.

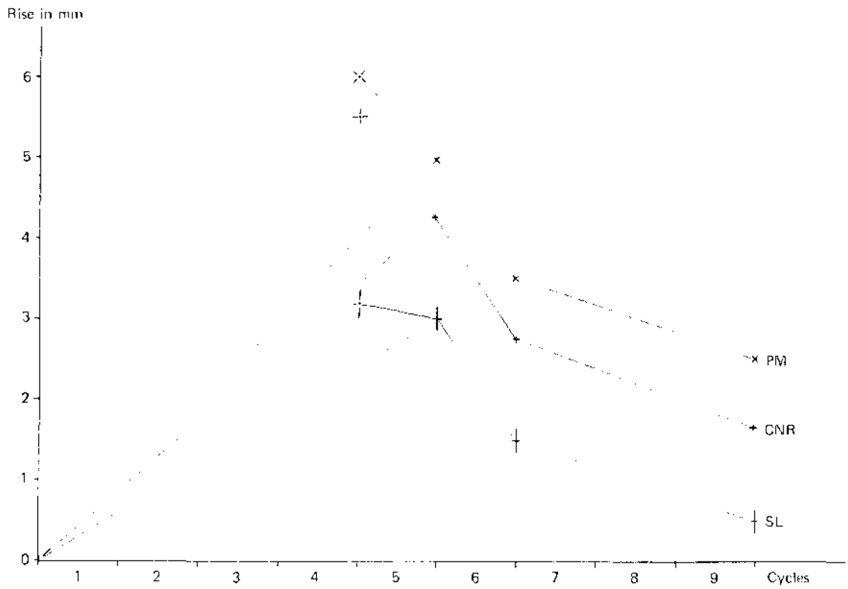


Fig. 28. The vertical movements of the objects of Experiments IIIb1 and IIIb2 plotted against time. A considerable rise for all objects is evident during the first five cycles of Experiment IIIb1. The position of the objects in moist condition shortly after the initiation of the fifth cycle is indicated by hollow symbols. At the initiation of the sixth cycle, the set-up was changed and Experiment IIIb2 started. A heavy weight was placed on the surface of the lime which caused subsidence of all objects during the sixth cycle. From the position of the objects at the end of the ninth cycle it is evident that the subsidence must have continued at a diminished rate for some time after the sixth cycle. The following objects are shown: PM = petrocalcic fragment, middle; CNR = clay nodule, right; SL = raña gravel, left.

5.2.6 Experiment IIIb2

At the end of the fifth cycle of Experiment IIIb1, a lead weight of 4.5 kg was placed on the lime surface in the container. This caused a pressure of 75 g/cm^2, which is roughly equivalent to the pressure in the soil, at a depth of 50 cm. The weight was applied during the full cycle. It was only removed when the container had to be transported in a dry condition. Special arrangements were made to assure fast drying, despite the weight on the surface. For this purpose, the lead weight was separated from the top of the lime surface by a layer of porous material, (ground brick), through which air was blown, in order to ensure fast evaporation of moisture. In this way, it was possible to cause this sample to dry as quickly as those which had uncovered surfaces.

The experiment was carried on for four cycles. The effect on the included objects was a net downward movement of 2.5 mm for all (Fig. 28). Despite the fact that no arrangements for detailed measurements of compaction were made, it could be observed that the surface of the lime went down about 2 mm, which is similar to the fall of the encased objects.

5.3 DISCUSSION

The experiments summarised in Table 13 were set up originally, as stated in the introduction of Chapter 5, to verify the occurrence of movements of objects contained in lime subjected to wetting and drying, and to confirm that these could be measured. When this was ascertained, five new questions arose, namely:

1. What causes the movements?
2. What is the mechanism of the process(es)?
3. Are the process(es) that cause these movements capable of producing a sustained rise of objects?
4. Which factors determine the process(es)?
5. Are the experimental conditions under which the rise occurred comparable with natural conditions in the soil?

The main cause of the movements can be identified. Furthermore it is possible to prove that the rise measured is not due to some temporary phenomenon but represents a sustained upward movement. The answers to the other questions, however, include an element of speculation, for the following reasons.

Time is the main limiting factor in most attempts to reproduce pedogenetic processes in the laboratory. This weighed especially heavily in this particular case, since an attempt was made to approach natural conditions as closely as possible. This implied that in the experiments drying was performed at temperatures not higher than 50°C, which made the minimum duration of one cycle about 20 days. Despite the fact that some of the experiments lasted for periods up to one year, their duration was too short to solve all questions satisfactorily.

Each of the individual experiments was carried out with the purpose of testing a specific assumption. If it became apparent that the assumption had to be rejected, a new one would be formulated and the experiment would be adapted to test this one. The explanations given in the following part have emerged gradually in the course of the investigation. As such the set-up of the sequence of experiments would have been different, had the testing been started with these ideas as the point of departure. This explains a lack of certain useful data such as, e.g., surface-heave measurements during Experiments Ia and IIIa.

The six variations introduced into the experiments are anyhow insufficient to cover the large number of factors and their interactions which evidently played a role. More experiments of a longer duration would be needed to settle the remaining problems. The five questions will be treated in the following sections.

5.3.1 *What caused the movements?*

Options to be considered to account for the movements registered are treated in the following sections (5.3.1.1-5.3.1.4).

5.3.1.1 Gas enclosure

Gas enclosure does indeed occur, in all experiments, that showed upward movement of objects. Proof for this can be found in the appearance of vesicles in the course of the experiment and in the decrease of the bulk density of the lime during Experiment II (Table 14). The fact that a gas is responsible for the surface heave is also clearly demonstrated by the temperature-related additional heave, indicated by arrows in Fig. 25. The X-ray photographs offer clear proof of the gradual increase of the gas accumulation in the course of the experiments (see e.g. Fig. 19).

It cannot be ruled out that a small part of the gas is CO_2, which is formed by the H ions in the water, which react with $CaCO_3$. The quantities cannot be large, however, since only small amounts of H ions were available, in the water used for moistening, and since bicarbonate would have formed if the CO_2 pressure had been locally raised too much. Notwithstanding this, the process may be worth mentioning, since it could exert a priming function on other processes of gas enclosure (personal communication, Van Reeuwijk, 1980).

Release of air, absorbed on the lime surfaces in dry state, upon wetting can conceivably contribute to the gas enclosure phenomena (personal communication, Koenigs, 1982).

Paletskaya et al. (1958), suggested that the release of CO_2 during the drying of a bicarbonate solution, causes vesicle formation in takyr soils.

Entrapment of air, due to irregular wetting, seems to be the only other option available to account for the gas enclosure phenomena observed. This process will be discussed in Section 5.3.2.

5.3.1.2 Swelling of clay nodules

Swelling of clay nodules, is evident in the movements registered in the first cycles of Experiments Ia and II (Fig. 21b and 23). The generally greater amplitude of movement of the clay nodules compared with the other objects, must be due to the swelling and shrinking which causes rise and fall of their centres of gravity. This process, however, does not lead to a consistently higher net rise, in the various experiments. In Ia it was apparently totally ineffective. Since rigid objects like stones and lead pellets were found to rise too, swelling of the clay nodules cannot be the main process responsible for the rise. It is possible that the swelling behaviour of the clay nodules, in conjunction with other processes, would in the long run cause these objects to rise more rapidly than the rigid ones. The experiments offer indications, that this may be so, (e.g., the performance of the right hand clay nodule of Experiment II, after 11 cycles as shown in Fig. 22).

5.3.1.3 Buoyancy of objects immersed in moist lime

Buoyancy of objects immersed in moist lime was suspected to be the main process responsible for the rise, at the initiation of the experiments. The experiments have shown, however, that there was also a rise in various objects, of a bulk density, much higher than that of the moist lime, such as, e.g., lead pellets and quartsitic raña gravels. The moist bulk densities of lime developed at different heights in the container during Experiment II are summarized in Table 14. Comparison with those of clay nodules (Table 9) shows that in dry state these are lower than the moist bulk densities of the lime, except for its upper layer. The moist bulk densities of the clay nodules, however, are approximately equal to the moist bulk densities of the lime of the lower part of the container. It is conceivable that in the initial stages of a cycle, when the lime was moist but the clay had not yet absorbed all the water it could take, the buoyancy effect combined with the shrinkage of the nodules contributed to their rise, provided that local liquifaction of the lime allowed for the displacements. Buoyancy cannot account for the rise of all objects, however.

5.3.1.4 Compaction

Compaction, leading to short-lived downward movement of objects, was evident in the results of some experiments (Ia and IIIb). Its effect may be present to a certain extent in all results. The net rise of objects and the net heave of the surface is always the balance between whatever compaction occurred and other processes operating in the opposite sense.

5.3.2 The mechanism of the air entrapment process

Review of all the options considered, leads to the conclusion that the only process to be held responsible for the movements of all types of objects is air entrapment. This process will be considered in more detail.

Water entering a capillary will expel the air contained in it or compress this air if it cannot escape. The maximum pressure (Δ Pmax) which can be generated in this way, can be calculated for round capillaries by means of the well known formula for capillary rise as given, e.g., by Hillel (1980):

$$\Delta P = (2 \gamma \cos \alpha)/r$$

in which:

ΔP = pressure difference between water under the meniscus and air over it

γ = surface tension; 72.7 mN/m for water at $20^{o}C$

α = contact angle; 0^{o} for pure water in contact with inorganic substances

r = radius of the capillary

The assumption of a contact angle of 0^{o} implying complete wetting is also used by Bolt & Koenigs (1972) for a soil-water system. They approximate the value of Δ Pmax for a 1 µm capillary as 1.6 bar and use the relation 1.6/r to find the Δ Pmax in bar for capillaries of which the radius (r) is expressed in µm.

Whether the Δ Pmax for air compressed in a capillary will indeed be reached depends, as Bolt & Koenigs (1972) point out, on the length of the capillary. Water entering a capillary from two sides may compress the occluded air to a spherical bubble in the middle where the two menisci meet and become stationary. The Δ Pmax will not be reached in the bubble if the capillary is not long enough to allow for sufficient compression. If such a bubble is formed, the pressure on the capillary wall returns to zero. To summarize it may be stated that Δ Pmax for a single round capillary depends on the radius and on the ratio between radius and length. The smaller the radius the larger Δ Pmax provided that the ratio radius/length is also small enough to allow sufficient compression to take place, to reach Δ Pmax before a bubble is formed.

For a plate capillary the formula that expresses Δ Pmax has to be modified. Since the meniscus in such a capillary does not have a spherical shape but takes the form of a semi-cylindrical trough, it can be derived that for a plate capillary of width d and assuming complete wetting, Δ Pmax = $\gamma/\frac{1}{2}$ d. This is half of what Δ Pmax would be for a round capillary with a radius equal to $\frac{1}{2}$ d.

The relation $\gamma/\frac{1}{2}$ d indicates the Δ Pmax that would be reached if the compression of air took place in a plate capillary open on one side only. Where plate capillaries occur between the calcite crystals of the powdery lime (see Section 4.6.1.2), the compression model is more complicated since water enters from all sides. In such a case an elliptical or circular bubble will form between the plates. This bubble is bounded on all sides by a meniscus of semi-cylindrical shape. For this situation the relation $\Delta P = \gamma$ / (1/R1 + 1/R2) is valid (see e.g. Hillel, 1980), in which R1 represents the radius of curvature perpendicular to the plates and R2 the radius of curvature parallel to the plates. In the case of pure crystalline lime a perfect fit of the crystal faces can be expected as such R2 will be very large in comparison to R1. During the compression of the bubble R1 remains constant but R2 reduces somewhat. Notwithstanding the latter fact it seems justified to neglect the term 1/R2 when estimating the order of magnitude of the pressure that develops in the plate capillaries. In this case the equation reduces to $\Delta P = \gamma/\frac{1}{2}d$, which is valid for plate capillaries open on one side only. By means of this formula it can be calculated that pressures will develop which range from 1.6 to 16 bar for plate capillaries that range in width (d) from 1 to 0.1 µm.

In the following paragraphs a model will be developed which describes air enclosure in the peculiar void system of the lime for those experiments that produced a net rise of the objects.

As mentioned in the discussion of the liquid limit of the lime (Section 4.6.1.2), the crystalline character of the calcite grains has a strong influence on the behaviour of this material. Upon moistening of the lime by pouring it into water, as was done in Experiment II and IIIb1, the calcite crystals tend to arrange themselves in packets of grains which adhere to each other by means of a thin water-film between their facets. These packets of crystals pile up randomly to form a structure with larger voids. Upon subsequent drying a structure results which does not show a continuous distribution from large to small pores but in which two different void systems can be recognized, namely a system of extremely narrow planar voids inside the crystal packets and a system of much larger voids between the crystal packets.

Upon remoistening this pore system behaves as follows. Water enters the larger pores rather rapidly. A certain amount of air is occluded in this pore system due to the fact that water enters the pore network from different places and blocks the exit for air trapped in the system.

Water will also enter the narrower voids but this wetting is much slower, since according to Bolt & Koenigs (1972) the flow resistance in narrow pores (0.1 μm class) exceeds the effect of the larger pressure deficit in this system. This effect retards the build up of pressure in the system as part of the air is expelled from the narrow voids in order to 'pump up' the larger voids. An important part of the narrow pores will, however, occlude air between the crystal faces. The retarded moistening of these planar voids allows for uniform wetting of the perimeter of the planar voids via the wider pores. As a result, compression of air between the crystal planes will take place.

The Δ Pmax of the wide pore system is governed by the diameter of the narrowest neck of this system which contains a meniscus. Relatively modest pressures result which lead to dislocations of the lime mass mainly in the upper layers of the container. The dislocations result from the failure of the larger pores in the upper zone where the overburden pressures are modest. Wetting of the narrow planar voids between the crystals aids the dislocations since it provides lubrication for movements of the crystals along their contact planes, as discussed in Section 4.6.1.2. Deeper in the lime mass the number of large pores in which air is occluded with a pressure sufficient to cause failure decreases sharply due to the larger overburden. In most instances the compressed air will escape. Only in exceptional cases is the smallest pore neck of the system so narrow that it provides for a Δ Pmax sufficient to overcome the larger overburden pressure and bring about failure.

This behaviour of the large pore system probably causes most of the permanent surface-heave due to increase in volume of the lime mass. It also explains the relatively steep bulk density gradient established in the lime during Experiment II (Fig. 26 and Table 14). Also contributing to this steepness is the fact that the large voids collapse in the deeper layers but are conserved in the upper layers. The observation that most of the surface heave occurred relatively abruptly one or more hours after the wetting had been initiated confirms the necessity of moistening the planar voids and lowering the liquid limit of the lime before dislocations can be produced.

The wetting of the narrow pore system causes an effect which differs from that of the large pore system. Water entering from all sides into the narrow planar voids between the crystal facets will compress the air up to considerable pressures (probably in the order of several bars since widths of the planar voids in the class 0.1-1 μm are to be expected). The area of the planar voids is very large compared to its width, as such Δ Pmax will be reached in most cases well before the air is compressed to a spherical volume in the middle. The compressed air in the bubbles will tend to dissolve into the water at a rate proportional with the gas pressure. The fact that only a small part of the surface area of the bubbles is in contact with the liquid slackens the pace of the dissolution. Notwithstanding this last fact, high pressure bubbles will probably be rather shortlived.

The effect of the occluded air between the crystals upon the lime mass is as follows. The crystal packets will expand somewhat in an accordion-like fashion in a direction perpendicular to the crystals that bound the planar voids. Since the crystal packets have a random arrangement, forces will be exerted in all directions by these aggregates. The calcite crystals become temporarily separated from each other by air cushions held in place by menisci that act like 'springs', the total resembling the air suspension system of a vehicle. The result of the multi-sided expansion is evident in the movements of the objects as illustrated in Fig. 24. Upon wetting of the lime mass the objects move in all directions except downward. The reason that downward movements are absent is the fact that compression of the underlying materials would take a greater force than uplift of overlying material.

Fig. 25 shows a surface heave which is in part reversible. The maximum heave measured in each cycle is the total of the heave due to the coarse pore system (mainly in the upper layers) and to the fine pore system (throughout the lime mass). The part of the heave which is reversible is probably mainly due to the fine planar void system and to a lesser extent to collapse of larger voids related to the coarse pore system.

5.3.3 Is the air entrapment process capable of producing a sustained rise of objects?

If the rise of the objects, were due solely to the increase of the volume of the lime below the objects, the rise process would be short-lived. It would mean that its importance, as a natural process would be very limited. The fact that the heave, according to Fig. 25, did not show any signs of diminishing after 11 cycles. does not mean that the process would have lasted indefinitely. If the bulk density had continued to lower, a moment would have come, when the reduced amount of solids could no longer support the void structure and collapse of voids would have occurred. An equilibrium would then have established itself between the creation of voids and their collapse. In fact the heave diagram shows that collapse on a small scale has already taken place during every cycle.

If the rise of the objects were due solely to the increase in volume of the lime, it would stop once the equilibrium was established. These considerations make it important to know, whether the bulk density decrease was indeed the only process active in the experiments.

Comparison of the bulk densities measured at the end of Experiment II, with that which existed at the initiation of Experiment II (Table 14), taking into account the rise of the objects registered, makes it possible to settle this question by a simple calculation.

In Experiment II, the average rise of all the objects registered (see Table 13), can be computed to be 7.4 mm. At the end of the experiment, their centres of gravity were situated at an average of 44.5 mm above the sand surface, whereas at the beginning, they were situated at 44.5 mm - 7.4 mm = 37.1 mm over the sand surface (Fig. 26). If the rise of the objects were to be entirely due to the increase of the volume of the underlying lime mass, which, encased in the container could only expand in a vertical direction, then the product of average distance between objects and sand surface and average bulk density before and after the experiment, would have to be equal. This is clearly not the case. Product before the experiment started: 37.1 x 1.435 = 53.2. Product after the experiment finished: 44.5 x 1.345 = 59.9. It can be calculated that the decrease in bulk density during 11 cycles accounts for:

$$\frac{37.1 \text{ mm} \times 1.435}{1.345} = 39.6 \text{ mm}$$

Of the distance to the sand surface at the end of the experiment this leaves 44.5 mm - 39.6 mm = 4.9 mm, unaccounted for. Consequently the only conclusion that can be drawn is that at the end of the experiment, more lime particles separated the objects from the underlying sand surface than before the experiment.

Of the total average rise of the objects registered in Experiment II, of 7.4 mm, the net average rise, which was not due to increase in volume of the lime, was 4.9 mm in 11 cycles. This means that the average net rise per cycle was in the order of 0.5 mm. The rise due to decrease of bulk density was 7.4 mm - 4.9 mm = 2.5 mm. The registered surface heave must be due entirely to decrease in bulk density of the lime. Unfortunately, for Experiment II, for all 11 cycles, no heave data are available. An extrapolation, however, can be made from the last four cycles, during which the total registered heave was 7.25 mm (see Fig. 25). For 11 cycles this would amount to:

$$\frac{11}{4} \times 7.25 \text{ mm} = 19.9 \text{ mm}$$

The change of the bulk density, of the upper 54 mm, enables the calculation of this distance at the beginning of the experiment:

$$\frac{54 \text{ mm} \times 0.92}{1.435} = 34.6 \text{ mm}$$

This means, that of the total heave of 19.9 mm, 54 mm - 34.6 mm = 19.4 mm has been accounted for. The remaining 19.9 mm - 19.4 mm = 0.5 mm must be due to the decrease of the bulk density of the lower half of the lime. These 0.5 mm differs from the 2.5 mm actually calculated. The difference probably lies in the fact that the basis of the computation was an extrapolation.

If increase in volume of the lime below the objects was the sole cause of their rise, the amount of lime between the objects and the sand surface would have remained constant. This leads to the conclusion that another process must have been active in order to account for the fact that more lime particles separate the objects from the sand surface at the end of the experiment than at the beginning. This additional process is very probably the result of the largely reversible accordion-effect of the calcite crystals. A model for this will be treated in the next paragraph.

Upon drying of the lime mass the crystal packets contract again and most small lime particles return to the position they occupied before the enclosed air forced them apart. Some dislocations, mainly shifting of crystals parallel to each other, may not, however, cause all small particles to return to their original positions. The chances that larger objects return to their original positions is much smaller since there is very little likelihood that the original void which they previously occupied will be reconstituted on drying. The larger the object and the more irregular its shape, the smaller the chance that the original void will be reconstituted. If only a few of the many calcite crystals that bounded this void fail to take up their original positions, the large object will not fit and cannot return to its original void. Consequently the wetting and drying of the lime mass will produce a net displacement of the large object. Since upon wetting all objects move in all directions except downward, (as mentioned in Section 5.3.2), consolidation of part of the movements of the large objects will include in the majority of the cases part of the upward component (see Fig. 24). In other words, there is a net rise of the larger objects from the majority of their displacements. majority of their displacements.

The aforementioned process has a close parallel in certain sieving procedures in the milling technology of cereals. According to Leniger & Beverlo (1971) sieving of the ground product is customarily performed with a rather thick layer of flour on the sieve. Under the influence of the shaking of the sieve a sorting process takes place. This causes coarse and irregular particles to concentrate at the surface of the layer, while fine and smooth particles concentrate at the bottom of the layer in contact with the sieve. This separation takes place irrespective of the mesh width of the sieve. The explanation of the sorting process is the same as that given for the objects encased in lime: coarse and irregular particles stand less chance of returning to their original level since small and smooth particles fill up the spaces that they formerly occupied.

The processes active in the lime experiment, are similar to those responsible for the formation of certain desert pavements, which regenerate rapidly upon removal, as discussed by several authors, including Cooke & Warren (1973), Bales & Péwé (1979), Jessup (1960) and Springer (1958). The latter tested the process experimentally, with soil materials derived from desert soils, with a vesicular structure which, though similar to lime, lack a fine planar void system. He demonstrates that stones embedded in material from these soils, will gradually rise to the surface if the total is subjected to wetting and drying. He measured a net rise of pebbles of up to 1.1 cm, in 22 cycles of wetting and drying. His explanation of the phenomenon is as follows: 'We might postulate that through swelling of the soil, the stone is lifted slightly. As the soil shrinks, cracks are produced around the stone and within the soil. Because of its large size the stone cannot fall into the cracks, but fine particles may either fall or be washed into the cracks. The net effect is an upward displacement of the stone.' Springer noted the air enclosure phenomenon and proposes the following mechanism: 'Upon becoming moist, the particles below the surface appeared to become rearranged and closely packed with air moving from the disappearing medium sized pores, into the larger spaces now created.'

Springer's postulate about the cracks produced around the stone does not hold true for the experiments with lime, since the X-rays show clearly that no voids are produced around rigid objects such as stones and petrocalcic fragments. His explanation of the air enclosure, being due to collapse of the medium sized pores does not hold true for the lime either. The experiments have shown that the bulk density lowered, whereas according to Springer compaction of the whole mass occurred.

It is unclear why Springer considers the process to be a continuous one, if he assumes collapse of small voids as the driving mechanism of air enclosure. He does not believe that the process stops once a certain amount of compaction (due to loss of air through the surface) has taken place, since he also states: 'Repeated wetting and drying caused a continual rearrangement of soil particles and voids.' In Springer's experiments, the driving force of the mechanism is not the collapse of voids, but apparently the capillary force that drives air out of the small voids into the larger ones, upon moistening. The process which he studies is probably active only up to a relatively shallow depth in the soil. His materials lack a fine planar void system and as such are supposed not to develop pressures that can cope with a large overburden of soil.

It must be remarked that Springer dried his samples at 90°C which means that a large part of the effect measured was due to the temperature-related expansion of air in the voids. This unnatural effect was much less evident in the experiments of this study, in which drying was performed at a temperature of 50°C only. Only about one third of the total heave can be attributed to the temperature effect as can be seen in Fig. 25.

For the clay nodules, Springer's explanation about the formation of voids in the dry state, which fill up during the next wetting, could indicate an additional process that has to be taken into account. In this case, however, the formation of voids was due to shrinkage of the clay nodules and not to that of the lime mass. The filling up of voids, is partially due to expansion of the lime mass and partially to swelling of the clay nodules under the influence of wetting. In the long run this could lead to a greater rise of the clay nodules compared with the rigid objects. Some indications of this have been treated in the foregoing section.

5.3.4 What factors determine the processes that lead to net rise of the objects?

The results of the experiments as discussed in the foregoing sections indicate the importance of the fine planar void system of the lime for the air enclosure process and the resulting rise of the objects. Several factors which play a role in these processes have been identified and will be treated in the following paragraphs.

Important factors influencing the establishment of an extensive fine planar void system can be derived from the experiments and from the determinations of the liquid limit (Section 4.6.1.2). The properties of the lime which were of great importance were: uniformity of the crystals, lack of growths on the crystal surface and purity of the material. These factors influence directly the way the crystals fit in the lime mass. The better the fit, the lower the liquid limit and the greater the air enclosure and net rise of objects in the experiments. Lack of net rise in Experiment IIIa was probably due to contamination of the samples by clay. Lack of net rise in Experiment Ia could either be due to the presence of a considerable amount of coarse cemented lime aggregates, or to the fact that the sample was not properly consolidated when the measurements started. Packing of the lime is a factor or prime importance for the establishment of an extensive fine planar void system. All experiments that produced a net rise of the enclosed objects were subjected to consolidation by pouring the dry lime into water.

Whether air enclosure and rise of objects will occur depends on the way of moistening (provided that the lime fulfils all the conditions described in the foregoing paragraph and has been properly consolidated). Experiments that were moistened by saturated flow showed the aforementioned processes but they were not provoked by unsaturated flow (Experiment Ib). Slow moistening probably leads to escape of all air from the pore system.

Whether the movements that are produced in the lime mass lead to net rise of the objects, depends on the behaviour of the lime mass during the air enclosure process. Dislocations during this process prevent the return of the objects to their original level and cause a net rise effect. Such dislocations are facilitated by low liquid limits (see Fig. 27) which in turn depend on the same characteristics that caused the development of the fine planar void system.

Overburden pressure is a factor that seems to have a strong influence on the air enclosure of the coarse pore system. The experiments have shown that decrease of bulk density due to failure of the capillaries as the result of the relatively modest pressures built up in this system, is mainly restricted to the upper 5 cm of the containers (Table 14). The movements related to the fine planar void system occur throughout the lime mass as the experiments have shown. The influence of much larger overburden pressures on the air enclosure in the fine planar void system can only be assessed on theoretical considerations, since the data acquired in Experiment IIIb2 are inconclusive where this aspect is concerned. This is because no X-rays were taken to cover a complete moist-dry cycle under the influence of increased overburden. The only conclusion that can be drawn from this experiment is that apparently the application of the overburden pressure caused consolidation of one or other of the two layers between the objects and the bottom of the container. This conclusion is based on the observation that the sinking of the objects and the surface was approximately equal, i.e., about 2 mm. This consolidation effect superseded any other movements that may have taken place in the lime mass during the four cycles that the experiment lasted (Fig. 28). The pressure that can be expected to build up in the fine planar void system has been quantified in Section 5.3.2 and is of the order of 4 bar, considering widths of the order of 0.1 μm for the planar voids. Even when taking into account that these pressures only act on part of the surface of the calcite crystals, it must be concluded that overburden pressures equivalent to the weight of several meters of soil material can be exceeded.

In the literature some information is found regarding air enclosure leading to the formation of vesicular structures. None of the studies, however, deals with the behaviour of crystalline materials which is largely governed by the fine planar void system. They rather deal with air enclosure due to failure of the coarser pores, a phenomenon mainly restricted to the surface soil.

Volk & Geyer (1970) describe what they call 'foam soils' from semi-arid areas of Morocco, Spain and S.W. Africa. They state that vesicles form, at a certain depth in the soil and then slowly move upward, through the plastic material. On their way up, they may expand further, due to heating, which creates a pressure that helps to rearrange the skeleton grains. They assume a way of moistening, which is rapid enough to permit air enclosure. Drying should take place with a speed sufficient to form a hard crust at the surface rapidly, but slow enough to permit upward movement of air bubbles, through the plastic soil mass upwards, before the system solidifies. According to these authors, the following conditions of the soil material are a prerequisite for air enclosure upon wetting:

1. High silt and fine sand content (40-70 %) and low clay content.
2. Low liquid limit and a very narrow interval between the moisture contents at which the materials behave as liquids and solids (the soils they describe tend to 'flow' over cliffs and produce 'draperies').
3. Tendency to strong crusting, to form a barrier that prevents air escape.

Evenari et al. (1974) carried out experiments similar to Springer's (Section 5.3.3), to explain vesicular features from the soils of the Negev desert. Their experiments, under laboratory conditions, aimed at the formation of vesicular structures in a variety of soil materials, subjected to wetting and drying. To simulate the formation of vesicular structures under stones, they introduced a modification in the set-up by placing a petri dish over the materials. This prevented the escape of air upon moistening. Good vesicular structures formed in the soil directly underlying the dish, after 20-25 cycles of wetting and drying. Non-covered surfaces did not develop vesicular structures, due to loss of air through the surface. Loess, fine sand and coarse sand were tested, the first two of which formed good vesicular structures, while the coarse sand performed poorly. Their interpretation of the cause of the formation of the vesicles is, the expansion of enclosed air. They also state that the phenomenon may be enhanced by the heating of the enclosed gasses due to the daily temperature cycle, under natural conditions. A similar phenomenon is described by Yaalon & Kalmar (1972), who registered surface heave in crusted soils, in which there is a slow air exchange (in the order of 0.5 mm). This is due to daily differences in temperature which cause significant volume expansion of soil air (up to a depth of 5 cm) under natural conditions.

5.3.5 Are the experimental conditions under which the rise occurred comparable with natural conditions in the soil?

The present treatment will be restricted to a comparison between experimental conditions and those common in the natural environment. Field evidence of the rise of clay nodules under natural conditions is presented in Section 6.2.1. The impediments to the processes listed in the foregoing section, will be reviewed one by one.

The nature of the pore system under natural conditions probably matches that of experimental conditions. This can be inferred since the packing under natural conditions (as derived from the bulk densities of Table 7) is in the same range as that indicated by the bulk densities developed during Experiment II (Table 14). The bulk densities of the lime of Profile Arroyo 1 at 260 cm even exceed those established at the initial stage of Experiment II.

A negative influence of admixture of coarse lime aggregates on packing, air enclosure and the resultant rise of objects may be inferred from a comparison of the results of Experiment Ia with those of Experiments II and IIIb in which these coarse fragments in the fraction 0.5-2 mm had been removed by sieving (Table 13). This observation could in turn lead to the conclusion that Experiments II and IIIb are not representative of natural conditions in the soil, since coarse fragments had been removed from the natural samples. In Section 4.9, however, the conclusion was drawn that pedogenetic processes are fossile in the high soils of which the lime samples had been derived. As such the sieving of the samples prior to the experiments does not create 'unnatural' samples, since the rise process is supposed to have been active under natural conditions before chemical redistribution of lime created the coarse aggregates that are nowadays found in the calcic horizons.

Moistening under natural conditions is probably characterised to a great extent by unsaturated flow. Uneven distribution of percolating rain water in the calcic horizon, through the cracks of the overlying Vertisol, is to be expected, with the coming of the first heavy showers of the wet seasons. Also to be expected is the phenomenon of unstable flow, due to wetting front instability, at the transition between the clay and the underlying silt-sized lime. This results in a wetting pattern of columns which have a core of saturated flow surrounded by a cylinder of unsaturated material (see Hillel, 1980). It seems that a considerable range of infiltration types can be expected under natural conditions. Some of these infiltration types are similar to those of the experimental conditions. It is worth noting that more air enclosure can be expected under natural conditions where moistening takes place from the top down, than under laboratory conditions where in all experiments, except Ib, moistening took place from the bottom up.

The question arises as to whether the net rise of objects observed in the experiments can be qualified as representative of the rise under natural circumstances. As mentioned in Section 5.3.4, the pressures generated in the fine pore system can be expected to be high enough to match overburden pressures equivalent to several meters of soil material. The rise process due to the fine planar pore system should be considered a cumulative process. As such a much stronger rise is expected to occur in thick soft lime horizons compared with that measured in the experiments.

Temperatures during drying were higher than those to be expected under natural conditions in the deeper layers of the soil profile, but no more than one third of the total heave evident in Fig. 25 may be attributed to this difference.

In conclusion, it may be stated that the value of 0.5 mm net rise per cycle calculated in Section 5.3.3 for Experiment II represents a minimum value which is probably exceeded in most cases under natural conditions in the soil. This is justified by the fact that the experiments have been carried out under conditions which, except for the temperature effect and the cumulative effect of thick lime layers, simulate those of the soil in the natural environment when the rise process occurred. Theoretical considerations imply that this conclusion must be valid for calcic horizons of a depth of up to several metres in the soil.

6 Behaviour of calcic horizons

In this chapter some processes active in the calcic horizons of the study area are treated, taking into account the results of analyses, experiments and surveys of the foregoing chapters. These processes are verified by field observations made in the survey area and by data from the literature on comparable regions. The field data for this chapter are mainly derived from the Miocene clay landtype. Some evidence from other landtypes is introduced when warranted by conditions sufficiently similar to those of the Miocene landtype.

Certain terms in this section are written in italics in order to indicate that they will be used as standardised terminology throughout Chapter 6.

One of the aims of this chapter is to formulate an acceptable theory on the genesis of the calcic horizons of the survey area. This genesis is not the starting point but the conclusion of the discussion. The point of departure is the question: 'How can soft calcic horizons become *mobile* in order to maintain themselves for a long period in an eroding environment without falling victim to erosion themselves?'.

In order to answer this question a model is tested in Section 6.1 in which it is assumed that dissolution in its upper part and recrystallisation in its lower part causes the calcic horizon to move downward *(migrate)* into the soil. This test shows that chemical dissolution processes cannot be expected to act fast enough under the conditions of the survey area to propel the horizon downward with a speed high enough to escape exposure by erosion.

Section 6.2.1 contains field evidence of the *rise process* of objects contained in a soft calcic matrix as observed in the experiments of Chapter 5. The source of the objects that rise upwards through the calcic horizon is found in the weathering zone. There is evidence that swelling and shrinking of the clayey soil materials accompanied by the infilling of the cracks by lime causes the *formation of a subterranean gilgaî relief*. This process brings about the formation of *clay pillars* which protrude into the soft calcic horizon and which upon breaking up into *clay lumps* introduce material into the soft calcic horizon. These clay lumps break up in turn into *clay nodules* which rise up through the calcic horizon and are *expelled* at its top. The combination of the rise process and the subterranean gilgaî formation is called the *mechanical replacement process*. It leads to a downward *migration* of the soft calcic horizon.

Section 6.3 contains an analysis of the factors which control the downward migration of the calcic horizon. A model is formulated that illustrates their combined effect under natural conditions. Computations show that the speed of the downward migration of the calcic horizon exceeds the speed computed in the chemical dissolution model and is capable of matching the common erosion rates of the area.

The question of how a calcic horizon reconstitutes itself after it has been locally damaged is treated in Section 6.4. Field evidence of local damage to calcic horizons is reviewed and explained on the basis of the mechanical replacement model.

Several factors may cause a disruption of the mechanical replacement process in the soft calcic horizon. Field evidence of disruptions of various types is presented and discussed in Section 6.5.

The implications of the mechanical replacement process for the genetic concepts on the soft calcic horizon are reviewed in Section 6.6. Since the soft calcic horizon can accumulate lime on its way downward, the search for its genesis can be narrowed to the genesis of a much thinner *'incipient continuous soft calcic horizon'* which starts the mechanical replacement process. For the genesis of this horizon a number of options from the literature are reviewed. It is concluded that the most likely process initiating the formation of this horizon is the illuviation of lime particles formed by evaporation of bicarbonate solutions in large cracks, towards the average level of the groundwater table.

6.1 THE ROLE OF THE CHEMICAL DISSOLUTION OF LIME IN THE MOBILITY OF CALCIC HORIZONS

This section deals with the question of whether chemical dissolution of lime can give sufficient mobility to calcic horizons in order to match representative erosion rates under present and past conditions in the survey area.

In Section 2.5 a review is given of the various existing theories on the genesis of calcic horizons. All authors in favour of a pedogenetic origin assume that the dissolution and recrystallisation of lime are factors influencing the formation process. Most authors agree that for thick calcic horizons, especially if formed on or in materials which do not consist for a large part of $CaCO_3$, a large time span will be necessary. Gardner (1972) computes ages between 0.4×10^6 yr and 2.5×10^6 yr for the formation of a thick 'caliche'.

Large time spans are assumed by authors in favour of aggradational and degradational modes of origin. In the case of the Miocene clay in the Mérida area, the aggradational model is discarded, since geological evidence shows that the Miocene clays have been subject to considerable erosion since their deposition (Section 3.3). This raises the question of how calcic horizons, after they have been formed, can remain intact over large periods of time when the soil in which they are contained is subject to erosion at the top and rejuvenation at the bottom.

For the Mérida case a degradational model is tested in which it is assumed that a calcic horizon keeps pace with a downwearing surface by dissolution at its top and crystallisation deeper down. Authors with similar concepts are quoted in the penultimate paragraph of the introduction of Section 2.5. The case is tested by calculating the maximum rate at which lime can be dissolved (see Fig. 29) and soil material

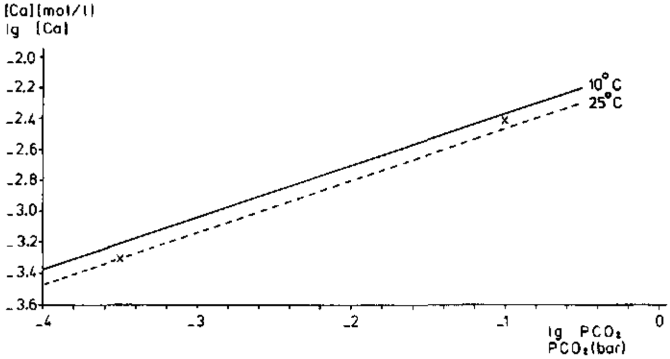


Fig. 29. Dissolution of $CaCO_3$ by water at various CO_2 pressures. The concentration [Ca] in mol/l is plotted as lg [Ca] against P CO_2 in bar as lg P CO_2, for two different temperatures. The dotted line represents lg [Ca] = 1/3 lg P CO_2 - 2.13 for 25°C while the solid line represents lg [Ca] = 1/3 lg P CO_2 - 2.03 for 10°C. Activities equal to unity are assumed. The two crosses (x) show the error made due to this assumption on the basis of values from Lindsay (1979) for the 25°C case. It is evident that these errors are small up to values of P CO_2 of 0.1 bar.

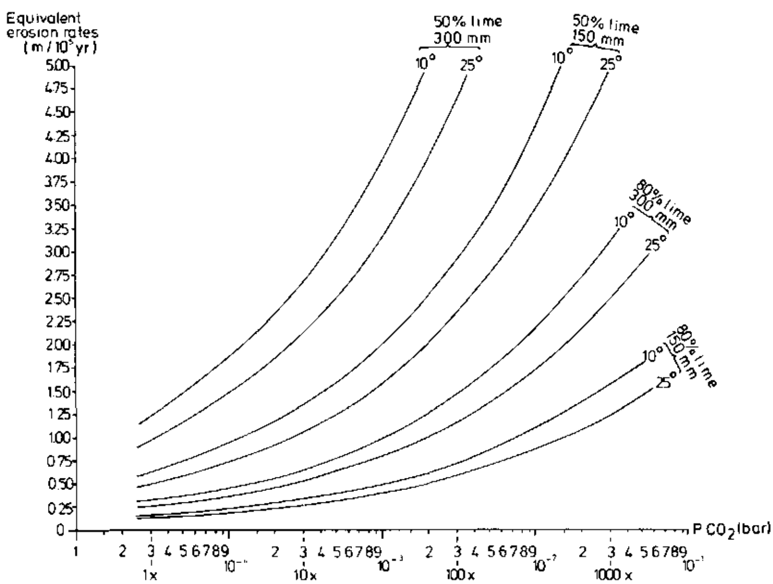


Fig. 30. Equivalent erosion rates which can be matched by the liberation of noncalcitic solids out of calcic horizons which dissolve due to leaching, plotted against P CO_2 on a logarithmic scale. The curves represent $A \times 10^{(1/3 \lg P CO_2 - 2.13)}$ for the case of 25°C and $A \times 10^{(1/3 \lg P CO_2 - 2.03)}$ for the case of 10°C. The factor A has values of 250, 500, 1000 and 2000 for lime contents and leaching intensities of (80%, 150mm), (80%, 300mm), (50%, 150mm) and (50%, 300mm) respectively. See explanation in the text. The area between the lines indicated by (10°, 80%, 150mm) and (10°, 50%, 150mm) is representative for the leaching of lime under present day conditions in the survey area. The factors 1, 10, 100 and 1000 indicate the ratio of the CO_2 pressure to the average atmospheric pressure of this gas. The calcic horizons are assumed to be pure $CaCO_3/Ca(HCO_3)_2$ systems. Activities equal to unity are assumed which allows for reliable approximations up to values of P CO_2 of 0.1 bar (see Fig. 29).

consequently liberated at the top of the calcic horizon, in order to compensate for soil losses due to erosion at the surface ('equivalent erosion rate'). On the basis of this simple model in which the recrystallisation of lime deeper down is not quantified, conclusions can be drawn as is described in Section 6.1.6. The so-called 'equivalent erosion rates' which can be matched by the aforementioned process are calculated for two temperatures: 10°C and 25°C; for two compositions of the calcic horizon: lime percentages (by weight) of 50 % and 80 %; and for two leaching intensities: 150 mm and 300 mm per year. All cases are considered for a range of CO_2 pressures varying from 1 to 1000 x the atmospheric CO_2 pressure. The results expressed in a rate of $m/10^5$ yr are shown in the form of a group of curves in Fig. 30. These rates are compared with various past and present erosion rates reported in the literature and with estimates of present and past erosion rates in the survey area. These data are summarised in Table 15.

The tested hypothesis is very similar to the one proposed by Knibbe in an unpublished note (1974b). He claims that the lime of both the Miocene and the Schist landtypes originates from these parent materials by a gradual concentration during the

Table 15. Summary of present and past erosion rates computed for soil materials of an average bulk density of 1.5 g/cm^3 from the sediment data reported in Section 6.1.4.

Erosion rate ($m/10^5$ yr)	Subject	Source	Conditions
1.7	Very large areas	Holmes (1965)	Average long-term (100 million years) erosion rate converted from rock-(BD 2.5 g/cm^3) to soil-(BD 1.5 g/cm^3) erosion
133	22 Italian catchments which total 28318 km^2	Gazzolo & Bassi (1964)	From suspended sediment data reported as representative for catchments that consist for 70% of easily erodible rocks. From a relationship based on 22 catchments varying in size from 226-8186 km^2, mainly located in Mediterranean climates.
58	Rio Guadajira catchment (816 km^2) representative for the survey area	Table 16 of this section	Estimated by means of an empirical regression model of Jansen & Painter (1974) for present day conditions in the survey area: 450 mm precipitation and 'steppe' vegetation.
141	id.	id.	Idem for conditions which deviate from the present ones in precipitation (800 mm) and vegetation (forest).
33-80	Landtype M of the map (Fig. 3)	Bergsma (1980)	Derived from soil loss predictions from an erosion hazard classification partially according to the universal soil loss equation.

downwearing of the surface. He assumes a CO_2 pressure of 15 times the atmospheric pressure and reaches the conclusion that the calcic horizon must have gone through at least 35 cycles of dissolution and precipitation while the surface was wearing down, during the last 1 million years.

6.1.1 The dissolution of $CaCO_3$

The dissolution of $CaCO_3$ in the soil is governed by the partial pressure of CO_2. The following relation is valid for a pure system under equilibrium conditions at a temperature of 25^oC:

$$\lg [Ca] = 1/3 \lg P\ CO_2 - 2.13$$

In this formula [Ca] is expressed as mmol/l and P CO_2 as bar. For the derivation of this relation in the carbonate/bicarbonate system see Bolt (1963). Substitution in this derivation of the values corresponding to 10^oC for the solubility coefficient of CO_2 (Durand, 1959) and the first and second dissociation constants for H_2CO_3 and the solubility product for $CaCO_3$ (Kharaka & Barnes, 1973), leads to the following relation valid for a temperature of 10^oC:

$$\lg [Ca] = 1/3 \lg P\ CO_2 - 2.03$$

These two relationships are graphically represented in Fig. 29.

6.1.2 Computation of the equivalent erosion rates that can be matched

On the basis of the equations of Section 6.1.1 it is possible to calculate the equivalent erosion rates to be matched by the dissolution of calcic horizons liberating insoluble material included in them. For this simplified model, in which recrystallisation of $CaCO_3$ lower down in the profile is disregarded, the following is borne in mind: The thickness of the layer of material liberated by the dissolution of $CaCO_3$ is proportional to the amount of water leaching the calcic horizon. It is inversely proportional with the bulk density of the material liberated and with the ratio of lime to non-calcitic solids in the calcic horizon. The concentration [Ca] has to be converted from mol/l to grammes of $CaCO_3$/l. This leads to the following combined factor by which the [Ca] has to be multiplied in order to find the equivalent erosion rate that can be matched, in cm/yr:

$$\frac{P \times C}{B \times S}$$

The symbols have the following meaning:

P = Annual amount of water leaching the calcic horizon in l/cm^2.

C = 100; The conversion factor from [Ca] in mol/l to the equivalent amount of $CaCO_3$ dissolved in g/l.

B = 1.5; The bulk density of the liberated solids. Compare Table 9 for the bulk density range of the clay nodules.

S = Number of grammes of $CaCO_3$ to be dissolved in order to liberate 1 g of non-calcitic solids.

Multiplication of the formula by 1000 converts the dimension of the conversion factor from cm/yr to m/10^5 yr:

$$A = 1000 \frac{P \times C}{B \times S}$$

For a case in which 150 mm of rainwater leaches a calcic horizon which consists of 80 % lime (which means that 4 g of lime have to be dissolved in order to liberate 1 g of non-calcitic solids), the following equation results for the equivalent erosion rate:

$$1000 \frac{0.015 \times 100}{1.5 \times 4} [Ca] = 250 [Ca] \ m/10^5 \ yr$$

For leaching at 25°C, substitution of the pertinent relation for [Ca] leads to:

$$250 \times 10^{(1/3 \lg P CO_2 - 2.13)} \ m/10^5 \ yr$$

Ditto for 10°C:

$$250 \times 10^{(1/3 \lg P CO_2 - 2.03)} \ m/10^5 \ yr$$

Similarly a conversion factor (A) of 500 results for 300 mm water leaching a calcic horizon of 80 % lime content. Leaching intensities of 150 mm and 300 mm for calcic horizons that consist of 50 % $CaCO_3$ by weight lead to conversion factors (A) of 1000 and 2000 respectively.

In Fig. 30 the results of these computations are plotted, leading to a group of curves that show the equivalent erosion rates to be matched on a linear scale, plotted against the P CO_2 on a logarithmic scale.

Under the present circumstances, leaching never exceeds 150 mm at level sites where all the rain penetrates. Most of the leaching takes place at temperatures of about 10°C since winterrains predominate (see Fig. 30). The lime content of the calcic horizons of the Miocene landtypes of the survey area varies from about 50-80 %. (See Fig. 30 and the analytical data of the soil profiles of Section 4.3.1.) As such the area between the curves marked (10°, 80 % lime, 150 mm) and (10°, 50 % lime, 150 mm) represents the maximum effect of dissolution to be expected for present day circumstances. The other curves of Fig. 30 are added to illustrate the effect of climatic conditions which may have prevailed in the past.

The following factors which would lower the equivalent erosion rate that can be matched are not quantified:

- Dissolution of lime depends on the grain size of the crystals; given the dominance of silt sized crystals in the calcic horizons of the survey area, the soil solutions can be expected to be undersaturated compared to the calculated values.
- Additions of lime from other sources to the surface such as, e.g., lime contained in aeolian dust, are disregarded.
- All pedogenetic processes that counteract the relative downward movement of lime such as homogenisation by biological and/or mechanical action and downward movement of solids in suspension (e.g. clay illuviation) are disregarded.

Factors not quantified that could speed up the migration process of the horizon are:

- Ion pair formation involving Ca^{++} and Mg^{++} enhances solubility. This effect is expected to be relatively unimportant, since all calcite is probably of the low-Mg type and dolomite and aragonite were not found in the X-ray diffraction of the material of the survey area. (Other soluble salts are absent in the calcic horizons of the survey area.)
- Transport of Ca^{++} through a diffusion process in a moist calcic horizon under the influence of a CO_2 pressure gradient between top and bottom of the horizon is not considered, since the concentration gradient of CO_2 over this distance is supposed to be low. It is known that diffusion processes play an important role in the transport of materials in the soil over very short distances where concentration gradients are high, such as, e.g., the formation of concretions and petrified roots. Another argument against the importance of diffusion processes in the transport of $CaCO_3$ in the soil is found in the fact that diffusion tends to heighten the CO_2 concentration in the zone where the $CaCO_3$ precipitates, which counters the process. A further (indirect) argument against the importance of diffusion of carbonates is found in the good relationship demonstrated by Jenny & Leonard (1939) between depth of carbonate accumulation and precipitation and by Arkley (1963) between depth of carbonate accumulation and depth of leaching, as mentioned in Section 2.5.2.1. It must be stressed that these authors found the relationship disregarding several factors like duration of moist soil conditions and CO_2 concentration in soil air, which are of importance for the diffusion process. Additionally it may be stated that Reeves (1976) discusses and rejects a diffusion model for calcrete formation.

6.1.3 The average CO_2 pressure in the soil

The literature contains reports of a range of CO_2 partial pressures in soils. Blatt et al. (1972) give a range of 10 to 100 x the atmospheric concentration for soil air. They observe that high concentrations are due to absorbtion of the gas molecules on clay surfaces and to the slow rate of upward diffusion of the gas. They state that in the root zone the concentration is maximal and measures at least 15 x that of the atmosphere. For deep groundwaters of humid temperate regions, however, Blatt et al. report that concentrations of up to 1000 x that of the atmosphere have been found. Lindsay (1979) uses 10 x the atmospheric concentration as a common reference level for soils. Jenny (1980) reports 10 x the atmospheric concentration of CO_2 as an average for soil air. Rightmire (1967) assumes in his radiocarbon study of caliches, CO_2 concentrations of up to 5 x the atmospheric concentration for arid areas.

It seems justified to regard 10 x the atmospheric concentration as a good average CO_2 concentration for soil air, for conditions of the study area under which leaching takes place. In places temporarily higher concentrations may occur, due, e.g., to release of CO_2 absorbed on lime surfaces. These effects, however, are very short lived. They play a role in the initial stages of wetting only, as demonstrated by Callot et al (1978). In the field during spring, pH values lower than 7.6 were not measured. The pH value of 7.6 can be calculated for a solution in contact with solid $CaCO_3$ in equilibrium with a CO_2 partial pressure of 10 x the atmospheric CO_2 pressure. Waterlogged conditions accompanied by high biotic activity, which could produce higher CO_2 concentrations, are very short-lived in the survey area too.

Introduction of this CO_2 concentration in Fig. 30 shows that the equivalent erosion rates that can be matched vary from 0.3 $m/10^5$ yr, for calcic horizons of 80 % lime content, to 1.3 $m/10^5$ yr for calcic horizons of 50 % lime content, both under present day circumstances of 150 mm leaching at $10^{o}C$.

6.1.4 Representative erosion rates

Unfortunately data on erosion rates based on measurements of suspended sediment yields of catchments of the area are lacking. The equivalent erosion rates that can be matched by the calcic horizon are compared with the following data (as summarized in Table 15), instead:

- Long term geological erosion rates for large areas.
- Measured present day erosion rates from comparable catchments in Mediterranean climates, derived from suspended sediment data of rivers.
- Erosion rate calculated for present day circumstances for a representative catchment near the study area according to an empirical formula.
- Erosion rate according to the same formula for the same catchment assuming a climate moister than the present one and for a denser vegetation.
- Erosion rates derived from soil loss predictions from an erosion hazard classification partially according to the universal soil loss equation (Wischmeier & Smith, 1978) applied to landtype M of the survey area.

Long term geological erosion rates for periods in the order of 100 million years, based on measurements of the amount of sediment discharged by large catchments and on the rate of exposure of diamond pipes in South Africa are estimated by Holmes

(1970) at approximately 1 m/10^5 yr in terms of unweathered rock.

Fig. 31 shows suspended sediment yields in t/km^2.yr^{-1} for 10 semi-arid and 10 sub-humid N. African catchments reported by Heusch & Milliès-Lacroix (1971). The catchments have been selected from their data on the basis of the similarity of the parent materials with those of the Mérida study area. The choice was restricted to marls, calcareous marls and marl-schist combinations. The total area represented by the semi-arid catchments is 59602 km^2 and the total area of the sub-humid catchments is 43764 km^2. The mean annual suspended sediment yields are plotted against the catchment sizes on logarithmic scales. The well known linear relationship between the logarithm of the catchment sizes and the logarithm of the sediment yields is evident for both climates. (The product moment correlation coefficient for the semi-arid data

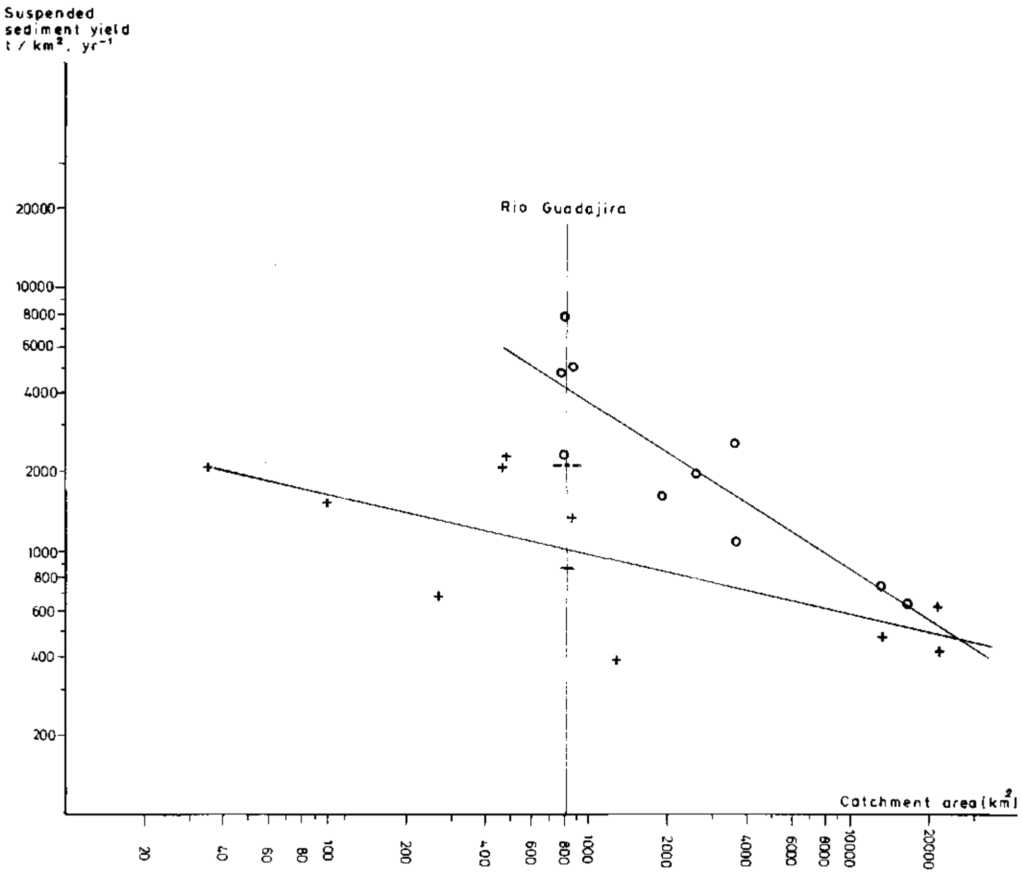


Fig. 31. Regression lines representing the relationship between mean annual suspended sediment yield and catchment size both plotted on a lg scale. The data represent 10 semi-arid (o) and 10 sub-humid (+) catchments from the Magreb. The catchments were selected from Heusch & Milliès-Lacroix (1971) on the basis of similarity with the survey area (marls, calcareous marls and marl-schist combinations). Estimates for the survey area from Table 16 have been indicated too to facilitate comparison: 450 mm precipitation as (-) and 800 mm as (-.-).

is -0.72, while it measures -0.87 for the sub-humid case.) The region between the two regression lines in the graph is representative for the survey area, since the local climate is a boundary case between semi-arid and sub-humid (Section 3.2). The Rio Guadajira catchment which is representative of the study area and for which the sediment yield has been estimated by means of an empirical formula is indicated too to facilitate comparison. The data consistently show higher sediment yields for the sub-humid case than for the semi-arid one. This fits with the general relationship established by Wilson (1973), between sediment yield and precipitation, based on 1500 catchments around the world re-calculated to a uniform size. He states that contrary to the well known relationship of Langbein & Schumm (1958), the sediment yield increases with the precipitation up to a value of 750 mm. At higher precipitations, the sediment yield decreases due to the well-known fact that increased precipitation promotes the growth of a vegetation which provides cover and protects the ground from the full force of the erosion processes. Langbein & Schumm (1958) claimed that this would cause a decrease in sediment yield from approximately 300 mm upwards.

Cazzolo & Bassi (1964) report for 22 Italian catchments, mainly in Mediterranean climates, totalling 28318 km^2 and varying in size from 226-8186 km^2, a relationship between sediment yield in suspended form and % area taken in by easily erodible rocks. This relationship was established disregarding the effect of catchment size on sediment yield. For cases comparable with the representative catchments of the survey area (approximately 70 % easily erodible rocks), they report a value of 740 $m^3/km^2.yr^{-1}$. This volume of material resulted from division of weight of the sediments by a bulk density of 2.7 g/cm^3. The equivalent amount of 2.7 x 740 = 1998 $t/km^2.yr^{-1}$ falls between the two regression lines of Fig. 31 for a large range of catchment sizes.

Jansen & Painter (1974) developed linear regression models for sediment yield of catchments for different climatic zones of the world, based on a number of parameters found to have a significant relationship with the sediment yield of the catchments used for their models. For the Rio Guadajira catchment the relationship which holds for relief length ratios > 3 m/km and C climates according to Trewartha (1943) applies:

$$\lg S = 3.055 - 1.125 \lg A + 0.585 \lg H + 1.104 \lg R + 3.056 \lg P + 3.053 \lg V$$

In which the symbols have the following meaning:

S = suspended sediment yield in $t/km^2.yr^{-1}$

A = size of the catchment in km^2

H = altitude of the catchment in m above sea level

R = relief/length ratio in m/km

P = precipitation in mm/yr

V = factor representing natural vegetation groups: desert = 1, steppe = 2, grass = 3, forest = 4.

Table 16. Sediment yield estimated for the Rio Guadajira catchment representative for the survey area, under present and past conditions according to an empirical regression model of Jansen & Painter (1974).

Size $A(km^2)$	Altitude H (m)	Relief/Length R (m/km)	Precipitation P (mm/yr)	Vegetation V	Sediment yield S $(t/km^2.yr^{-1})$
816	700	7.35	450	3 (steppe)	874
816	700	7.35	800	4 (forest)	2108

Table 16 summarises the result of the aforementioned formula applied to the Rio Guadajira catchment which is representative of the Miocene clay and Schist landtypes of the survey area. The Rio Guadajira passes less than 1 km from the southwestern tip of the survey area. The table shows the suspended sediment yield in $ton/km^2.yr^{-1}$ for present day circumstances as well as for a case which is assumed to have higher precipitation and a forest vegetation and which may represent conditions of the recent past. The results plotted in Fig. 31 show that the present day case, 450 mm precipitation and a vegetation cover qualified (due to human influence) as steppe, falls very close to the line of the semi-arid data. The case for an assumed precipitation of 800 mm and forest vegetation plots intermediate between the sub-humid and semi-arid data. The same tendency of increase of sediment yield from semi-arid to sub-humid according to Wilson (1973) is evident here. It is interesting to note that according to Gehrenkemper (1979), a natural steppe vegetation also existed in large areas of the Mediterranean during the early stages of the Würm glaciation. Taking into account that the model of Jansen & Painter (1974) was developed from catchments exceeding 5000 km^2 in size but is applied in this case to a catchment of approximately 800 km^2, the coincidence with the N. African data can be qualified as quite reasonable.

Bergsma (1980) reports estimates for erosion hazard of several landtypes in the Mérida area partially based on the universal soil loss equation. For the area coinciding with the unit M of the map (Fig. 3) he reports an estimate of 5-12 tons of soil loss per ha per year. The erosion hazard is the soil loss that is predicted to take place under present day conditions of land use and management. His estimates are equivalent to erosion rates of 500-1200 $t/km^2.yr^{-1}$. This seems to concur well with the estimates made by means of the empirical formula of Jansen & Painter (1974) for the Rio Guadajira catchment under present day circumstances, especially considering that not all the material actually eroded does leave the catchment immediately.

Naturally the erosion rate estimates based on empirical formulas are bound to be subject to some considerable error. As an approximation of the order of magnitude of the erosion rate, however, they are no doubt valid, as their comparison with actually measured data for similar conditions in Italy and N. Africa indicates.

Since it is the purpose here to judge the calcic horizon's capacity of escaping exposure due to erosion by migrating downward in the weathering zone, all values quoted so far in this section have to be converted to the erosion rates of soil material. A bulk density of 1.5 g/cm^3 for this material, which is the basis of the calculation in Section 6.1.2, is used for this purpose. Table 15 lists the erosion rates converted by this factor.

For the erosion rates based on sediment yield of catchments, the factor sediment delivery ratio has to be drawn into the comparison. This factor is defined as sediment yield/gross erosion. The delivery ratio quantifies the proportion of the total sediment produced in the catchment that actually leaves this area. The lower the delivery ratio, the larger the quantity of sediment that settles inside the catchment. The larger the catchment, the stronger the influence of this factor as can be seen from the slope of the lines of Fig. 31. The difference between the upper value of the estimate by means of the universal soil loss equation, which measures gross erosion, and the estimate for the Rio Guadajira shows this sediment delivery effect too. For calcic horizons outside the valley bottoms of the catchment, gross erosion is a determining factor irrespective of the fact that part of its products settle in the valley bottoms. Gross erosion determines whether calcic horizons are stripped bare of their soil cover or not. As such the erosion rates determined on the basis of suspended sediment yield of catchments have to be increased proportional with the inverse of the sediment delivery ratio to express their effect for the calcic horizons. It is not easy to quantify the sediment delivery ratio. Comparisons between sediment yield and estimates by means of the universal soil loss equation are normally used for this purpose. For the Rio Guadajira, the sediment delivery ratio is probably rather high, since most of the fine textured materials leave the catchment in suspended form. No estimate of the sediment delivery ratio is made, however. For the purpose of the present study it is sufficient to indicate that gross erosion rates which matter for the exposure of calcic horizons are always larger than the rates based on sediment yields. This should be taken into account when considering the rates of Table 15 which are based on suspended sediment yield.

6.1.5 Comparison of the equivalent erosion rates that can be matched by the calcic horizon with erosion rates common for the survey area

Comparing the erosion rates of Table 15 with the equivalent erosion rates to be matched by the calcic horizon as expressed in Fig. 30 and neglecting the other factors mentioned in Sections 6.1.2 and 6.1.4, the following result is obtained:

Only the non-representative long-term erosion rates can be matched by the dissolution process under a CO_2 partial pressure of 10 x the atmospheric pressure in the soil for the most favourable case of 300 mm leaching and a lime content of the calcic horizon of 50 %.

The rate calculated for the Rio Guadajira under present day circumstances exceeds the equivalent erosion rate to be matched by the dissolution process under conditions of 150 mm leaching and 50 % lime, for a CO_2 concentration of 10 x that of the atmosphere at 10°C, by a factor of approximately 40 x. The rate computed for the Rio Guadajira under circumstances which may represent the recent past exceeds the rate to be matched by the dissolution process under conditions of 300 mm leaching and 50 % lime for a CO_2 concentration of 10 x that of the atmosphere at 10°C, by a factor of approximately 50 x. Assumption of the improbably high CO_2 content of 100 x that of the atmosphere, lowers these factors for the abovementioned two cases to 20 x and 25 x respectively. On the basis of this the lime dissolution model is rejected.

The assumed higher precipitation values accompanied by forest vegetation may well be representative for the Post-Glacial warm period in the Mediterranean as mentioned by Frenzl (1967). Fig. 30 shows that a shift from winter- to summerrain has little influence on the amount of leaching since the temperature curves of 25°C and 10°C run close together.

For the testing of the lime dissolution model as the sole cause for the downward migration of the calcic horizon, there is no need to draw the larger climatic variations of the Pleistocene into the comparison. The duration of the Post-Glacial period is long enough to allow a rejection of the lime dissolution model.

6.1.6 Conclusion

It is not necessary to test a more complex dissolution model of calcic horizons, in which the lime is supposed to recrystallise in the lower part of the horizon in order to be dissolved again in the next cycle when dissolution exposes it at the top, since the following conclusions can be drawn.

The dissolution of lime in a soil solution in equilibrium with a CO_2 partial pressure now common in soil air, does not cause a continuous soft calcic horizon to migrate downward with enough speed to escape exposure by erosion under the present conditions in the survey area. This is evident from calculations of suspended sediment yield of representative catchments.

If ion pair formation due to interaction of Mg^{++} and Ca^{++} were to occur it would have an enhancing effect on the mobility of calcic horizons, diffusion of Ca^{++} under influence of a CO_2 pressure potential would also have an enhancing effect. The combined effect of these two factors, however, would be largely offset by the combination of factors that tend to decrease the mobility of calcic horizons: undersaturation of the solution, additions of lime to the surface, homogenisation of the profile and illuviation of non-calcitic solids. It is highly improbable that the balance of all these factors would amount to an increase of the equivalent erosion rates that the calcic horizon can match, by a factor of 40, which would be needed to invalidate the conclusion of the foregoing paragraph.

It is highly improbable that prevailing conditions in the recent past in the survey area caused the calcic horizons to have sufficient mobility, exclusively via the dissolution process, to escape exposure by erosion.

If chemical lime transport had been the only process responsible for the downward migration of the well-developed soft calcic horizons of the survey area, they would long ago have been caught by the prevailing erosion. This would have led to much more widespread exposure, hardening and subsequent destruction of these horizons than is witnessed in the present situation.

Additionally it may be stated that the assumption of a geogenetic origin of the calcic horizons (Section 2.5.1) would not invalidate the foregoing conclusion. The same downward migration would have to be assumed to explain why calcitic materials deposited in some period between the Miocene and the present, happen to be found now all over the area mostly within 1 m of the surface of the soils.

The fact that the foregoing calculations show that the leaching process is too slow to account for the downward migration of the calcic horizon, does not invalidate Knibbe's (1974b) postulation entirely. His assumption that the lime originated from these parent materials may still be valid, if there is another process with a speed sufficient to account for the migration of the calcic horizon synchronous with the wearing down of the surface.

6.2 MOBILITY OF SOFT CALCIC HORIZONS RESULTING FROM THE MECHANICAL REPLACEMENT PROCESS

In this section an alternative for the dissolution model of Section 6.1 is presented by means of which the soft calcic horizons can migrate downward. In this model subterranean gilgaï formation along the lower boundary of the soft calcic horizon interacts with the rise process inside this horizon. Together they constitute the mechanical replacement process as is illustrated in Fig. 38. The two constituent processes will be treated separately in the following sections.

6.2.1 Rise of clay nodules (and other objects)

This process has been studied in detail in the experiments described in Chapter 5. Fig. 38 depicts the process under natural circumstances in a schematic form. The conditions under which it is operative are discussed in Section 5.3.4. In the field a number of facts (1-7) have been observed which indicate that the clay nodules have indeed risen through the soft calcic horizon.

(1) The distribution pattern of the clay nodules in the Riola 1 profile, as drawn by Knibbe (1974b), shows that the clay nodules decrease in size with the height over the clay lumps from which they issue. This size distribution is indicative of a progressive break up of the clay nodules as they rise upwards. The larger the distance covered, the longer they have been subjected to wetting and drying. The same phenomenon was observed in the Arroyo 1 profile. Countings and size measurements were not undertaken, because most large clay nodules desintegrated into many smaller ones upon

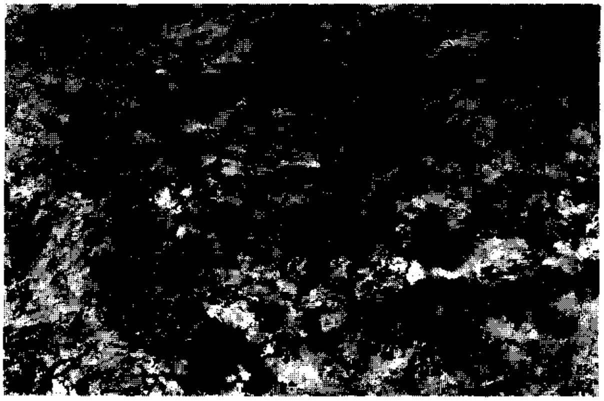


Fig. 32. Transition of the soft calcic horizon towards the overlying petrocalcic horizon of Profile Arroyo 1 (Site 2). The photo covers the horizons between 40 and 80 cm depth. The visible part of the knife measures 13 cm. The arrows indicate a concentration of clay nodules which have been hampered in their upward movement by the hardening of the petrocalcic horizon.

removal from the profile. This fact is probably due to the long exposure to which they have been subjected in the roadside cut.

(2) Fig. 32 of Profile Arroyo 1 shows indications of interaction between rising clay nodules and the formation of lime fibres. Apparently the clay nodules were still

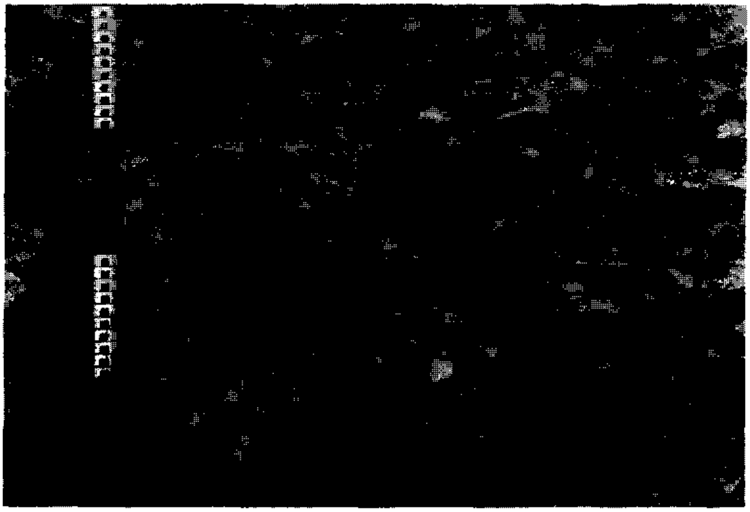


Fig. 33. Profile Arroyo 1. Two arrows indicate a white lime fibre that intersects a band of dark coloured clay nodules. The lime fibre apparently formed when the rise process of the clay nodules had come to a virtual standstill.

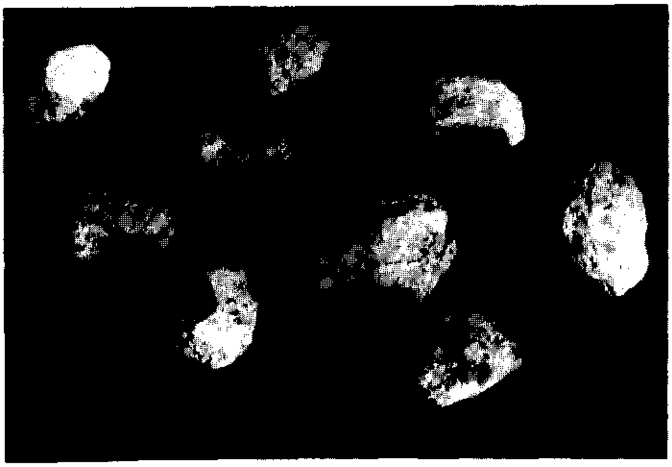


Fig. 34. Clay nodules varying in size from 0.5-1.5 cm taken from a soft calcic horizon in an exposure of Miocene clay at Site 7 (Guareña). The characteristic surface of the clay nodules with both angular and rounded edges indicates that they gradually broke up while moving upwards through the lime. The nodules were isolated in the lime and did not form clusters.

rising when the upper part of the originally soft calcic horizon became exposed and started to harden in places. The photograph shows that bands of rising clay nodules were hampered in their movement and were forced to follow a narrow passage. In Fig. 33 it is shown, however, that a lime fibre cuts through a band of clay nodules without causing any disturbance. This combination shows that the slackening of the speed of the clay nodule rise and the initiation of local hardening were synchronous. The formation of lime fibres due to chemical deposition, continued after the rise of the clay nodules had become insignificant.

(3) The shape of the clay nodules is evidence of their gradual desintegration on their way upward (Fig. 34). The clay nodules often show a sub-rounded shape with both rounded and plane or angular faces. The round faces are probably their original contours while the plane and angular faces have formed due to their breaking up during the rise.

(4) Several clay nodules are partially covered by dark iron and manganese coatings. This coating was probably acquired during or shortly after their separation from larger clay lumps when they were still subject to strong gleying. Mangans are still prominent in this zone as reported in both the profile- and the micromorphological-descriptions. A similar type of reasoning was adopted by Blokhuis et al. (1968) to account for carbonate glaebules covered by mangans which are found in Vertisols well above the gley zone in which they are supposed to have acquired these mangans. They assume that the glaebules have risen in the soil due to churning. This process may

Fig. 35. Roadside cut at Site 5, south of the village of Arroyo de San Servan. The abrupt smooth boundary between a soft calcic horizon and the overlying surface soil has a slope of 1% from the left to the right of the photo in the direction of the road (away from the observer). The boundary owes its abrupt and smooth character to a very active mechanical replacement process which expels the clay from the lime. The calcic horizon is overlain by a surface soil of 40 cm.

either imply that the glaebules rose relative to the surrounding clay matrix (like the clay nodules in relation to the lime) or that clay and glaebules rose simultaneously as a disturbed mass.

(5) The fact that the clay nodules are non-calcareous in their interior (profile descriptions of Section 4.3.1), notwithstanding the fact that they are encased in almost pure lime, indicates that their residence time in this material under alternating wet and dry conditions cannot be long. This implies a relatively high speed for their rise upward through the lime. Those encased in or under petrocalcic horizons may have occupied such positions much longer without becoming calcareous since the dense petrocalcic horizon prevents moistening once it has formed.

(6) The abrupt smooth upper boundary of the soft calcic horizon that is also generally described in the literature (Section 2.3), is considered proof of the rapid expulsion of clay nodules from the lime matrix by the rise process. In the survey area a striking example of this type of horizon boundary is presented in Fig. 35, showing a profile in a road cut located approximately 1500 m S.W. from Arroyo de San Servan. The only feasible explanation for this abrupt boundary seems to be fast expulsion of clay from the soft calcic horizon. The expulsion must be fast and active since biological homogenisation would obliterate the abrupt horizon boundary if it were slow or inactive. Alternative explanations (a) and (b) can be ruled out as follows:
6(a) Slow movement of horizons relative to each other was postulated by Ruellan

(1970) as one of the reasons for the accentuation of the upper horizon boundary of soft calcic horizons. In this particular case it is not probable that the contact is a shear layer since the slope of the horizon boundary was measured to be only 1 %.
6(b) Another possibility is to assume a sedimentary origin for the calcic horizon. In this case, however, the calcic horizon contains only 45 % lime by weight while the rest is made up of clay nodules. It seems highly improbable that such a mixture would have been deposited (recently) in a quiet environment.

(7) The fact that air enclosure has occurred is indicated by the lowering of the bulk density of the lime with decrease in depth as reported in Section 4.6.1.1. Frequent occurrence of voids (vacuoles) is reported for soft calcic horizons of Algerian soils, e.g., by Durand (1959).

In the literature a number of profiles are described which show similarity with the features of the Profiles Arroyo 1 and Riola 1 (1-5).

(1) Gile & Peterson (1966) describe the morphology of the so-called K horizons. They mention two polygenetic soils on the Mid-Pleistocene la Mesa surface along the Rio Grande Valley in southern New Mexico, USA: the Rotura soil and the Cacique soil, both of which have K horizons. From the descriptions the following is quoted. For the Rotura soil: 'At its upper margin the K horizon contains a few spheroidal inclusions of weakly calcareous or non-calcareous, reddish brown, somewhat sticky material, which suggest incomplete engulfment at Bt horizon peds by upward encroaching carbonate'. For the Cacique soil: 'It grades across a clear boundary to a K1 horizon consisting of a carbonate-whitened matrix enclosing numerous spheroidal masses of reddish brown, slightly calcareous to non-calcareous sticky Bt-horizon material. These inclusions lend a cellular appearance and are suggestive of engulfment by carbonate of a pre-existing Bt-horizon'.

(2) Gardner (1972) mentions a 'somewhat lumpy or nodular structure' for the top of the calcic horizon which forms the transition zone between an overlying petrocalcic horizon and the underlying sandy parent material of soils from Mormon Mesa County, Nevada, USA. He states that both the petrocalcic and the calcic horizon have a higher clay and silt content than the underlying material.

(3) Netterberg (1980) describes a 'powder calcrete' on Dwyka shale in which scattered pockets of clay derived from the underlying material occur. The underlying weathered shale is fissured and shattered. Many fissures are filled with powder calcrete.

(4) Wilbert (1962) publishes a photograph of a profile from Chaouïa Berrechid, Morocco, that shows a striking resemblance with Fig. 5 of Riola 1. Translating from the French and adding between brackets the terminology given in Section 2.2.1 yields the

following description: 'A laminar zonal crust (laminar petrocalcic horizon) covers a chalky or tuffaceous, stratified deposition (continuous soft calcic horizon), containing some small soft clay pebbles. The total rests on a clay loam with big calcareous spots (discontinuous soft calcic horizon) which have been subject to the phenomenon of 'mowing' through solifluction on the slope from left to right in the photograph. The total represents the Moulouyen resting on a loam which is strictly Villafranchien. Under this total, deposits from the pluvial period called Saletien.' The clay pebbles are probably equivalent to the clay nodules of the Riola and Arroyo profiles; the more so since they are found overlying a striped zone similar to the one of Riola 1. The author does not give an explanation of the genesis of the 'clay pebbles'. He shares Durand's (1959) opinion that most soft calcic horizons are due to deposition under wet circumstances. As such he considers the whole profile as an assemblage of several different deposits.

(5) Distribution patterns of stones and other coarse constituents in the calcic horizon are often chaotic in comparison with normal sedimentary structures. Such distribution patterns are indicative of the rising up of objects through the calcic horizon. Brown (1956) reports similar phenomena. He expresses the following opinion for the origin of the chaotic distribution: 'The complete mixing of clastics found in caliche is best explained by soil animals and plants aided by alternating wet and dry periods which caused opening and closing desiccation cracks and by the thrusting accompanying freezing and thawing'.

6.2.2 Subterranean gilgaî formation

The processes of soil formation in heavy cracking clay soils of tropical and sub-tropical regions with an alternating moist and dry climate which lead to the formation of Vertisols are well known and extensively described, e.g., Dudal (1965), Soil Survey Staff (1975) and Young (1976). Processes such as the formation of cracks that open and close due to swelling and shrinking, formation of surface gilgaî relief, churning and the development of slickensides and bicuneate elements are evident throughout the study area. In the Miocene clay landtype they are particularly well expressed and they also affect the sub-soils of soils with thick soft calcic horizons. In these cases, interaction of the swelling and shrinking of the clay underlying the soft calcic horizon with the movement of this lime in moist condition causes the formation of an unusual horizon configuration. In the profile descriptions so far, this is indicated as the 'striped zone'. Fig. 38 illustrates this process in a schematic way. It is described step by step in the legend (Section 6.2.3). In the survey area there are numerous indications that the formation of the 'striped zone' has much in common with the formation of a surface gilgaî microrelief in normal Vertisols. As such the process has been called subterranean gilgaî formation.

According to Hallsworth & Beckmann (1969): 'The general hypothesis of gilgaî formation is that the soil cracks on drying, and that on rewetting the material does not return to its original position.' The agreement in the literature on the main processes that form (surface) gilgaî, is reflected in the description of the Vertisols in the Soil Taxonomy System (Soil Survey Staff; 1975). The main stages mentioned are:

- Formation of a crack pattern.
- Material drops into the cracks under the influence of surface processes.
- Swelling of the clay on moistening which results in the building up of pressure, due to the infilled cracks and/or uneven wetting of the profile.
- Release of the pressure in an upward direction by deformation of the clay mass in a pattern related to the crack pattern.

This leads to the characteristic surface microrelief called gilgaî. It leads to the formation of groved shear planes called slickensides and typical bicuneate or lenticular structural elements, all of which are used as diagnostic criteria for Vertisols. The falling down of the soil material into cracks leads to cyclic movements of the soil mass, which are called churning or pedoturbation.

A characteristic difference between the formation of subterranean gilgaî and surface gilgaî is that the former cannot lead to real, complete churning of the upper soil layers since the clay pillars, which are equivalent to the mounds of the surface gilgaî, break up via clay lumps into clay nodules which disappear from the cycle by rising up through the calcic horizon as illustrated in Fig. 38.

Paton (1974) is one of the few authors who disagree with the generally accepted opinion on the formation of gilgaî microrelief. He describes horizon transitions in heavy clay soils which indicate that tongues of the underlying clay penetrate in the overlying clay layer. He calls these tongues 'fingers' or 'mukkara'. He favours load casting as the main cause of this horizon configuration since he does not find cracks in the underlying clays.

The horizon pattern of the Riola and Arroyo profiles shows similarity with some examples of Paton. There are numerous indications, however, that this is caused by a gilgaî process in the sense of Soil Taxonomy. The following aspects may be considered.

- The cracks clearly penetrate the clay layer, which shows abundant evidence of pressure and dislocation in the form of slickensides and wedge-shaped structural elements.
- The occurrence of slickensides in the soft lime fill of large cracks (Fig. 36), is a strong indication of pressure exerted on this material.
- The aforementioned features are evident in the micromorphological descriptions too. Evidence of shearing by forces so strong that even calcite crystals were crushed is reported in Section 4.5.1.2.

The intrusion of lime into cracks is also clearly demonstrated by Experiment II (Fig. 27), in which lime penetrates a cracked clay nodule. An even more striking example of lime penetration into a layered Miocene deposit was encountered in the survey area. Fig. 37a shows a profile which is located at Site 8 near Guareña, while

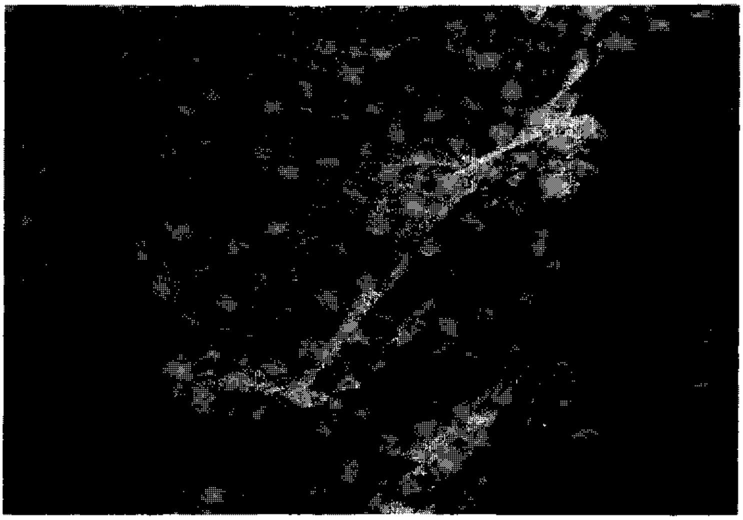


Fig. 36. Detail from the striped zone of Profile Riola 1 (Site 1). The lime which has penetrated the cracks of the Miocene clay shows clear slickensides indicating the considerable pressure exerted by the clay but resisted by the lime. The detail is from the B23ca horizon which occurs at a depth of 250-325 cm (Figs. 5 and 6). Photo courtesy M. Knibbe.

Fig. 37b shows details from that profile. The material is for the major part moderately coarse textured, but contains fine textured layers. The sandy material shows some vertical cracks, while the fine textured layers have split up into numerous angular blocky structural elements. Soft powdery lime is present in the vertical cracks and between the angular peds of the horizontal fine textured layers. The porous, moderately coarse textured material between the fine textured layers contains less than 0.1 % lime. The fine textured layers and the vertical cracks have a very high lime content, as can be estimated visually. The fact that the porous material is virtually non-calcareous, indicates that the lime was probably transported to the positions it presently occupies from the overlying calcic horizon through the cracks and not in solution through the porous sandy materials. The mechanism is probably the action of soft powdery lime which when moistened becomes a viscous mud, penetrating through the cracks into the voids of the fine textured layers. It seems that the lime 'jerks' its way stepwise into these voids by liquifying upon incipient moistening and subsequently resisting the pressure exerted by the swelling clay in the fine textured layers as these are moistened. This form of penetration is identical to the one illustrated in Fig. 38.

In the literature, several descriptions of the irregular lower boundary (Section 2.3) of soft calcic horizons contain references to features which are similar to those in the soils from the Mérida area:

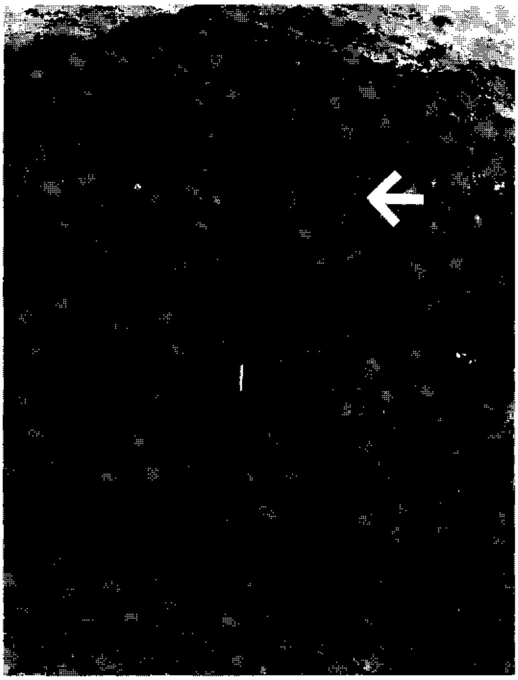


Fig. 37a. Profile in a road cut along the southern bank of the canal del Zujar, approximately 200 m east of the spot where it is crossed by the road from Guareña to the railway station (Site 8 in Fig. 3). The profile shows a remnant of a soft calcic horizon, indicated by a white arrow, which has infiltrated the underlying strata in a very unusual way. The hammer included as a reference is 30 cm long.

Fig. 37b. Detail from Fig. 37a which shows the lime in a crack of the sandy material (arrow a) and between the angular fragments of the clayey stratum (arrow b). The photograph was taken from the soil layer indicated by two black arrows in Fig. 37a. The pen measures 10 cm.

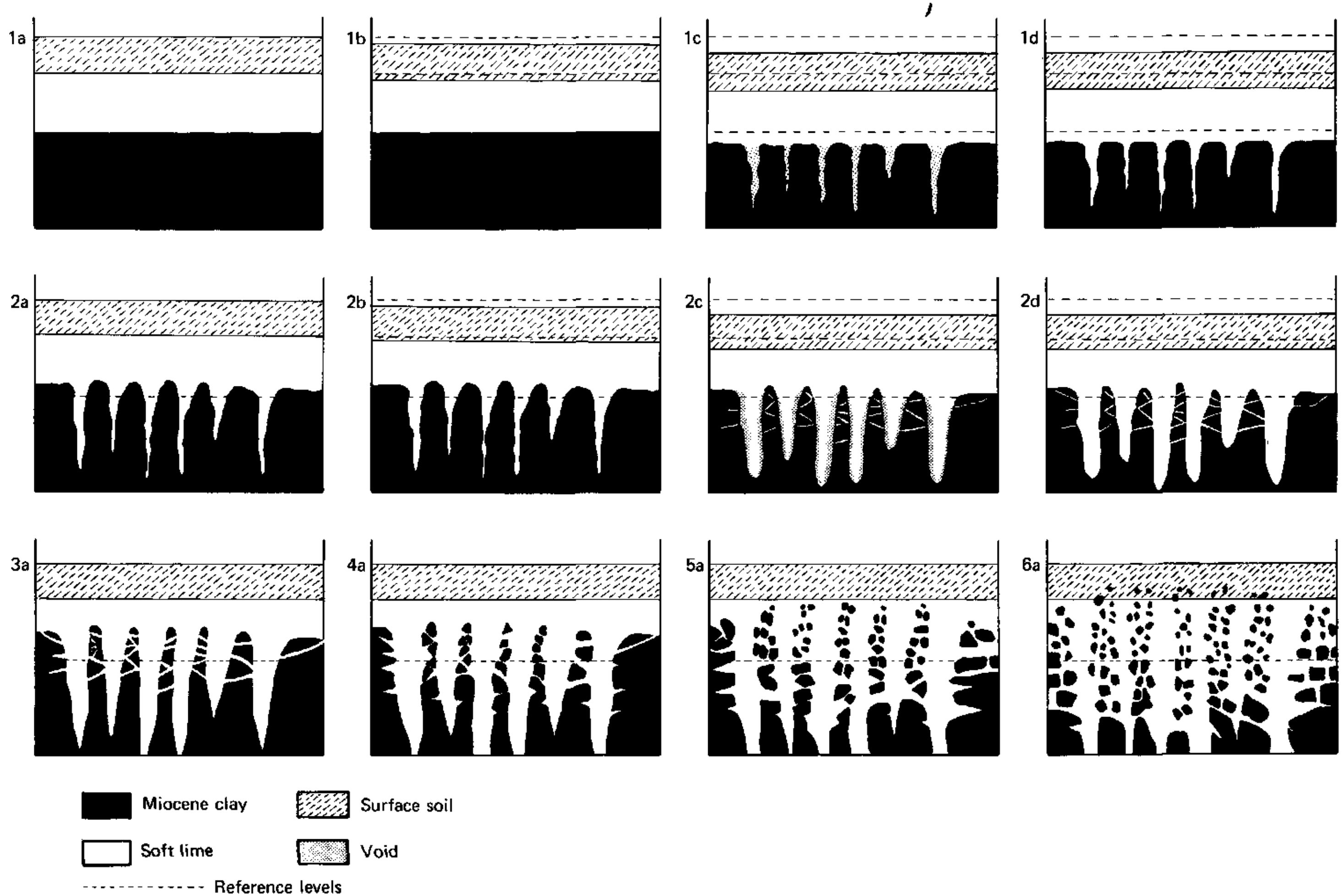


Fig. 38. A schematic representation of the interaction of subterranean gilgaĭ formation and clay nodule rise leading to a mechanical replacement process of a soft calcic horizon. A detailed explanation is given in the text.

- Reeves (1970) describes various structures found in the contact zone of 'caliche' and underlying material. He offers as an explanation for the irregular boundary the following sequence of events: drying, fracturing, buckling and subsequent filling of the resultant voids. The material that fills the voids and makes the deformations permanent is vadose silt. This material which consists of silt-sized calcite crystals is considered as very mobile by Blatt et al. (1972) who mention its presence in the voids of many rocks as a sediment that post-dates the formation of these voids by dissolution.

- Durand (1954) mentions lime masses in the cracks of a clay.

- Dumas (1969) discusses a 'striped zone' with vertical traces.

- Gile et al. (1966) describe rough prisms coated with thin layers of laminar carbonate.

- Ruellan (1968) states that in a similar zone the lime accumulation is influenced by root systems.

- Mathieu et al. (1975) describe the infiltration of 'calcite mud' in the cracked substratum underlying calcic horizons.

It seems that in the Mérida region the subterranean gilgaï formation is not restricted to the zones of Miocene clay from which most of the evidence for these processes presented in the foregoing sections has been drawn. Very similar phenomena have been observed, e.g., on weathering schists, arkoses and limestones.

The widespread presence of these phenomena throughout the dry climatic zones of the world can be explained by the fact that most clay minerals formed in the presence of lime are of the 2 : 1 lattice type and show a high swell and shrink potential. Poor crystallinity of clay minerals in the formative stage may also enhance the swell and shrink potential of the weathering zone. Mohr et al. (1972) describe Vertisols in kaolinitic materials which owe their characteristics to the latter factor.

Other factors that may aid the penetration of lime in the weathering zone independent of swell and shrink are chemical replacement (épigénie) and the force exerted by crystallising lime. These factors are discussed in Sections 6.6.2 and 6.6.3 respectively.

6.2.3 A mechanical replacement process as a combined result of the rise- and gilgaî formation-processes

The combined effect of subterranean gilgaï formation and clay nodule rise is represented in Fig. 38 in which the process is schematically condensed to five cycles, each of one year's duration. The first two cycles have been divided into four seasons each. The sequence is described as follows:

1a. The initial situation in mid-winter. Both lime and clay are moist.

1b. The situation in early summer. The lime has dried out first due to evaporation from the top. This has led to some decrease in volume of the lime (see Chapter 5) and

Fig. 39. Horizontal cut of the striped transition zone between the soft calcic horizon and the Miocene clay at a depth of 260 cm in Profile Arroyo 1 at Site 2. The lime-filled cracks show a roughly hexagonal pattern which is similar to gilgaĭ surface patterns. The rounded shape of the lime pockets is due to pressure developed when the lime penetrated the cracks. This process is called 'subterranean gilgaĭ formation'.

to a minor subsidence of the surface soil.

1c. The situation in mid-summer. The drying has proceeded into the clay layer, resulting in loss of volume of the clay mass. The surface soil has subsided and a network of shrinkage cracks has formed in the clay. In projection these cracks show a hexagonal pattern as is evident in Fig. 39 which shows a horizontal coupe of the striped zone of the Arroyo 1 profile.

1d. The situation in autumn when the first rains have fallen. The lime has remoistened leading to air enclosure, local liquifaction and remoulding especially near the large voids which have filled up with lime. In the schematic drawing it has been assumed that the increase in volume of the lime due to air enclosure was compensated for by the subsidence caused by the infilling of the cracks. As such the surface soil has not moved.

2a. The situation in mid-winter when sufficient rain has fallen to moisten the whole profile. After the lime had moistened and filled the cracks, the clay (which is more slowly permeable) started to moisten and swell. The voids, however, did not close since the lime (after some compression) resisted the exerted pressure due to the fact that the angular calcite grains trapped in the cracks interlocked and developed a grain pressure. Evidence of this is shown, e.g., in Fig. 36. The result was that the plastic clay changed shape, releasing the pressure by rising up between the cracks in the form of pillars. Heaving and deformation of the overlying lime mass caused the soil surface to return to its original level.

2b. The situation in early summer. The lime has dried out and the surface has subsided slightly.

2c. The mid-summer situation. The clay has dried out and the cracks have reopened. Voids have formed between the lime fill and the walls of the cracks. The pillars have cracked and have split into clay lumps. The surface has subsided due to the decrease in volume of the clay.

2d. The situation in autumn. The lime was remoistened by the first rains resulting in air enclosure, local liquifaction and remoulding. The voids along the walls of the cracks have filled in, while minute quantities of lime penetrated between the lumps. The surface soil did not subside since the infilling of the cracks was compensated for by the air enclosure in the lime.

3a. The mid-winter situation. The clay was moistened and has swollen. The clay pillars have extended further into the lime mass since the lime in the cracks resisted the pressure. The clay lumps moved relative to each other and more lime entered the cracks that separate them. The soil surface has returned again to its original position.

4a. The mid-winter situation after one more full cycle has passed. The cracks have penetrated further into the clay and the clay pillars protrude further into the soft lime and have broken up into clay lumps which in turn have separated into clay nodules. The latter have become subject to the rise process in the soft lime.

5a. The mid-winter situation after one more full cycle has passed. The cracks have extended further downward and the pillars have been largely broken up via clay lumps into clay nodules. The latter have risen and have almost reached the surface soil.

6a. The mid-winter situation after one more full cycle has passed. The processes have proceeded further and some clay nodules have been expelled from the soft calcic horizon and have been incorporated into the surface soil where they desintegrate and mix with the soil material.

It is evident that in the field the effect of each cycle is much smaller than indicated in Fig. 38. The starting point as presented in drawing 1a does not exist in reality (see Section 6.6.4). The schematic representation, however, gives an impression of the interaction of the gilgaî formation and the rise process as they occur in the natural environment (documented in Sections 6.2.1 and 6.2.2).

The mechanical replacement process will lead to an increase in thickness of the surface soil as more and more clay is added to it. Consequently the calcic horizon will migrate downward. If surface erosion removes soil material from the surface soil and these losses are compensated for by clay nodules from below, the whole system will migrate downward. The latter case is represented in Fig. 43, which deals with deformation of structures due to this migration.

For the M landscape of the survey area the downward migration can be derived from proof by negative demonstration, as mentioned in Section 6.1.6: If no process existed to cause the downward migration of the calcic horizon synchronous with the downwearing of the land surface by erosion, the calcic horizons of this landscape would all have been stripped bare of their soil cover. This would have led to a much more widespread hardening of the calcic horizon than is witnessed in the present situation, and soft calcic horizons not crowned by petrocalcic horizons on their tops would be virtually absent. Of the two options open for such a migration, namely the chemical transport of lime and the mechanical replacement process, the chemical dissolution is ruled out in Section 6.1 since the speed of this process is not in proportion with the erosion rates estimated by various different means for the M landscape. The mechanical process can cause a migration speed of the calcic horizon which is of the same order of magnitude as the rates of erosion estimated. This aspect is treated quantitatively in Section 6.3.

Due to the downward migration of the soft calcic horizon, cases may arise in which the calcic horizon contains objects 'non-related' to either the material presently overlying and underlying this horizon. The 'residence time' of objects contained in the fine crystic matrix of the soft calcic horizon depends mainly on their size (Chapter 5). Objects the size of the calcite crystals will probably not be expelled at all, while larger objects rise up in the horizon. Large stones may not rise as fast as clay nodules of similar dimensions as suggested by the result of Experiment IIIb1 of Section 5.2.5. As a result fine-grained mineral constituents probably accompany the horizon for extended periods while it migrates downward. Larger objects accompany it for shorter periods, before they are expelled from the top of the horizon. The result of the temporary enclosure of objects of all sizes may be that in the course of time, the mineral suite of the calcic horizon becomes different from that of both the overlying and underlying horizons. This can result from the gradual accumulation of minerals from different parent materials through which the calcic horizon has passed. In such a case the calcic horizon contains some additional minerals not present in the overlying or underlying horizons.

No mineralogical investigations have been carried out to verify this for the M landscape in the Mérida area. In the literature, however, this occurrence is verified with reference to soft calcic horizons in Algeria described by Durand (1959), as mentioned in Section 2.5.1. He supports his thesis that these horizons are geogenetic by pointing to deviating mineralogy and to the large variation in surface characteristics of the quartz grains of these horizons. Brown (1956) reports differences in mineral composition between 'caliche' and overlying soil. Mathieu (1974) quotes Margat et al. (1954) who report the presence of rounded stones in a calcic horizon unrelated to the substratum and conclude that lime and stones were deposited by fast-flowing waters. Lattman (1973) reports a high degree of coincidence between: 'Poorly sorted non-calcareous fan deposits possessing over 50 % of pebble size in the surface layer' and 'extensive and well-developed lime cementation'. He suggests that the pebbles may have initiated the cementation by developing lime beards. It cannot be excluded, however, that the pebbles have been contained in the calcic horizon and are now being liberated due to dissolution of the lime.

6.3 FACTORS CONTROLLING THE MECHANICAL REPLACEMENT PROCESS

Both the aforementioned processes, rise of objects and subterranean gilgaï formation, which together constitute the mechanical replacement process are dependent on alternating wet and dry soil conditions. Only in that part of the soil in which these conditions prevail can the replacement process take place and the calcic horizon migrate. The soil materials are subject to upward movement. Their rate of production along the weathering front is of course a limiting factor for the transport of material. The calcic horizon is restricted in its movement; it is encased between the soil surface on the upper side and the weathering front or the average mean groundwater table, whichever is shallower, on the lower side.

In a landscape in which equilibrium exists, the speeds with which the soil surface, the weathering front and the groundwater table migrate downward are equal. Temporarily, disturbances of this equilibrium may occur, which modify the size of the zone in which the calcic horizon migrates downward. Factors determining the rate of migration of the soil surface, the groundwater table and the weathering front are as follows:

- The soil surface of any landscape generally erodes at a speed determined by climate, vegetation, soil and/or parent material and tectonic events which shape the landscape and determine the relief.
- A groundwater table establishes itself in the soil at a certain distance from the surface as the result of the development of an equilibrium between addition and removal of water. In most cases this results in a groundwater table which reflects the surface relief in a generalised form. Changes in addition of water are mostly related to changes in climate: amount, distribution and form of precipitation, together with changes in the vegetation which result from this. Changes in removal are mostly due to changes in the dissection pattern of the landscape: changes in depths and intricacy of the pattern and downwearing of the divides.
- In the course of time, other parent materials may be exposed by erosion, leading to the formation of different soils. Such changes may affect the permeability of soil and parent material and influence both the addition and the removal of groundwater.
- The weathering front proceeds downward at a speed mainly controlled by parent rock and climate. The depth of the groundwater table also plays a role, since weathering under the groundwater table is minimal, compared with weathering over it. The weathering processes are generally most active in the zone in which groundwater fluctuates.
- Lime penetrates the weathering zone as mentioned in Section 6.2.2 and exerts an accelerating influence on both physical and chemical processes. Several authors claim this (Goudie, 1972). Young (1964) describes fracturing of sandstone cobbles embedded in caliche. In his opinion the main cause of the fracturing is the force exerted by the crystallising calcite which is fed by a bicarbonate solution in the pores. The same phenomenon is reported by Capolini & Sari (1975). See also Section 6.6.3. Nahon

et al. (1977) state that calcic horizons are capable of digesting fossile laterite crusts.

As a consequence of the accelerating influence of the calcic horizon on the weathering, it is common to find the lower boundary of the calcic horizon coinciding with the weathering front, which in turn is positioned generally close to the average groundwater table. If the weathering front maintains a reasonable distance from the soil surface, the soft calcic horizon retains its original characteristics, if it can match the speed with which the system moves down. (Exceptions to this case are dealt with in Section 6.5.)

Various types of calcic horizons can be observed in the study area. They vary in thickness, composition and depth and in the type of horizon boundary which they share with overlying and underlying horizons. The main types that occur have been described in Chapter 4. In many cases the various types show gradual lateral transitions (Fig. 10) which suggest that different types descend from each other. This is explained by a dynamic model which shows how a calcic horizon is subject to changes in morphology and depth in the course of time (Fig. 40). This figure illustrates how the calcic horizon reacts to the movements of weathering front, groundwater table and soil surface in a landscape with a surface which is being worn down in various erosion cycles. This gives a schematic representation of the fate of a profile (the position of which is indicated by an arrow in the cross-sections of the landscape). The x axis represents time and the y axis represents the distance covered in a downward direction by respectively: the soil surface, the top of the soft calcic horizon, the bottom of the soft calcic horizon which coincides with the weathering front, and the average groundwater table. The figures under the graph correspond to the situations in the different erosion cycles, which have been represented in the cross sections. The parent material is assumed to be easily weatherable, so that the calcic horizon will rapidly follow a falling groundwater table. The erosion cycles are initiated by headward erosion of the drainage system, which causes a fall of the groundwater table throughout the area. Downwearing of the divides follows the incision of the drainage ways.

The following sequence of events is illustrated in the model (Fig. 40):

1. In the initial situation there is equilibrium. The surface soil is worn down slowly. Losses of material on the surface are compensated by the clay nodules that rise through the soft calcic horizon. (The clay nodule content of the calcic horizon is relatively low.) The bottom of the calcic horizon is situated close to the average groundwater table.
2. An erosion cycle has been initiated. Incision of the drainage system is taking place, leading to a rapid fall of the groundwater table of the area. Surface erosion has not yet increased much. The calcic horizon reacts to the falling of the groundwater table by an increase in the upward transportation of clay. It expands in thickness equivalent to its dilution by the clay nodules. It becomes 'bloated' by the clay it consumes and whose former space it invades. In an extreme case, the continuous

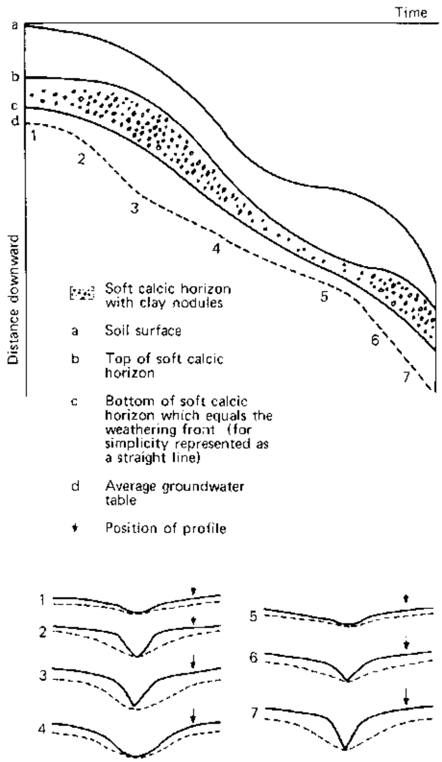


Fig. 40. A dynamic model for the behaviour of a soft calcic horizon that migrates down under the surface of a landscape subject to various cycles of erosion. Time is plotted on the horizontal axis. Distance covered in a downward direction by the soil surface, the calcic horizon and the average groundwater table are plotted on the vertical axis. The schematic cross sections at the bottom of the figure correspond in number with the various situations of the graph. Detailed explanation is found in the text.

soft calcic horizon may change temporarily into a discontinuous soft calcic horizon (Section 6.5.3).

3. Surface erosion due to downwearing of divides is now increased and a new equilibrium is established. The higher loss of surface material is compensated by an increased transportation of clay through the calcic horizon. The bottom of the calcic horizon has not been able to keep pace with the rapidly falling average groundwater table and is further separated from it.

4. The incision of the drainage system has reached base level. This leads to a decrease of the speed at which the groundwater table falls and the calcic horizon is catching up with it. The transportation of clay through the calcic horizon diminishes. The calcic horizon itself diminishes in size as it purifies itself from the large quantities of clay nodules. The surface erosion starts to diminish too.

5. A new equilibrium has been established between the reduced surface erosion and

the reduced transportation of clay. The bottom of the calcic horizon is situated close to the groundwater table again.

6. A new erosion cycle has started. Incision of the drainage system causes the groundwater table to fall. The bottom of the calcic horizon follows and the transportation of clay through the calcic horizon starts to increase. Surface erosion has not yet accelerated.

7. Surface erosion has increased and can just be matched by the increased transportation of clay through the 'bloated' calcic horizon.

In nature a number of variations and complications of the aforementioned model may occur. In the contact plane of lime and parent material a perched water table may establish itself. This may control the downward movement of the calcic horizon during the period it persists. Another complication may arise from the establishment of a so-called 'dead horizon' which is a dry zone that separates the rain-moistened upper part from the groundwater-moistened lower part of the calcic horizon. This latter complication will be dealt with in Section 6.5.3.

The model of Fig. 40 is an illustration of the boundary conditions by which the movements of the soft calcic horizon in long-term perspective are governed under natural conditions in a landscape subject to degradation. The present day situation in those parts of the Miocene clay landscape that are not covered by petrocalcic horizons corresponds with Situation 3 of Fig. 40, because groundwater tables have fallen deeply in the last few thousand years. This is due to the man-induced destruction of the natural vegetation which has increased run-off and has minimised groundwater recharge (Section 3.4). Locally this has induced the formation of discontinuous soft calcic horizons. All variations covered by the model of Fig. 40 can be found in the cross section Fig. 10. Other evidence that backs up this model is found in the following paragraphs.

In the Guareña cut (Site 7) it was noted that at rather short lateral intervals there were marked differences in habitus and depth of the soft calcic horizon. They coincide with the presence or absence of a petrocalcic horizon on top of the soft calcic horizon: where the petrocalcic horizon is present, the soft calcic horizon is pure and not deeper than 120-150 cm. Where the petrocalcic horizon is absent, the calcic horizon is full of clay nodules and its depth is over 240 cm. These differences occur over a lateral distance of only 20 metres. The differences in depth and habitus of the soft calcic horizon have probably arisen after the local hardening of the calcic horizon (Section 6.5.4). Where the petrocalcic horizon made the infiltration of rainwater almost impossible, the soft calcic horizon could not follow a rapidly falling groundwater table on its way down. Where no petrocalcic horizon impeded the infiltration, the soft calcic horizon could follow the groundwater table downward, becoming 'bloated' by the lime it consumed in the process.

The relative abundance of weakly developed soils (Xerochrepts) with soft calcic horizons on slopes in many landtypes (Section 3.5) shows that the calcic horizons have moved down in the profile, synchronous with the downwearing of the slopes. The weak profile development makes it improbable that sufficient time has passed to account for the lime accumulation in these profiles by other processes, e.g. by crystallisation from laterally moving groundwaters.

Coque (1955) described a case in Tunesia, in which downward bending of calcic horizons towards the limits of drainage ways is evident. This indicates that calcic horizons follow the groundwater table, which is drawn down by local incision.

Ruellan (1968) describes weak traces of hydromorphism as a common feature of calcic horizons. These have also been observed in the Riola and Arroyo profiles, in the lower part of the soft calcic horizon. They support the fact that the bottom of the calcic horizon, which coincides mostly with the weathering front, is often found near the average groundwater table.

Before making an estimate of the speed with which the soft calcic horizons can move downward, the process sketched in Fig. 40 must be examined critically. The velocity with which the calcic horizon moves down depends on two processes: subterranean gilgaî formation and rise of clods of weathering products produced by it. The rise of materials can only occur if the gilgaî formation detaches them. The continuity of this process, however, is not dependent on the removal of its products. This is illustrated in Point 2 of the discussion of Fig. 40, which shows that in extreme cases continuous soft calcic horizons may become discontinuous. If the gilgaî formation accelerates to a speed which is so high that the rise process cannot transport the products upward sufficiently quickly, the soft calcic horizon becomes clogged with the weathering products. All upward movement will stop if the fragments come into contact with each other and form a 'skeletal structure'. This does not mean, however, that the movement of the calcic horizon stops. The swelling and shrinking of the clay continues. The soft lime continues to fill the cracks that are formed in the weathering zone, but the fragments of weathering products contained in the lime cannot follow and are left behind. The result is that the calcic horizon leaves its 'skeletal structure' behind and continues its downward migration. The process by means of which the lime migrates involves a partial replacement of the underlying material which differs from the mechanical replacement process to which this material is subjected by the migration of a *continuous* soft calcic horizon. The discontinuous soft calcic horizon does not entirely rework the horizon through which it passes; it only widens its fissures temporarily. As such the process should rather be called *'active penetration'*. Fig. 41 illustrates clay nodules left behind by a calcic horizon in which they formed a skeletal structure. In other cases it has been observed that skeletal structures consisting of petrocalcic fragments have been left behind. Whether discontinuous soft calcic horizons can reconvert into continuous soft calcic horizons is discussed in Sections 6.5.3 and 6.6.4.

The complex relationship between the rise process and the gilgaî formation as discussed in the foregoing paragraph, has to be taken into account when making an estimate of the speed with which the soft calcic horizon can move down. The contribu-

Fig. 41. Detail of soil monolith E11 of the ISM. The photograph represents the part between 35 and 50 cm depth. Several clay nodules indicated by arrows are present in a clayey matrix. They form the parent material of this horizon. The clay nodule in the middle of the upper part of the photograph has a length of 5.5 cm. The location of Profile E11 has been indicated in Fig. 4. The clay nodules have been left behind by a calcic horizon which followed a rapidly falling groundwater table. Photo courtesy ISM.)

tion of the rise process to the movement of the calcic horizon can be quantified by applying the results of the experiments of Chapter 5. Under natural circumstances net rises of more than the measured values are probable.

In Section 5.3.3 it was concluded that the net average rise of the different objects was in the order of 0.5 mm per cycle. This means that by the rise process only, the calcic horizon is capable of migrating down at a speed that is the product of this rise and its content of clay nodules. Taking into account the bulk density data reported in Section 4.6, the lime content by weight, as used in Fig. 30, can be taken as equal to the content by volume, since the bulk densities of lime and clay are similar, at depths of about 1 metre in the profile. The following rates of movement are found:

- For a calcic horizon with 20 % clay nodules by volume: 1/5 x 0.5 mm = 0.1 mm/yr.
- For a calcic horizon with 50 % clay nodules by volume: 1/2 x 0.5 mm = 0.25 mm/yr.

These values correspond with 10 and 25 m/10^5 yr respectively.

Only by means of the rise process can continuous soft calcic horizons remain continuous while travelling downward. A prerequisite for this is that the transport capacity of the rise process exceeds or matches the supply of soil material into the calcic horizon by the gilgaî formation. The rates of movement calculated apply to such cases. They show that the rate of movement of continuous soft calcic horizons is of the same order of magnitude as erosion rates common in the survey area (Table 15). If the requirement that the soft calcic horizon remains at least partially continuous while migrating down is dropped, much larger rates of movement are possible. The speed with which a discontinuous soft calcic horizon can actively penetrate the clay is governed by the crack volume available. This speed cannot easily be quantified but it is probable that a discontinuous soft calcic horizon can easily follow a falling groundwater table downwards, provided that moistening of the lime during each winter-season continues.

Summarising, it is concluded that continuous soft calcic horizons can match the erosion rates common in the survey area, while discontinuous soft calcic horizons are capable of exceeding these rates.

6.4 RECONSTRUCTION OF CALCIC HORIZONS WHICH HAVE BEEN LOCALLY DAMAGED

Occasionally it is observed in the field that calcic horizons are interrupted locally. A few examples will be given. Two general types can be distinguished:

- On its way downward a calcic horizon encounters an object which is unweatherable or slowly weatherable. When this object is by-passed, a local interruption of the calcic horizon results.
- Sometimes the calcic horizon is breached locally as a result of gully erosion. When the gully fills up, a 'plug' of material interrupts the continuity of the calcic horizon.

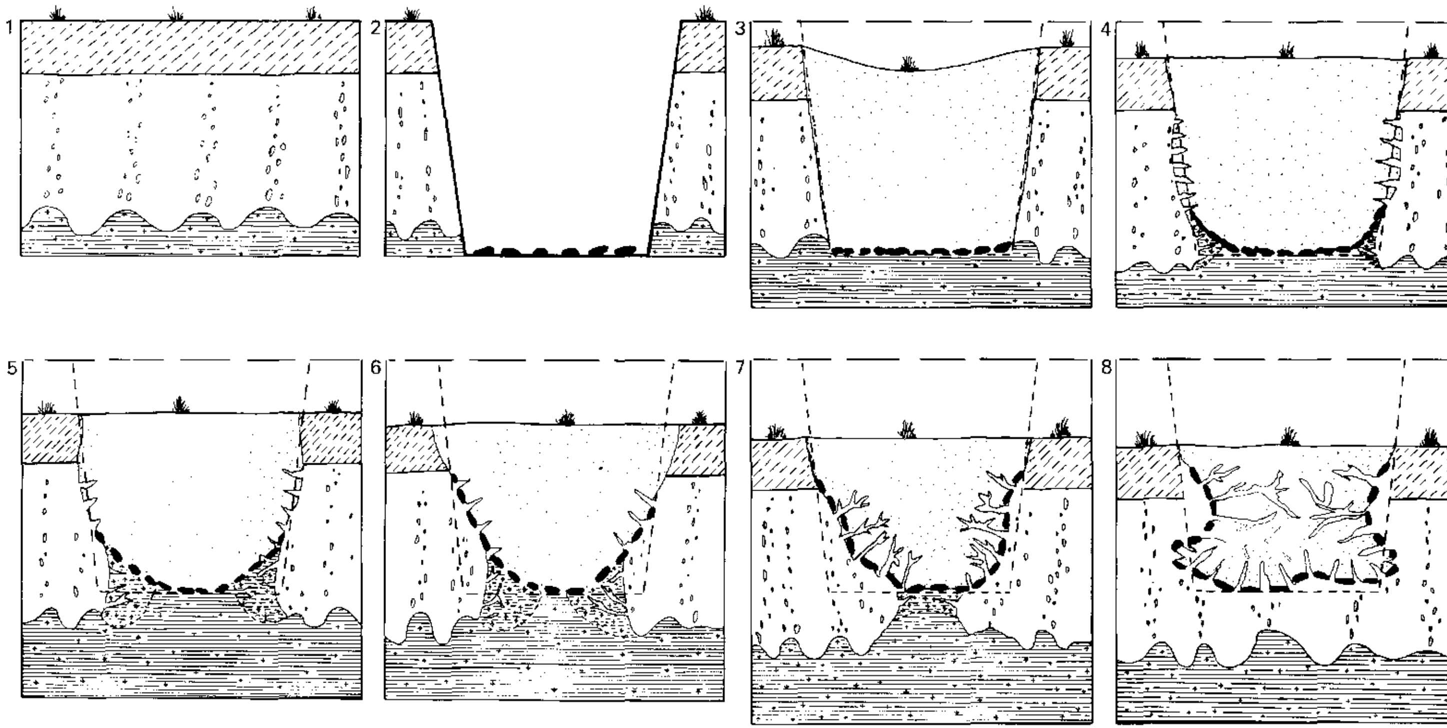
The fact that such 'scars' are only rarely found in calcic horizons, while encounters of both types must have been numerous in their long history, is a strong indication that they are able to reconstitute themselves. In both cases the scars are 'repaired' by lateral movement of lime which closes the gaps synchronously with the downward movement of the whole system. Though never fluid in its entirety, the behaviour of the soft calcic horizon, when viewed in time, has much in common with the behaviour of a liquid. The tendency to form abrupt upper boundaries is one of the properties it has in common with a fluid. Another is the lateral movement of calcic material in the profile. The reason is that locally and temporarily the calcic horizon is in a fluid state (as demonstrated e.g. by Fig. 27 and Figs. 37ab).

Fig. 42 shows a profile with a soft calcic horizon in the process of by-passing an unweatherable object. The object in this case is a dike of fine-grained basic intrusive rock, which forms a so-called lamprophyre in a body of contact metamorphous hornfelsic schist just N. of Mérida. The calcic horizon actively penetrates the hornfelsic saprolite, from which several fragments have been detached and are contained in the horizon. The average lime content of the horizon, as measured from two samples on either side of the inclusion, was 76 % (mass fraction).

Fig. 42. A dike of fine-grained material (lamprophyre) is being by-passed by a soft calcic horizon. The fine-grained basic material is less weatherable than the rocks which it intrudes (hornfelsic schists). Green saprolite from schist is present as a continuous phase below the weathering front at 170 cm. Fragments of this saprolite occur in the soft calcic material on either side of the dike. The photograph was taken in an excavation at the parking lot of the Mérida football-field indicated as Site 6 in the Schist landtype (Fig. 3). Each block of the measuring tape represents 10 cm.

Examples of 'repair' of damage inflicted by erosion gullies on a soft calcic horizon can be found in the exposure of Miocene clay, along the road towards Guareña, in the extreme eastern corner of the survey area (Site 7). In this cut several structures are present, representing various phases of regeneration of calcic horizons which have been incised locally by gully erosion. The infilled gullies are by-passed by the calcic horizon on its way down. The lime penetrates laterally under the gully bottom and causes characteristic deformation patterns. At a later stage lime penetrates the gully fill, which may lead to a total disrupture of the original structure. The process is schematically reconstructed in Fig. 43. The following steps are distinguished:

1. The initial situation is stable: surface erosion and clay transport through subterranean gilgaî formation and clay nodule rise maintain an equilibrium resulting in a slow downward movement of the entire soil system.



Soft lime

Clay that has passed through the calcic horizon

Clay that has been formed by in situ weathering

Sandy clay gully fill

----- Limit of former gully

Stones

Sandy clay gully fill of which the cracks are penetrated by lime

Clay wedge under the gully of which the cracks are penetrated by lime

Clay nodules rising through the soft lime

— — Former soil surface

Fig. 43. Schematic representation of the various stages in which an infilled erosion gully is by-passed, deformed and expelled by a soft calcic horizon. Detailed explanation is given in the text of Section 6.4; Stage 6 to be compared with Fig. 44 and

2. An erosion gully has dissected the soil and has cut through the soft calcic horizon and into the transition zone of this horizon with the underlying clay. On the flat bottom stones are deposited.
3. The gully is filled up by a sediment of sandy clay. The slow downward movement of the surface and of the calcic horizon continues. (There may have been some local hardening of the lime previous to the filling of the gully, but to avoid complicating the case, this has not been indicated.)
4. The downward migrating calcic horizon passes the gully bottom and the lime starts to move laterally into cracks in the clay mass underlying the gully. This causes an increase in volume of the wedge-shaped clay masses under the gully. These wedges, which increase in volume by receiving more lime with every cycle of wetting and drying, exert a pressure on the overlying stone layer, which consequently curves upwards. The filling of the gully has been completed now and the surface is even. Lime also starts to enter the sandy clay plug laterally along the gully walls. This causes some volume increase, which is reflected in a slight deformation of the shape of the gully. Local hardening of the lime retards the influx into the plug.
5. The lime proceeds further both downwards and laterally. The expanding wedges of cracked clay receive more lime. At their sides they loose only small amounts of clay in the form of clay nodules, since these are mainly trapped under the gully. The force exerted results in a strong deformation of the stone layer, which marks the former gully bottom. Through the gully walls more lime penetrates the sandy clay plug subjecting it to more deformation. Surface erosion shaves off any surface relief that results from these deformations.
6. The expanding clay wedges from either side of the gully bottom have now proceeded so far under the gully that they almost meet in the middle. At their sides they are gradually 'eaten up' by the process of clay nodule formation. The clay nodules move to the surface. Lime now starts to move through the curved stone layer into the sandy clay plug, subjecting it to further deformation. Fig. 44 illustrates a situation in the Guareña cut which is represented by this stage of the process.
7. The expanding clay wedges have met. Lime entering the sandy clay plug causes a strong deformation of this plug. Since the support which the clay wedges offered at the bottom has largely fallen away, the pressure in the plug is now no longer released towards the surface, but towards the adjacent soft lime, leading to further deformation of the stone layer.
8. The clay wedges under the gully have now been completely removed by the migrating soft calcic horizon. Lime continues to enter the sandy clay plug, which responds by further expansion in all directions. The lime content, inside and outside the stone layer, tends to even out. Eventually the total gully fill will be expelled at the surface and eroded.

Fig. 45 illustrates a stone distribution pattern in the Guareña cut, which matches Stage 8 of the figure.

Not all erosion gullies incising calcic horizons are assumed to pass through the

Fig. 44. The curved stone layer indicated by arrows forms the deformed bottom of a gully which dissected a soft calcic horizon in Miocene sediments at Site 7 near Guareña. The processes responsible for the present configuration are explained in Fig. 43, of which Stage 6 represents the present degree of development. Texture and lime content of the materials over and under the stone layer differ significantly. Augerings in the adjacent field confirmed that the feature has an elongated shape. Each block on the measuring tape represents 10 cm.

aforementioned Stages 1 to 8. Only deep gullies will run this full sequence; shallower ones may not get further than Stage 6'before they are discharged from the calcic layer. This applies to the gully in Fig. 44, which will not deform to reach Stage 8. Originally it was much shallower than the gully shown in Fig. 45.

6.5 INTERRUPTION AND/OR CHANGE OF THE REPLACEMENT PROCESS IN SOFT CALCIC HORIZONS

The processes responsible for the migration of the soft calcic horizon can be interrupted for a variety of reasons. Such interruptions may lead to hardening of the horizon or to a change of its habitus from continuous to discontinuous. These changes may be partial or complete. The change in habitus may be reversible. The following sections treat the cases that are distinguished.

6.5.1 Encounters with slowly weatherable parent materials

If on its way downward, the soft calcic horizon meets a kind of parent material that is not readily weatherable, the supply of weathering products will diminish. In this case, the supply of material upwards through the soft calcic horizon will not keep pace with the downwearing of the surface, which will lead to its exposure. Then

Fig. 45. The irregular stone layer indicated by arrows was marked with chalk in the field prior to the taking of the photograph to bring out this detail more clearly. It forms the remnant of the stony bottom of an erosion gully which has been deformed and is now in the process of being expelled by the calcic horizon into which it had cut its bed. Fig. 43 explains the stages of the process that causes the deformation. The present day situation conforms with Stage 8 of it. The photograph was taken at a road cut in Miocene clay at Site 7 near Guareña. Remnants of hard lime layers in al almost vertical position are present just outside the stone layer in the upper left hand corner. Every block of the measuring tape represents 10 cm.

important changes occur. In a relatively short period, the horizon becomes hardened and impermeable. For a description of the causal processes, see Section 6.5.4. A petrocalcic horizon forms and this increases run-off, leading to a general lowering of the groundwater table. As it is highly resistant to erosion, it brings the erosion rate down to approximately zero for an extended period. The destruction of the petrocalcic horizon is a slow process, in which a mechanical break up due to physical factors plays a major role, as mentioned by Lattman (1973) and (1977). Recementation of the produced rubble may occur and prolong the destruction period.

In the Mérida area, a good example of the interruption of the processes is found in the arkose landscape. In virtually every case in which the arkose surface is exposed, the material is interspersed with petrocalcic fragments, from which it can only be distinguished by means of a hand lens. The explanation is that the soft calcic horizon, which developed in the Upper-Miocene clayey material, migrated downwards and hit the resistent Mid-Miocene arkose, on which it hardened.

Locally, as mentioned in Section 3.5, calcic horizons have also been found on top of granite and gneiss. They probably descended onto the acid rocks from another overlying material (probably Miocene), which has since been removed by erosion. Upon its removal, it left behind the calcic horizon in the contact plane with the new parent material. The top of this horizon is usually hard, while soft lime is present in the cracks of the saprolite.

6.5.2 Surface erosion exceeds the transport capacity of the soft calcic horizon

If the rise process of weathering products through the soft calcic horizon cannot keep pace with the rate of downwearing of the surface, the soft calcic horizon will finally be exposed. This might occur if extremely high erosion rates persist for some time and/or if there are drastic climatic changes, which diminish the transport capacity of the soft calcic horizon. Accelerated soil erosion is probably the main cause of this phenomenon. Under natural conditions, tectonic events might also induce it locally. Drastic changes in the amount and distribution pattern of the precipitation leading to an increase of the run-off at the expense of infiltration, can also bring about the exposure of the calcic horizon. In all these cases, rapid hardening of the surface and reduced permeability and infiltration result.

Whether the entire calcic horizon will fossilise, or only the upper part, depends on the groundwater regime. If the groundwater table continues to be fed by infiltration of rainwater into the adjacent non-hardened surfaces, it may fall slowly enough to allow a small part of the lower soft calcic horizon to follow. If the hardening of the surface occurs synchronously over large areas, the fall of the groundwater table may be so rapid, that no part of the calcic horizon will be able to follow it. If the first case applies a split-up of the calcic horizon results.

It is indeed common in the Mérida area to find petrocalcic horizons underlain by soft calcic horizons which are continuous, these in turn being underlain by soft calcic horizons which are discontinuous (Fig. 10).

In the literature, double and even multiple calcic horizons are frequently described. Some of these, e.g., the profile represented on page 135 of Ruellan (1970), could well be the result of such a split-up.

In the Miocene clay area, some exposure and subsequent hardening of calcic horizons has taken place. The phenomenon is quantified in the description of the soil distribution pattern, as described in Section 3.5 and illustrated by the cross section of Fig. 10. The aerial photograph shown in Fig. 4 shows the exposed petrocalcic horizons in very light tones. A comparison of the aerial photograph and the cross section shows that the petrocalcic horizons are restricted to the rims of the interfluves bordering the valley sides and to some isolated ridges. The light grey areas around these outcrops owe their relatively light colour tone to the presence of petrocalcic fragments, dispersed throughout the landscape by plowing and erosion processes. The very light-toned areas indicate the true petrocalcic horizons, formed in the zones where erosion has been strongest. The valley pattern is related to fault lines, as indicated by Jung (1974), but the exposure of the calcic horizons has been caused by erosion, mainly brought about by human disturbance of the natural vegetation. Rapid incision of the valley system due to tectonic causes, may have set the stage for this man-induced erosion.

6.5.3 Changes in habitus of the calcic horizon due to changes in moisture regime

As mentioned in Section 6.3, the continuous soft calcic horizon may change its habitus to become a discontinuous soft calcic horizon, when changes occur in its moisture regime. Whether the entire horizon converts to this form or only part of it, depends on the way in which the moisture regime changes.

A rapid fall of the groundwater table may create in the profile a so-called 'dead horizon'. This, according to Buringh (1979), is an 'always dry' zone below the rain-moistened part of the profile which occurs at shallow depth in arid regions. In semi-arid regions it may be present at greater depth. This zone separates the rain-moistened upper profile parts from the groundwater-moistened lower parts (Franz & Franz, 1967). If a dead horizon is created which occurs in the middle of a continuous soft calcic horizon, the effect will be an interruption of the link between the gilgaï formation in the groundwater-moistened zone below and the rise process in the rainwater-moistened part above. When this link is cut, the lower part of the calcic horizon will become discontinuous due to the amount of soil material introduced which is not removed. The middle part in the dead zone will remain immobile for the time being and the upper part will purify itself completely of inclusions since the rise process in the rain-moistened zone continuous but is not fed by new additions from below.

It is interesting to consider the movement of the entire system including the dead zone in a degrading environment. The surface will be lowered by erosion and consequently the rainwater-moistened zone will also be lowered and penetrate the upper part of the dead zone. The dead zone will in turn lower as the groundwater table falls. The result is that new soil material formerly contained in the dead zone is worked up towards the surface soil by the rise process, while the dead zone penetrates and immobilises part of the discontinuous soft calcic horizon below. When the movement of the system continues the upper rain-moistened zone will also penetrate the discontinuous soft calcic horizon immobilised in the dead zone. The soil material of this zone will now be introduced into the continuous soft calcic horizon by a gilgaï formation process that resumes its activity and will subsequently be discharged from this horizon by the rise process.

The foregoing discussion shows that the presence of a dead horizon in a profile does not necessarily preclude the movement of soft calcic horizons by means of the mechanical replacement process. The effect of the dead zone is restricted to separating the direct link between the gilgaï formation and the rise process and acting as a temporary storage zone for the soil materials that are being moved to the surface. The establishment of the dead zone, however, affects the appearance of the calcic horizon, which will convert its lower part in a discontinuous soft calcic horizon separated from its continuous upper part by a zone relatively poor in lime.

It is conceivable that thick discontinuous soft calcic horizons reform to become much thinner continuous soft calcic horizons. If the average groundwater table stabilises for a certain period, the lime, unable to move further downward, will accumulate at this level. The swelling and shrinking active in this zone will progressively discharge clay with the accumulation of lime at this level. Given sufficient time, this may lead to the reconstitution of a continuous soft calcic horizon.

As mentioned in Section 6.3, several observations in the survey area indicate that a dilution process of the soft calcic horizon has taken place, e.g., the cross section shown in Fig. 10. It confirms the observation of Ruellan (1970) that between the different types of calcic horizons there are gradual transitions which occur laterally and vertically. He concludes from this that the different types of calcic horizons descend from each other. He specifically mentions the formation of continuous soft calcic horizons from discontinuous calcic horizons of the same type. His statement implies that reconstitution of continuous soft calcic horizons from discontinuous soft calcic horizons is possible in some way or other.

6.6.4 The process of hardening upon exposure

Examples of exposure leading to hardening of calcic horizons are numerous in the literature. Gile et al. (1965) observe that truncation of a profile with a plugged (calcic) horizon offers circumstances favourable for the development of a laminar horizon, since it brings the plugged (calcic) horizon within reach of more frequent wetting. Yaalon & Singer (1974) discuss the formation of an indurated calcic horizon on soft chalk rocks and state that the laminar crust can form sub-aerially without an overlying cover of soil. Gigout (1960) mentions that once the soft calcic horizon is exposed by erosion, this materials hardens as rainwater flows over its surface, causing dissolution and recrystallisation.

Lattman (1973) describes 'case hardening', which is a non-pedogenic form of cementation on vertical and near vertical exposures. It is caused by surface water which flows over these exposures and dissolves fine-grained calcareous material and redeposits it as cement. It can establish itself in a few years only and it affects various different materials. He distinguishes 'case hardening' explicitly from the development of petrocalcic horizons, which he supposes to be formed in the way Gile postulates, as treated in Section 2.5.2.1.

Reeves (1970) makes a similar distinction between slow induration of petrocalcic horizons according to Gile's process and rapid regional induration and formation of a laminar zone which occurs when caliche becomes plugged or when the top of it is exposed. According to him this rapid induration will start when only a thin soil layer remains overlying the soft calcic material. He states: 'No deeply buried laminated zone has been observed in the studied areas that does not somewhere exhibit evidence of past exposure'. By this he implies that laminated petrocalcic horizons can only be formed at or near the surface. He quotes the following reasons for the soft calcic horizon to remain soft when not in contact with the surface: A written communication by Gile that this is due to insufficient carbonate accumulation. A written communication from Blank who believes that the caliche remains soft because of the frequent presence of moisture, which contributes to solution, rather than precipitation of the carbonate. His comment on this last observation is that it contradicts the observation that moisture on the surface does cause induration.

In the survey area it was observed that exposed cuts of soft calcic horizons harden superficially in a very short time when exposed to surficial wetting. For example, a profile dug in a soft calcic horizon in a roadside ditch in 1973 was found to have undergone considerable surficial hardening in 1979. Hardening of roadside cuts was mentioned also by Ruellan in a remark made during the discussion of Menillet's (1975) paper. On the other hand vertical or overhanging roadside cuts that never moisten were found to retain soft calcic horizons for extended periods, e.g., the profile shown in Fig. 35. This combination of facts indicates that hardening will take place only if both water and carbon dioxide (from the atmosphere) are available to make chemical redeposition possible. This is logical, since the formation of soluble $Ca(HCO_3)_2$ can only take place in the presence of these two substances. In permanently wet circumstances, no changes affect the soft calcic horizon due to lack of CO_2. In permanently dry circumstances, no changes affect the soft calcic horizon due to lack of water. Only in the intermediate cases, in which both ingredients are present, does redistribution of lime take place. This means that optimum conditions for hardening are found at or near the surface, where moistening is frequent and where atmospheric CO_2 is freely available. Under a shallow topsoil, these conditions are fulfilled while additional CO_2 is available from the decay of organic matter. Deeper in the profile moistening will be less frequent, while the diffusion of atmospheric CO_2 towards these sites is slower. Hardening may not take place, or may be very slow.

Where the transport processes in the soft calcic horizon are active, the process of hardening will be checked. The lime mass is then constantly agitated due to the action of the weathering products (as evident in the micromorphology, Section 4.5). A certain amount of recrystallisation of the lime will undoubtedly occur, but before this redistribution can build bridges between the spar grains of the soft calcic horizon, the 'churning action' has moved them relative to each other. As such spar grains can be expected to grow evenly on all sides when subjected to a slow redistribution of lime. The fact that Netterberg (1980) reports that 'powder calcretes' are only to be found on top of clays and weathered mudrocks, could be an indication that the 'churning process' is indispensable if the cementation of lime is to be avoided.

Several soils in the area show evidence of the counter-activity of the two aforementioned processes in those soft calcic horizons which have stalled near the surface. Fig. 46 shows a clay mass trapped under the hardening petrocalcic horizon. A part of the clay seems to have been forced into a narrow vertical void. A very similar case is mentioned by Watts (1977), who describes diapiric folds due to the upward

Fig. 46. Detail of the soft calcic horizon of Profile Arroyo 1 (Site 2). Dark-coloured bands of clay nodules have been hampered in their upward movement by the local cementation of the light-coloured calcic horizon. The arrow points to a clay mass that has been forced into a narrow vertical void. The hammer which serves as a reference has a length of 30 cm.

injection of swelling clays into a pre-existing calcrete. Several soft calcic horizons in the area contain in their upper parts many broken platy petrocalcic fragments which conceivably owe their genesis to the formation of hard fibres of redistributed lime which were later broken up, when the 'churning process' resumed its activity.

Many authors who claim that the formation of thick petrocalcic horizons, contrary to surficial hardening, is a very slow process, base this claim on the fact that such thick petrocalcic horizons are found on old surfaces only. This is a dangerous conclusion, since cause and result could well be mixed up: surfaces with thick petrocalcic horizons are often very old, since petrocalcic horizons are so resistant to erosion. The best argument for slow formation of thick and often laminated petrocalcic horizons is more likely to be found in the nature of the hardening process. As soon as the surface layer has hardened, its permeability to both water and air becomes impeded. This means that the further the hardened zone grows, the lower the permeability becomes and the slower it grows.

The formation of thick laminated petrocalcic horizons is a complex process which involves more than simple downward leaching of lime dissolved in the upper layers. Apparently, dissolution of lime also takes place well below the surface, after which the solution may be sucked back by capillary action to the surface where it evaporates. Yaalon & Singer (1974) report that the higher porosity of the lower nari (lime crusts) is due to solution of fine $CaCO_3$ fragments. Siesser (1973) reports similar phenomena. He has observed unfilled pore spaces directly underlying hardpan calcrete beds. In his opinion this suggests that the supply of upward drawn carbonate was arrested before the voids were filled.

As described in Section 4.5 the laminations of the petrocalcic horizon seem to be the result of redeposition of lime. In certain layers the lime percentage increases and consequently the concentration of clasts lowers, while the reverse applies to other laminae. The force exerted by crystallising calcite (Section 6.6.3) probably plays a role in this process. Brown (1956) writes of these bands: 'The only difference between the bands and the material they enclose appears to be in the higher percentage of cement in the bands. These bands apparently have no relation to sequential deposition but have formed in secondary fractures and open spaces. No means were found to correlate them with the spatial orientation of the specimens.' Experimental evidence for the formation of calcite fibres in a sand column is presented by Dumont (1975). Sabelberg & Rohdenburg (1975) postulate that the formation of fibres in calcareous materials owes its origin to air enclosure, which prevents vertical infiltration of water and forces the solution to spread out in a horizontal plane.

6.6 GENESIS OF CALCIC HORIZONS

In this text a distinction is made between calcic horizons (according to Soil Taxonomy) which are continuous and those that are discontinuous. In the first case soft powdery lime forms a continuous phase while in the second no continuous phase of this material is present. This distinction is important since the mechanical replacement process, consisting of subterranean gilgaï formation and the rise process, can only act when continuous soft calcic horizons are present. Discontinuous soft calcic horizons can migrate by means of 'active penetration' but they do not cause complete displacement of the layers through which they pass. The minimum requirements for the first process to take place are the presence of soil materials which swell and shrink seasonally and the presence of a calcic horizon which contains sufficient lime (of such purity, grain size and crystallinity that it displays a low liquid limit) that - after the formation of the subterranean gilgaï - a continuous phase is formed by it in the upper part of the horizon.

If, at least for the continuous soft calcic horizons of the Miocene clay, the mechanical replacement process has been furnished with sufficient evidence, the search for their genesis can be narrowed. It can be concentrated on the processes that created the conditions under which the replacement could be initiated.

If the calcic horizon maintains itself for a long period, escaping erosion and accumulating lime steadily from the weathering of the strata through which it passes (Sections 2.5 and 6.1.6), the search can be restricted to those processes that initiate this phenomenon and 'prime the pump'. The very magnitude of the lime accumulations that has puzzled many researchers in this field in other areas, does not form a problem in the case of the Miocene clay of the Mérida zone if these horizons are viewed as dynamic phenomena instead of static features. No sources other than the

Miocene clay have to be considered to account for the *amount* of lime present.

The mechanical replacement process can be active in continuous soft calcic horizons which are much thinner than the present ones from the survey area. The continuous soft calcic horizon which just fulfils the minimum requirements for the gilgaï formation and the rise process as aforementioned will be called 'continuous incipient soft calcic horizon'.

The various modes of genesis proposed in the literature (Section 2.5) will be reviewed critically in the search for the processes that could form such horizons. In this review the *form* of the accumulation is considered to be much more important than the *source* of the lime, since the total quantities required for the continuous incipient soft calcic horizon are supposed at any rate to be modest. The review includes processes that lead directly to a continuous horizon and those which lead via a discontinuous to a continuous soft calcic horizon. Fig. 47 shows the main options in schematic form. The four options are discussed in Sections 6.6.1-6.6.4. Conclusions are summarised in Section 6.6.5.

6.6.1 Geogenetic: Sedimentation of lime in an aqueous environment

Deposition of lime in a lacustrine environment is a mode of formation which can account for pure continuous soft calcic horizons. Such deposits are apparently extensive in N. Africa where they are described, e.g., by Coque (1962) for Tunesia and Durand (1959) for Algeria. For Turkey they are described by Meester (1971). (See further Section 2.5.1.) Such deposits could conceivably play the role of incipient soft calcic horizons, starting the mechanical replacement process after the end of the lacustrine cycle.

In the case of the Miocene clay, this origin is not probable, since the follow-

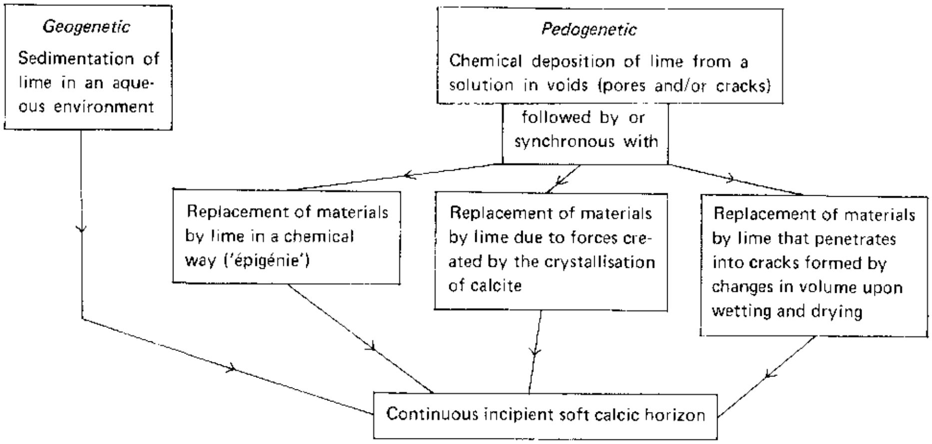


Fig. 47. Schematic presentation of the various options for the formation of a continuous incipient soft calcic horizon.

ing facts have to be taken into account:

- Fossil remains have not been found in the calcic horizons. All features described in the micromorphology can be explained by pedogenetic processes. The fact that macro-fossils are absent could still be attributed to their expulsion at the top of the horizon. But micro-fossils which, due to their size, are not subject to this process, were not found either.
- The extension of continuous soft calcic horizons, not only in the present day Miocene clay landscape but also in many different surrounding landscapes of a completely different nature, makes the lacustrine hypothesis improbable.
- Stable isotope ratios for the carbonates of the Riola profile indicate that the carbonates, if of sedimentary origin at all, have been recrystallised in the soil (Section 4.7).

6.6.2 Pedogenetic: Replacement of materials by lime in a chemical way ('épigénie')

The formation of calcite in a finely dispersed form throughout the soil mass is a common phenomenon. Such lime accumulations are called 'distributions diffuses' in the terminology of Ruellan (1970). The lime precipitates as $CaCO_3$ from a solution which contains calcium bicarbonate in ionised form. The precipitation may be induced by the evaporation of the solution, upon which calcium bicarbonate, which cannot exist in solid form, converts to calcium carbonate, with loss of carbon dioxide. Changes in the partial pressure of carbon dioxide in the solution, e.g., due to temperature changes, also affect the solubility as demonstrated in Fig. 29. It is assumed that the first crystals are formed in the small voids that constitute the pore space of the soil mass. As such a content of more than about 40 % by volume may be difficult to attain, since most soils do not have more pore space. The filling of the pore space will probably not lead to a lime content high enough to initiate the mechanical replacement process. In order to arrive at higher lime contents, this deposition must be accompanied by other processes by which the amount of lime in the horizon increases and the amount of clasts decreases.

This section reviews the role of the chemical replacement process of non-calcitic solids by lime in the transformation of discontinuous to continuous soft calcic horizons. The role of the force of crystallisation exerted by calcite is treated in Section 6.6.3.

The solution of silicate minerals is a very slow process which can occur only at very high pH values. The pH of a solution in contact with a solid phase of $CaCO_3$ is governed by the partial pressure of CO_2. Callot et al. (1978) measured the variation over a period of time of the pH of several lime samples that were moistened in contact with the atmosphere. They found that within a few minutes, a pH of approximately 9.5 was established, which gradually decreased in the course of several hours to 8.4, which they consider indicative of equilibrium with the atmospheric CO_2 concentration.

The influence of several factors on this process was investigated. It turned out that CO_2 absorbed on the surface of the calcite particles is an important controlling factor. Another factor is the degree of dilution of the system, or under dynamic conditions, the speed of percolation. The highest pH values were reached by relatively coarse-grained calcite (low amount of CO_2 absorbed) and strong dilution. Such conditions can be expected in calcic horizons for short periods only. The zone in which they are expected to occur lies well below the root zone with its high CO_2 pressure.

Degens & Rutte (1960) mention the presence of corroded quartz and felspar grains together with some secondary silica in a calcic horizon. They explain that the high pH which results from the saturation of bicarbonate solutions in these horizons has caused these phenomena. They claim that quartz and felspars are replaced 'metasomatically' by carbonates.

Nahon & Ruellan (1975) report an exchange mechanism of silicates and lime in a profile on marl in Senegal. The phenomenon which they call 'épigénie' consists in symmetric replacement. Higher in the soil lime replaces quartz, clay and dolomite while lower in the soil dolomite, attapulgite (palygorskite) and quartz are formed, replacing the calcite.

Millot et al. (1977), Millot (1979) and Ruellan (1980) claim that 'épigénie' in the sense of isovolumetric replacement of non-calcitic minerals by calcite occurs in many different materials. They find evidence of this process in schists, granites, quartsites and argillites of both micromorphologic and macromorphologic nature. This process is found to have two concurrent modes of operation in the same soil. Firstly, the rock minerals transform to clays which in turn are 'epigenised' by calcite. Secondly, the calcite replaces the rock minerals directly. The mechanism of the replacement process and the removal of its products are not yet properly understood.

Corroded silicate minerals are features commonly reported in calcic horizons (Section 2.2.2). Their frequent occurrence could just as well be proof of long periods of residence in the horizons in which they are found, as of rapid corrosion of the grains due to the high pH values.

The following has to be taken into account when trying to explain the formation of the incipient continuous soft calcic horizon by local chemical replacement of silicates by lime.

- The process which generates high pH values only lasts for a short period and probably occurs only once a year.
- The process requires a high initial $CaCO_3$ concentration.
- The process is favoured by coarse- rather than fine-grained calcite due to its CO_2 absorption in a dry state.
- If the process occurs it is assumed not to restrict itself to a very narrow zone in the soil.

6.6.3 Pedogenetic: Replacement of materials by lime due to forces created by the crystallisation of calcite

Lime accumulating in the void system of a soil as discussed in Section 6.6.2 may expel non-calcitic solids by means of the force exerted by crystallising calcite. This force plays a role in the formation of calcic horizons according to several authors. Apart from the data on weathering in Section 6.3, the following is important.

Yaalon & Singer (1974) state that volume expansion, because of the growth of carbonate cement, is possible and common in unconsolidated sediments, but that this process was not observed in the formation of a lime crust from chalk.

Watts (1980) states that high supersaturation occurs with rapid evaporation and is a requirement for displacive calcite crystallisation in calcretes.

Boulaine (1978) quotes an experiment by C. Plet proving that carbonates, just like sulphates, are capable of pushing the pre-existing elements aside while crystallising. He does not, however, give a literature reference for this experiment.

In the Soil Taxonomy System (Soil Survey Staff, 1975) the following statement regarding a petrocalcic horizon is found: 'Gravel sand and silt grains have been separated by the crystallisation of carbonates in at least parts of the laminar subhorizon'.

Brown (1956) acknowledges the role of the force of crystallisation in certain specific cases but does not want to apply it to randomly oriented calcite crystals, such as those that commonly make up soft calcic horizons. He notes: 'Some investigators have demonstrated this force in the laboratory; but apparently no one has shown that a group of $CaCO_3$ crystals, in an aqueous medium, randomly oriented in space and free to grow in any direction, will grow in opposition to constricting objects rather than in the direction of least resistance'. Brown's argument that a mass of non-aligned crystals could not be expected to grow preferentially in opposition to a constricting force needs comment on two points.

- Crystals generally have a preference for growing along a certain axis (Section 2.2.2). A different concentration is in equilibrium with the different facets of the crystal. Whether or not they change this habit will depend on the degree of supersaturation and the constricting force.
- Even if a mass of crystals which does not have a preferred orientation grows without any preferential direction, a point will be reached in which the overall effect of this multi-sided growth will be the building up of pressure.

Wieder & Yaalon (1974) state that non-carbonate clay present in a lime nodule is partially expelled to the fringes of the nodule and into the matrix. A similar observation is made on the effect of the force of crystallisation in glaebules by Truc (1975).

Concerning the role of the force of crystallisation in the formation of continuous incipient soft calcic horizons, the following should be taken into account.

- It is supposed to be a relatively slow process which only takes place in the presence of supersaturated bicarbonate solutions.
- The process is not specific for certain limited zones in the soil profile.

6.6.4 Pedogenetic: Replacement of materials by lime that penetrates into cracks formed by changes in volume upon wetting and drying

In the foregoing two cases, deposition of lime throughout the void system was considered as a prerequisite for the formation of continuous soft calcic horizons. Here the accent is on chemical deposition of lime in the larger voids.

The deposition of fine-grained calcite in large cracks and voids is a common phenomenon in calcareous soils. The bicarbonate solution in the soil matrix is drawn by capillary forces towards the walls of the voids, where it evaporates. This process is more appropriate to the larger rather than the smaller voids, since the evaporation in the larger ones is stronger. A film of fine-grained calcite is formed in this way in a crack each dry season. Results of stable isotope analysis of lime samples from Profile Riola indicate that evaporation has played a role in the precipitation of the lime (see Section 4.7).

Transport in suspension of the calcite crystals formed in the large cracks is expected, when the first rain of the winter season washes down through these passage ways. The lime in the cracks can be expected to descend to a specific level controlled by the groundwater table where no cracks occur. Such transport of fine silt-sized calcite crystals is reported by Blatt et al. (1972): 'The material known as vadose silt is found in the voids of many carbonate rocks that are subject to weathering. It fills both original and newly formed voids.' Since micro-crossbedding has been observed in thin sections, Blatt et al. presume it to be deposited by water with velocities in excess of 40 cm/sec. These velocities are probably attained by water which moves down through the vadose zone, from the exposed surface towards the groundwater table.

When the lime accumulates in the larger voids just overlying the average level of the groundwater table, a replacement process is initiated, provided the cracks open and close. In a process similar to that illustrated in the first two stages of Fig. 38, lime will 'jerk' into the cracks which extend up to the average groundwater table, forcing the soil material to deform in order to accomodate the pressures that it creates by its swelling. Gradually more lime works its way down to this narrow zone, just overlying the average groundwater table and more soil material will be expelled from this zone until a continuous soft calcic horizon is formed.

Concerning this process, the following has to be taken into account.
- It will be operative only in soil materials that swell and shrink.
- The process may concentrate considerable amounts of lime in a relatively narrow zone in a rather short period.

6.6.5 Conclusions

For the Miocene clay landtype under conditions similar to the present ones in the study area, the process sequence of Section 6.6.4 has led to the formation of incipient continuous soft calcic horizons. This process is the fastest and most efficient way to concentrate lime in a narrow zone. The other two options are less probable for the transformation of discontinuous calcic horizons to continuous ones. Chemical replacement of non-calcitic solids and replacement of solids by crystallising lime are both slow processes which are not specific to a narrow zone in the soil. Consequently much lime has to be accumulated in the voids of a thick layer of soil before the latter two processes can take effect. In a landscape like that of the Miocene clay it is to be expected that erosion of the surface soils will catch up with the accumulation zones before either of these two processes takes effect and forms an incipient continuous soft calcic horizon.

For the genesis of continuous soft calcic horizons in materials which do not produce large amounts of swelling clays upon weathering, in landscapes not subject to such strong erosion as that of the Miocene clay, chemical dissolution of non-calcitic solids and/or crystallisation forces of lime may be important factors. These may be active, e.g., in the saprolite zones of the schist soils as mentioned in Section 6.2.2. It is conceivable that such profiles are 'hybrid cases': Penetration of lime into the weathering zone is mainly due to chemical replacement or to the crystallisation forces, but transportation of chunks of detached soil material through the soft calcic horizon is similar to that of the clay nodules of the Miocene clay profiles. The profile of Fig. 42 may well represent sych a 'hybrid case'.

The geogenetic alternative treated in Section 6.6.1 is considered improbable taking into account the distribution of continuous soft calcic horizons throughout the landscapes of the survey area.

7 Implications

7.1 ROLE OF CALCIC HORIZONS IN LANDSCAPE DEVELOPMENT

The active role of calcic horizons in shaping the relief of dry areas has been stressed recently by Ruellan et al. (1977) and Nahon et al. (1977). They claim that chemical replacement of non-calcitic solids by lime, épigénie, plays an important role in the lowering and aplanation of surfaces in dry areas, via its regulating effect on the advance of the weathering front. This process, however, is slow while the details of its operation and the removal of its products are still unclear. Combination of this process with the rise process of the calcic horizon as discussed before accounts much better for the relatively fast aplanation of landscapes under dry conditions ('hybrid case', Section 6.6.5).

The épigénie would act as a precursor for the other process. Saprolites could conceivably be formed rapidly by the chemical replacement process acting in fissures and along the boundaries of the mineral grains of the rocks. In this case only a minor part of the total volume of the rock would have to be replaced by lime in order to create a saprolite. The rise process of the soft calcic horizon acting upon the saprolite fragments subsequently transports large quantities of this material towards the topsoil to outweigh the effect of erosion on the surface.

Deep penetration of lime into saprolites of, e.g., the schist landscape was frequently observed in the survey area. Transport of saprolite fragments towards the surface soil of this landscape through a calcic horizon is evident. Deeply weathered granites overlain by a thick mantle of loose material are very common east of the survey area. In most instances the deeply weathered granites and their overlying soils contain fair quantities of lime which may have been the agent that formed the deep saprolites. The lime in the granite and schist landscapes may well have been inherited from materials previously overlying these rocks which have been completely removed by erosion, in the same way as the lime of the petrocalcic horizons of the arkose landscape is supposed to be inherited from the Miocene clay formerly covering this landscape. This is explained in Section 6.5.1.

The role of the calcic horizon in levelling landscapes can be reversed when the soft calcic horizon becomes exposed and hardens locally. The horizon now acts as a shield on the surface which effectively protects it from erosion. Continuation of the erosion in adjacent parts, where no exposure and hardening has occurred, will cause the hardened parts to stand out in the landscape. This may well account for the way in which, in the Mérida area, the edges of the plateaus in the Miocene clay landscape stand out. Part of the locally rolling relief of the arkose landscape is considered to be due to the protection afforded to its tops by the presence of a petrocalcic horizon.

In the literature, the role of the petrocalcic horizon as a protecting agent of surfaces is often mentioned, e.g., Dumas (1969) and Lattman (1973). There is a widely spread misconception that, since petrocalcic horizons are often found on top of older surfaces, they must necessarily be older than non-hardened calcic horizons in adjacent landscapes (which continued to erode after the petrocalcic horizon had fossilised the other parts). It is clear that in concluding this, cause and result are easily confused.

Petrocalcic horizons may assert their influence on landscapes for very long periods. Multiple calcic horizons are evidence of various cycles of degradation and aggradation. A well-studied case is the so-called 'caprock caliche' overlying the mainly non-calcareous Ogallala formation in the Llano Estacado of W. Texas and E. New Mexico (USA). As mentioned in Section 2.5.2, Brown (1956) and Reeves (1970) are in favour of an aggradational mode of formation while Price (1933) and Bretz & Horberg (1949) advocate a degradational one for the caprock.

Brown describes this formation in the following way: 'Caliche underlies the soils of the northeastern Llano Estacado as single, double, or in a few places multiple layers, each consisting of relatively unindurated caliche grading upward into the indurated caprock'. Both Brown and Reeves consider the genesis of this complex as entirely aggradational. The arguments for this mode of formation are that aeolian contributions of lime are common in this environment while the material underlying the caprock is often incapable of supplying it. Degradational modes of formation are excluded by Brown since he expects degradation to lead to sealing of the carbonate layer which would prevent further migration.

Introduction of the concept of a mobile soft calcic horizon which migrates downward yields a more plausible theory on the mode of formation of this layered caliche complex. Soft calcic horizons which proceed downward in calcareous aeolian materials can keep ahead of the eroding surface and accumulate lime in the process. The hardening of this layer will occur after it has been exposed. If the calcic horizon encounters on its way down unweatherable or slowly weatherable material, it will settle on top of it and harden superficially, forming a caprock. This caprock is capable of protecting itself from erosion during long periods. It will maintain itself until aggradation of new calcareous aeolian material buries it. A new soft calcic horizon forms in this material and migrates downward until it hits the unweatherable underlying caprock. As soon as this happens its surface becomes exposed and hardens superficially to form the next caprock of the sequence. In this way subsequent cycles of *aggradation and degradation*, which may tie in with the climatic variations of the Pleistocene, leave their residues as a series of hard and soft calcic horizons superimposed on the Ogallala formation, each cycle being represented by a soft calcic horizon and its upper hard caprock.

This model reconciles the degradation favoured by Price and Bretz & Horberg with the aggradation advocated by Brown and Reeves. It explains satisfactorily all the variations in appearance of the caliche complex as described by Brown. As such, thicker caliches in the valleys are explained by more aggradation, while local absence of one member of the sequence can be explained on the understanding that locally no aggradation took place in that particular cycle. The silicate in the various caliches is probably a remnant of the last soil materials trapped in the horizon after its top hardened.

Application of the model in which aggradation and degradation alternate makes the dating of the lowermost caprock as Pliocene questionable. If the first calcic horizon had lowered itself on a Cambrian rock, it would not have been Cambrian either!

An interesting parallel for this alternating aggradational and degradational mode of formation is formed by the observation of Sabelberg & Rohdenburg (1975) for calcic horizons in Morocco and Spain. They claim that thick calcic horizons are mostly polygenetic and are due to an 'accumulation effect' in which several soil-forming phases have contributed, which may have acted in different climatic cycles. They state that often it can be shown that thick calcic horizons split up into a number of separate soils, each with its own thinner calcic horizon.

Watts (1980) probably refers to similar cases when he mentions for Kalahari calcretes: 'Composite profiles represent recurring episodes of calcrete formation. They may be identified by a stacking, with overlap, of individual calcrete profiles.'

In summary it may be stated that lime is a very tenacious component of landscapes in dry regions. It may escape erosion in soft condition by means of the mechanical replacement process and hardens when eventually caught up by the eroding surface. It resists erosion, when hard, for long periods. When finally dissolved its products may re-form to become a mobile soft calcic horizon again.

7.2 DATING OF CALCIC HORIZONS

The absolute dating of carbonates of calcic horizons by means of the C14 method is unreliable due to the following. Incorporation of CO_2 from living matter in carbonates upon formation accounts for only half of the total C in these substances, the remainder being made up of much older 'dead' C ('limestone dilution effect'). As such their C14 ages can be expected to be one half life (app. 5570 yr) too old. This is discussed, e.g., by Williams & Polach (1971). Recrystallisation of carbonates causes incorporation of recent carbon and makes C14 ages of carbonates too young.

Comparison of C14 ages of carbonates with C14 ages of organic substances from the same horizon shows that later contamination of carbonates with recent C generally outmatches the limestone dilution effect, as data from Bowler & Polach (1971) show. As such most carbonate C14 ages turn out to be too young. This effect is the more exaggerated the wetter the climate. Williams & Polach (1971) made similar comparisons for the arid zone and found in this case the limestone dilution effect dominant over later contamination by more recent C, which caused carbonate C14 ages to be too old.

Netterberg (1969) and (1978b) defines the age of calcrete as the age of the onset of calichification. He proposed careful selection of carbonate samples in order to distinguish the various phases of the process evident in a horizon.

Carbonate-based C14 dates of calcic horizons are mostly interpreted as being accurate only relative to each other within one profile. Gile et al. (1966) use such data in this sense and Williams & Polach (1971) report several sequences in this form. The general tendency found is that the lime from calcrete profiles increases in age with depth. From this the conclusion can be drawn that calcretes grow from the bottom upwards. The younger age of the upper part can also be attributed, however, to the incorporation of more recent C in the top layers where recrystallisation processes are active.

One sequence from Gile et al. (1966) and two from those reported by Williams & Polach (1971) show an age reversal at the bottom of the sequence. This is an exception to the tendency of increase of age with depth.

In the interpretation of carbonate-derived C14 dates it seems worthwhile to consider the possibility that the mechanical replacement process is active or has been active in the horizon of which the sample was derived. The aforementioned profiles with age reversals could, e.g., be interpreted very well by assuming that this process has been active during the formation. This yields the following model. If calcium carbonate is released from a parent material overlain by a soft calcic horizon, part of this calcium carbonate will recrystallise in the weathering zone, incorporating modern C from soil-CO_2. A large part of the material from the weathering zone is, however, transported by the mechanical replacement process of the calcic horizon towards the surface soil. Here it weathers and releases the rest of the old carbonate which incorporates modern soil-CO_2 as it dissolves and leaches down towards the upper part of the soft calcic horizon. In this way it is possible to account for the entire sequence of carbonate C14 ages which increase in age with depth, but decrease in age at the bottom of the calcic horizon.

Other effects of the mechanical redistribution processes to be expected are homogenisation of lime in the soft calcic horizon, leading to uniform carbonate ages for the entire horizon. Contrarily, upward expulsion of carbonate aggregates cemented by more recent recrystallisations may lead to an enhancement of the apparent youthfulness of the upper part of the calcic horizon.

All the aforementioned facts should be given due consideration when interpreting carbonate-based C14 dates.

An important principle of relative dating in the earth sciences is that in undisturbed sequences each layer post-dates that which it underlies. Furthermore, objects encased in undisturbed sequences of layers are used to date these layers. The mechanical replacement process active in migrating calcic horizons has to be taken into account when applying this.

Surface soils consisting of materials expulsed by underlying soft calcic horizons may not easily be recognised as 'disturbed'. Nor may objects placed in these horizons by the soft calcic horizon be easily recognised as originating from deeper layers. As such it is conceivable that failure to recognise the effects of the mechanical replacement process of soft calcic horizons leads to errors in relative dating. When determining the ages of calcretes, based on the age of artefacts found in or on top of them (e.g. Netterberg, 1969 and 1978b), the influence of the aforementioned phenomena should be checked.

7.3 AGRICULTURE

The degree up to which man is responsible for the deterioration of the soils of the world cannot be assessed everywhere with certainty. It is definitely not correct, in the case of calcic horizons, to take the model of a mobile soft calcic horizon as the standard case under natural conditions. This would imply that all petrocalcic horizons consequently would have to be considered as anthropogenic. The occurrence of old multi-layered petrocalcics all over the world as discussed in the first section of this chapter is clear evidence that petrocalcic horizons can form without human intervention. Yaalon & Singer (1974) showed that petrocalcic horizons must have been common in Israel in Roman times since the material was mined for construction purposes. As mentioned in Section 2.4, the fact that the petrocalcic horizons are increasingly common towards the arid climates also shows that they are natural phenomena under specific circumstances.

The model of Gile et al. (1966) in which, as mentioned in Section 2.5.2.1, the petrocalcic horizon is the natural end-product of gradual plugging of a soil horizon by infiltrating lime, does not seem to be universally acceptable either.

It seems probable, especially in the transitional zones between sub-humid and semi-arid climate, that many petrocalcic horizons occur that have formed from soft calcic horizons, due to interruption of the equilibrium between surface erosion and the upward transport of material by means of the mechanical replacement process in these horizons. Human interference with the natural vegetation must have been the main cause. In the entire Mediterranean this may have been an important factor in the well known decline of agricultural production towards the end of the Roman era.

Identification of those areas where this has not happened yet, but which are in danger of suffering the same process, seems important. Soil conservation measures in such areas could turn out to be highly efficient. They need not stop erosion entirely. Rather the aim should be to make sure that soil erosion does not supersede the threshold rate at which the equilibrium between the mechanical replacement process and erosion is broken. Measures that enhance infiltration of rainwater help to maintain the equilibrium. Moisture conservation measures as quantified in the model of Huizing (1979) (Section 3.6) do not only serve agricultural production but also contribute to the maintenance of the equilibrium since they discourage erosion and stimulate the activity of the soft calcic horizon.

7.4 CLASSIFICATION

The mechanical replacement of material by the soft calcic horizons is a pedogenetic process, the activity of which should be reflected in natural soil classification systems.

If further study of the redistribution phenomena, under natural circumstances has yielded a better understanding of the different influencing factors, a subdivision of soft calcic horizons should be devised according to the activity of the process. Factors that can be identified are: moisture regime, groundwater regime and grainsize, purity and liquid limit of the lime. It seems advisable to distinguish continuous and discontinuous soft calcic horizons since the relative proportions of lime and soil are important parameters in the replacement process.

It may be possible to subdivide the petrocalcic horizons into those formed directly by the process of plugging described by Gile et al. (1966) and those that owe their origin to exposure of originally mobile soft calcic horizons. Type and degree of conservation of the enclosures seems to be an important criterion for this distinction.

Summary

A field study was carried out in an area situated around the city of Mérida in Badajoz province in the south-west of Spain, with the main purpose of explaining the presence of different types of calcic horizons at or near the surface of landscapes which are subject to erosion.

The area is part of the catchment of the Guadiana river and, apart from the level valley of this river, consists mainly of undulating landscapes on granite, schist and Tertiary deposits. The soils predominantly classify as Inceptisols, Alfisols and Vertisols. Soft calcic horizons both of the discontinuous and continuous types and locally with hardened tops occur frequently in the soils on Tertiary sediments. They are also present on schist and are locally encountered on the granite. The area has for the larger part been stripped of its natural vegetation and has been brought under agriculture. Some areas are now being irrigated. The climate is typically Mediterranean, semi-arid tending towards sub-humid.

The investigation concentrated in the first instance specifically on an undulating Miocene clay landtype, a cross section of which (Fig. 10) reveals that the calcic horizons follow the relief and are laterally continuous though they show different forms which gradually merge into each other. In essence there are two profile types:

1. The tops and plateau rims have a thin surface soil overlying a continuous calcic horizon. The upper part of this is hardened. It merges via an irregular boundary into an underlying discontinuous calcic horizon consisting of masses of soft lime in Miocene clay. The transition zone between the continuous and discontinuous calcic horizon is characterised by slickensides that occur both in the clay and in the lime. Clay nodules of which the inner part is non calcareous are found both in the soft and hard lime.
2. Soils of the valley bottoms differ from the aforementioned type in the presence of a thick colluvial surface soil and in the absence of hardening in the lime. The other phenomena (irregular lower boundary, slickensides and clay nodules) are also present in these profiles.

Samples of both soil types were drawn for analysis and micromorphological investigations. As well as routine analyses, other tests were carried out as follows. The liquid limit of the lime was determined and found to be very low. Bulk density was determined on undisturbed samples of both lime and clay while of the clay samples the coefficient of linear extensibility (COLE) was determined. Furthermore, on some lime samples the stable isotope composition was determined and the presence of micro-

fossils was investigated. The result of the latter investigation was negative. The position in the landscape of the calcic horizons, the results of the analyses and the study of the micromorphology show that in the present case these horizons are pedogenetic features. It is shown that surface soils and clay nodules are both derived from the underlying Miocene parent material.

Laboratory experiments were carried out on the lime and clay nodule samples in order to study the way in which these materials behave in relation to each other under circumstances which match those in the soil, and to explain the phenomena observed. For this purpose, clay nodules, stones and hard petrocalcic fragments were embedded in soft lime and alternately dried and moistened. The results were registered by means of stereo radiography. The radiographs showed that all objects rose upon moistening and fell upon drying. In a number of cases this led to a net rise of the objects. The driving force behind these movements could be shown to be the pressure of air enclosed in the crystalline lime as a result of moistening. It is clear that the large objects regardless of their constitution are more inclined to conserve the ascending component than the fine particles. They therefore move upwards relative to the surrounding fine lime.

On the basis of the field observations and the results of the experiments, the following explanation for the genesis of the observed horizon configuration is given. When fine crystalline lime overlies swelling clay and the system is subjected to moistening and drying, an irregular transition between the two materials will develop which can be interpreted as a subterranean gilgaï microrelief. Upon drying, cracks form in the clay into which lime flows upon remoistening. This process leads to the introduction of clay into the soft calcic horizon, since the lime that flowed in resists the pressure exerted by the swelling clay. The clay then forms protrusions into the lime. These protrusions or 'clay pillars' break up into smaller fragments which once present in isolated form in the lime come under the influence of the rise process re-created in the experiment. The clay nodules are now transported upward through the calcic horizon and expelled at its top, so that they adjoin the surface soil. The result of this mechanical replacement process is a downward movement of the entire calcic horizon (Fig. 5 and Fig. 38). This process is fossile in the calcic horizons with hardened tops which, due to their impermeability, do not moisten anymore. In calcic horizons which have not hardened the process must still be active. Comparable phenomena were locally observed in calcic horizons in other landtypes.

Under natural conditions an equilibrium establishes itself between the lowering of the calcic horizon and the simultaneous upward transport of soil material to the surface soil inherent in this on the one hand and on the other hand the erosion to which this surface soil is subject. Disturbance of this equilibrium can lead to the exposure of the horizon which results in hardening and fossilisation of the entire system. (The latter has occurred in the profiles along the plateau edges of the Miocene clay landtype.) A disturbance of the equilibrium can also lead to a change in habitus of the horizon from continuous to discontinuous. If on its way down the horizon hits unweatherable or difficultly weatherable material the equilibrium is disturbed and erosion causes exposure which is followed by hardening. Examples of calcic horizons that 'foundered' on arkose or granite are found in the area. Local 'damage' of the calcic horizon due to incision of erosion gullies or by encounters with unweatherable veins or dikes is 'repaired' by the horizons since the lime is able to shift somewhat in a lateral direction while moving down.

Comparison of the estimates of erosion rates in the area with those of the rate of downward movement of the calcic horizon shows that these are of the same order of magnitude. It is probable that the calcic horizon in discontinuous form is able to develop considerably larger rates of downward movement and as such is able to stay ahead of a considerably stronger erosion. In an alternative model in which the lowering of the calcic horizons was assumed to be due entirely to leaching (dissolution followed by crystallisation at greater depth) it could be calculated that the displacement of the calcic horizon was quite unable to match the estimated erosion rates of the area. The dissolution model is therefore rejected as the main cause for the downward movement of the calcic horizons of the area.

Since the calcic horizon can accumulate lime from the materials it traverses on its way down, the explanation of the present thick continuous calcic horizons may depart from the assumption that they started their existence long ago as much thinner horizons. For the genesis of these 'incipient calcic horizons' a number of options are discussed. As the most probable manner of development, the following is assumed. Calcite crystals that form every dry season as efflorescences in cracks of heavy clay soils are washed down by the first rains of the following wet season to the bottom of these cracks. Swelling and shrinking of the clay in interaction with liquifaction of the lime lead to a gradual replacement of the clay by lime, as discussed under the formation of the subterranean gilgaî relief. As such, finally at the level where all cracks end, a continuous soft calcic horizon is formed from a discontinuous one. This horizon starts its movement downwards when the groundwater table lowers in eroding landscapes.

For the formation of an 'incipient calcic horizon', other options such as geogenetic sedimentation, replacement of soil material by crystallising lime and chemical replacement of material by lime are considered to be less probable in this particular case.

The described mechanical replacement process has implications for a number of disciplines, as follows.

1. It is an important factor in the genesis of landscapes in which soft calcic horizons have a planating influence on the relief but when locally hardened bring about the opposite. The well-known 'caprock caliche' from the Llano Estacado of Texas and New Mexico which consists of several soft and hard lime layers can be explained as resulting from several cycles of aggradation and degradation.

2. The process should be kept in mind in interpreting C14 datings of calcic horizons. The ability of the calcic horizon to place objects derived from underlying

formations in the soil overlying the horizon without the latter having to be considered as 'disturbed' has importance for datings that are based on these objects (archeology).

3. It is important to realise that erosion in landscapes with soft calcic horizons may become very noxious for agriculture when a certain threshold value is exceeded. If the erosion rate becomes so large that the equilibrium in the replacement process is disturbed, exposure followed by irreversible hardening of the lime will occur.

4. The process should be incorporated in soil classification.

This publication also includes a literature review of calcic horizons which, besides nomenclature and micromorphology, contains information on horizon sequences, occurrence in relation to specific climatic zones, genetic and agricultural aspects.

Samenvatting

Een veldstudie werd uitgevoerd in een gebied gelegen rond de stad Mérida in de provincie Badajoz in het zuidwesten van Spanje, met als voornaamste doel de aanwezigheid te verklaren van verschillende typen kalkhorizonten aan of nabij het oppervlak van landschappen die aan erosie onderhevig zijn.

Het gebied is deel van het stroomgebied van de rivier Guadiana en bestaat buiten het vlakke dal van deze rivier vooral uit glooiende landschappen, op graniet, schist en Tertiaire afzettingen. De gronden die hierop ontwikkeld zijn behoren voor het grootste deel tot de Inceptisolen, de Alfisolen en de Vertisolen. Zachte kalkhorizonten zowel van het discontinue als het continue type en locaal met verharde top, komen veelvuldig voor in de gronden op de Tertiaire sedimenten. Ze zijn ook aanwezig op de schist en worden locaal op graniet aangetroffen. Het gebied is voor het grootste deel van zijn natuurlijke vegetatie ontdaan en in cultuur gebracht. Enige gebieden worden geirrigeerd. Het klimaat is typisch Mediterraan, semi-aried tenderend naar subhumied.

Het onderzoek concentreerde zich in eerste instantie vooral op een glooiend Mioceen kleilandschap waarvan een dwarscoupe (Fig. 10) toont dat de kalkhorizonten het relief volgen en lateraal continu zijn, zij het dat ze verschillende vormen vertonen die geleidelijk in elkaar overgaan. In essentie zijn er twee profieltypen:

1. De toppen en plateauranden hebben een dunne bovengrond waaronder een continue kalkhorizont aanwezig is. Het bovenste deel hiervan is verhard. Het gaat via een onregelmatige grens over in een onderliggende discontinue kalkhorizont bestaande uit zachte kalkmassa's in Miocene klei. De overgangszone tussen de continue en discontinue kalkhorizonten wordt gekenmerkt door glijvlakken (slickensides) die zowel in de kalk als in de klei voorkomen. Kleiknollen welke van binnen kalkloos zijn worden zowel in de zachte als in de harde kalk aangetroffen.
2. De dalbodemgronden verschillen van de voorgaande in de aanwezigheid van een dikke, colluviale, bovengrond en in de afwezigheid van verharding van de kalk. De andere verschijnselen (onregelmatige ondergrens, glijvlakken en kleiknollen) zijn in deze profielen eveneens aanwezig.

Van de beide bodemtypen werden monsters voor analyse en micromorphologisch onderzoek getrokken. Naast de routine-analyses werden de volgende bepalingen gedaan. Van de kalk werd de vloeigrens bepaald die uitzonderlijk laag bleek te zijn. Het volumegewicht werd aan ongestoorde monsters van zowel kalk als klei gemeten terwijl van de kleimonsters ook de lineaire uitzettingscoefficient (COLE) werd bepaald. Tevens werd aan een aantal kalkmonsters de stabiele isotopensamenstelling bepaald en

werd onderzocht of microfossielen aanwezig waren. Het resultaat van dit laatste onderzoek was negatief. Uit de landschappelijke ligging van de kalkhorizonten, de analyseresultaten en de micromorphologie blijkt dat deze horizonten in het onderhavige geval pedogenetische vormingen zijn. Ook bleek dat de bovengronden en de kleiknollen beide van het onderliggende Miocene moedermateriaal afstammen.

Met monsters van kalk en kleiknollen werden laboratoriumexperimenten uitgevoerd teneinde het gedrag van deze materialen ten opzichte van elkaar te bestuderen onder omstandigheden overeenkomend met die in de bodem en zo een verklaring te vinden voor de waargenomen verschijnselen. Hiertoe werden kleiknollen, stenen en harde kalkfragmenten ingebed in zachte kalk en afwisselend gedroogd en bevochtigd. Door middel van stereoradiografie werd het resultaat hiervan geregistreerd. De röntgenfoto's toonden aan dat alle voorwerpen opwaartse bewegingen maakten bij bevochtiging en neerwaartse bij droging. Dit leidde in een aantal gevallen tot een netto stijging van de voorwerpen. De drijvende kracht voor deze bewegingen blijkt naar kon worden aangetoond luchtinsluiting in de kristallijne kalk te zijn tengevolge van bevochtiging. Het is duidelijk dat de grote objecten, ongeacht hun samenstelling, meer geneigd zijn de opgaande component te behouden dan de fijne delen. Zij bewegen zich daardoor opwaarts ten opzichte van de hen onringende fijne kalk.

Op grond van de veldwaarnemingen en de resultaten van de experimenten wordt de volgende verklaring voor het ontstaan van de waargenomen horizontconfiguratie gegeven. Als fijne kristallijne kalk op zwellende klei ligt en het systeem wordt blootgesteld aan bevochtiging en droging zal zich tussen de twee materialen een onregelmatige overgang ontwikkelen die kan worden geinterpreteerd als een ondergronds gilgaî microrelief. Bij droging ontstaan scheuren in de klei waarin de kalk bij herbevochtiging vloeit. Dit proces leidt tot de introductie van klei in de zachte kalkhorizont omdat de ingevloeide kalk, de door de zwellende klei uitgeoefende druk weerstaat. De klei vormt dan uitstulpingen in de kalk. Deze uitstulpingen of 'kleipilaren' breken in de kleinere fragmenten op, welke eenmaal geisoleerd in de kalk aanwezig, onder de invloed van het in het experiment nagebootste stijgproces komen. De kleiknollen worden nu door de kalkhorizont omhoog getransporteerd en aan de bovenzijde uitgescheiden zodat zij zich bij de bovengrond voegen. Het gevolg van dit mechanisch vervangingsproces is een neerwaartse beweging van de gehele kalkhorizont (Fig. 5 en Fig. 38). Dit proces is fossiel in de kalkhorizonten met verharde top die tengevolge van hun ondoorlatendheid niet meer bevochtigen. In de onverharde kalkhorizonten moet het proces nog actief zijn. Vergelijkbare verschijnselen werden locaal in kalkhorizonten in andere landschappen gevonden.

Onder natuurlijke omstandigheden stelt zich een evenwicht in tussen de daling van de kalkhorizont en het daaraan inherente transport van bodemmateriaal naar de bovengrond aan de ene kant en de erosie waaraan deze bovengrond onderhevig is aan de andere kant. Verstoringen van dit evenwicht kunnen leiden tot blootlegging van de kalkhorizont hetgeen resulteert in verharding en fossilisatie van het gehele systeem. (Dit laatste heeft zich in de profielen langs de plateauranden van het Miocene kleilandschap voorgedaan.) Ook kan een verstoring van het evenwicht leiden tot een verandering van de habitus van de horizont van continu naar discontinu. Als de horizont onderweg naar beneden op een onverweerbaar of moeilijk verweerbaar materiaal stuit wordt het evenwicht verbroken en treedt expositie door erosie, gevolgd door verharding, op. Voorbeelden van kalkhorizonten die zo op arkose of graniet 'gestrand' zijn worden in het gebied aangetroffen. Locale 'beschadiging' van de kalkhorizont door insnijding van erosiegeulen of door ontmoetingen met onverweerbare aders of gangen, worden door de horizont 'gerepareerd' omdat de kalk zich tijdens de neerwaartse beweging van de horizont ook enigermate lateraal kan bewegen.

Vergelijking van schattingen van de erosiesnelheid in het gebied met die van de daalsnelheid van de kalkhorizont toont aan dat deze van dezelfde orde van grootte zijn. Het is waarschijnlijk dat de kalkhorizont in discontinue vorm nog aanzienlijk hogere daalsnelheden kan ontwikkelen en zo een nog aanzienlijk sterkere erosie kan voorblijven. In een alternatief model waarin de daling van de kalkhorizonten geheel aan inspoeling (oplossing gevolgd door uitkristallisatie op grotere diepte) werd toegeschreven kon worden berekend dat de daling van de kalkhorizont in het geheel niet in staat was de geschatte erosiesnelheden van het gebied te evenaren. Het inspoelingsmodel wordt als hoofdoorzaak voor de neerwaartse beweging van de kalkhorizonten van het gebied daarom verworpen.

Aangezien de horizont op zijn weg naar beneden kalk kan accumuleren uit de materialen die hij doorloopt kan er voor de verklaring van de genese van de huidige dikke continue kalkhorizonten van worden uitgegaan dat deze hun bestaan lang geleden als aanzienlijk dunnere horizonten zijn begonnen. Voor de genese van deze 'incipient calcic horizons' worden een aantal opties besproken. Als meest waarschijnlijke vormingswijze wordt de volgende aangenomen: Kalkkristallen die zich ieder droog seizoen in de vorm van uitbloeiingen in spleten van zware kleigronden vormen worden door de eerste regens van de daaropvolgende natte tijd naar beneden gespoeld tot de bodem van deze spleten. Zwel en krimp van de klei in wisselwerking met vervloeiing van de kalk, leidde tot een geleidelijke vervanging van klei door kalk, zoals bij de vorming van het ondergrondse gilgaïrelief besproken. Zodoende ontstaat uiteindelijk op het niveau waar de spleten eindigen uit een discontinue een continue kalkhorizont. Bij daling van de grondwaterstand in eroderende landschappen vangt deze horizont zijn beweging naar beneden aan. Andere opties voor het ontstaan van een 'incipient soft calcic horizon', te weten geogenetische sedimentatie, verdringing van bodemmateriaal door ter plaatse kristalliserende kalk en chemische vervanging van bodemmateriaal door kalk, worden als minder waarschijnlijke vormingsprocessen beschouwd voor het onderhavige geval. Het beschreven mechanisch vervangingsproces heeft de volgende implicaties voor een aantal vakgebieden:

1. Het is een belangrijke factor in de landschapsgenese waarbij de kalkhorizonten in zachte toestand een vervlakkende invloed op het relief uitoefenen maar in locaal verharde toestand juist het omgekeerde bewerkstelligen. De bekende uit meerdere harde en zachte kalklagen bestaande 'caprock caliche' van de Llano Estacado in Texas en New

Mexico kan als resultaat van meerdere cycli van aggradatie en degradatie van het landschap ter plaatse worden verklaard.

2. Bij de interpretatie van C14 dateringen van kalkhorizonten dient met het proces rekening te worden gehouden. Het vermogen van de horizonten om objecten afkomstig van onderliggende formaties in de bovengrond te plaatsen zonder dat deze laatste als 'verstoord' moet worden beschouwd heeft belang voor dateringen die zich op deze voorwerpen baseren (archeologie).

3. Het is van belang zich te realiseren dat erosie in landschappen met zachte kalkhorizonten zeer schadelijk kan worden voor de landbouw als bepaalde grenswaarden overschreden worden. Indien de erosiesnelheid zo groot wordt dat het evenwicht in het vervangingsproces onderbroken wordt treedt expositie gevolgd door irreversibele verharding van de kalk op.

4. In de bodemclassificatie dient het proces een plaats te krijgen.

De publicatie bevat tevens een literatuuroverzicht betreffende kalkhorizonten dat naast nomenclatuur en micromorphologie, informatie bevat over horizont-sequenties, voorkomen in afhankelijkheid van specifieke klimaatzones, genetische en landbouwkundige aspecten.

Resumen

Un estudio de campo fue llevado a cabo en una zona ubicada alrededor de la ciudad de Mérida en la provincia de Badajoz en el suroeste de España, con el proposito principal de explicar la presencia de diferentes tipos de horizontes cálcicos en o cerca de la superficie de paisajes sujetos a la erosión.

La zona hace parte de la cuenca del Río Guadiana y fuera de la llanura aluvial, de este río está formada principalmente por paisajes ondulados sobre granitos, esquístos y depositos terciarios. Los suelos se classifican predominantemente como Inceptisoles, Alfisoles y Vertisoles. Horizontes cálcicos blandos, de los tipos descontínuous y contínuous y localmente con topes endurecidos ocurren con frequencia en los suelos sobre los depósitos terciarios. Están presentes también sobre esquístos y han sido encontrados localmente sobre granitos. La zona ha sido desprovista en su mayor parte de la vegetación natural y dedicada a la agricultura. Algunas zonas están ahora bajo riego. El clima es típicamente Mediterráneo, semiárido con tendencia hacia subhúmedo.

Desde el principío la investigación se concentró específicamente en el paisaje ondulado de arcillas miocenas. Un corte en él (Fig. 10) revela que los horizontes cálcicos siguen el relieve y son lateralmente contínuos no obstante que muestran formas diferentes y se funden gradualmente entre sí.

Essencialmente hay dos tipos de perfiles:

1. Las cimas y las márgenes de las mesitas tienen un suelo superficial delgado yacente sobre un horizonte cálcico descontínuo. La parte superior se encuentra endurecida. Por medio de un limite irregular se convierte en un horizonte cálcico descontínuo subyacente el cual consiste en masas de cal blanda en arcilla miocena. La zona de transición entre el horizonte cálcico contínuo y descontínuo está caracterizada por 'espejulas' (superficies acanaladas y lisas) presentes en la arcilla y en la cal. Tanto en la cal blanda como en la dura, se encuentran nódulos de arcilla cuya parte interior no es calcárea.
2. Los suelos de los fondos de los valles difieren del tipo arriba mencionado en la presencia de un suelo superficial coluvial potente y en la ausencia de endurecimiento de la cal. Los otros fenómenos (límite inferior irregular, espejulas y nódulos de arcilla) están también presentes en éstos perfiles. Muestras de ambos tipos de perfiles fueron tomadas para analisis e investigaciones micromorfológicas. Junto con los analisis de rutina se efectuaron otras determinaciones: El límite de liquidez de la cal fué determinado y resultó muy bajo. La densidad aparente fué establecida sobre muestras no disturbadas de arcilla y cal y al mismo tiempo se obtuvo el índice de

dilatación lineal (COLE) de las muestras de arcilla. Además, fué determinada la composición isotópica estable de algunas muestras de cal y inspeccionada la presencia de microfosiles. El resultado de ésta última investigación fue negativa. La posición de los horizontes cálcicos en el paisaje, los resultados de los análisis y el estudio de la micromorfología, demuestran que éstos horizontes, del presente caso, son fénomenos pedogenéticos. Ha sido establecido que los suelos superficiales y los nódulos de arcilla fueron derivados del material mioceno subyacente.

3. Sobre muestras de cal y nódulos de arcilla fueron ejecutados experimentos de laboratorio para estudiar la manera en la cual éstos materiales se comportan mutuamente bajo condiciones semejantes a las encontradas en el suelo y explicar así los fenómenos observados. Con éste propósito fueron enterrados nódulos de arcilla, piedras y fragmentos petrocálcicos duros en cal blanda lo cual fué humedecido y secado alternativamente. Los resultados fueron registrados por medio de estereoradiografía. Los radiogramas mostraron que todos los objetos subieron al humedecerse y descendieron al secarse. Esto condujo en un cierto número de casos, a una subida neta de los objetos. Se pudo comprobar que la fuerza motriz de éstos movimientos fué la présion del áire incluída en la cal cristalina como resultado del humedecimiento. Es evidente que los objetos largos, indiferentes de su constitución, son más aptos para conservar el componente ascendente que las partículas finas. Por ésta razón ascienden en relación a la cal fina circundante.

En base de los observaciones de campo y los resultados de los experimentos, se presenta la siguiente explicación para la génesis de la configuración, de horizontes, observada. Cuando la cal fina cristalina sobreyace a arcilla dilatable y el sístema esta sujeto a humedecimiento y secado, se desarrolla una transición irregular entre los dos materiales la cual se puede interpretar como un microrelieve gilgaî subterrâneo. Al secarse, se forman grietas en la arcilla dentro de las cuales fluye la cal al rehumedecerse. Este proceso lleva a la introducción de arcilla en el horizonte cálcico blando, ya que la cal incorporada resiste la présión ejercida por la arcilla dilatante. La arcilla forma entonces protusiones dentro de la cal. Estas protusiones o 'pilares de arcilla' se agrietan formando fragmentos más pequeños los cuales una vez presentes en forma suelta en la cal, están sujetos al proceso de ascenso reproducido en el experimento. A continuación los nódulos de arcilla son transportados hacia arriba a través del horizonte cálcico y expulsados al límite superior de manera que se juntan al suelo superficial. El resultado de éste proceso de sustitución mecánica es un movimiento de hundimiento de todo el horizonte cálcico (Fig. 5 y Fig. 38). Este proceso es fosil en horizontes cálcicos con topes endurecidos los cuales, debido a su impermeabilidad, no vuelven a humedecerse. En los horizontes cálcicos que no se han endurecido, el proceso debe ser aún áctivo. Fenómenos comparables fueron observados localmente en horizontes cálcicos de otros tipos de tierra.

Bajo condiciones naturales se establece un equilibrio entre el hundimiento del horizonte cálcico y el transporte simultáneo de material de suelo hacia arriba, al suelo superficial lo que es inherente en este hundimiento, de un lado y por otro, la erosión a la cual está sujeto el suelo superficial. La disturbación de éste equilibrio puede ocasionar la exposición del horizonte la cual resulta en el endurecimiento y fosilización del sistema entero. (Lo último ocurrió en los perfiles a lo largo de las margenes de las mesitas del tipo de tierra de la arcilla miocena.) La alteración del equilibrio puede llevar también a un cambio en el habito del horizonte, de contínuo a descontínuo. Si en su hundimiento el horizonte toca material no meteorizable o dificilmente meteorizable el equilibrio se pierde y la erosión ocasiona su exposición seguida por endurecimiento. Ejemplos de horizontes cálcicos 'zozobrados' en arcosa a granito se encuentran en la zona. Los 'daños' locales de los horizontes cálcicos producidos por la incisión de cárcavas de erosión o encuentros con vetas o diques no meteorizables son 'reparados' por los horizontes ya que la cal es apta para moverse algo en sentido lateral mientras se está bajando.

La comparación de las proporciones de erosión de la zona con las del hundimiento del horizonte cálcico muestran que éstas son del mismo orden de magnitud. Es probable que el horizonte cálcico en forma descontínua sea capaz de desarrollar proporciones de hundimiento mucho más elevadas y de esta forma igualar a una erosión mucho más fuerte. En un modelo alternativo en el cual el hundimiento del horizonte cálcico fué atribuído completamente a lixiviación (disolución seguida por cristalización a mayor profundidad) se pudo calcular que el desplazamiento del horizonte cálcico era absolutamente incapaz de igualar las proporciones de erosión estimadas para la zona. El modelo de disolución es por eso rechazado como causa principal del hundimiento de los horizontes cálcicos de la zona.

Puesto que los horizontes cálcicos son capaces de acumular cal de los materiales que atraviesa en su vía hacia abajo, la explicación de los presentes horizontes cálcicos contínuos y potentes, puede partir de la suposición de que éstos se iniciaron hace bastante tiempo como horizontes mucho más delgados. Para explicar la genésis de éstos 'horizontes cálcicos incipientes' se discute un número de opciones. Como la manera más probable se asume la siguiente. Los cristales de calcita que se forman en cada estación seca como eflorescencia en las grietas de suelos arcillosos pesados son lavados hacia el fondo de estas grietas por las primeras lluvias de la siguiente estacion húmeda. La expansión y contracción de la arcilla, actuando junto con la licuefacción de la cal llevan a una sustitución gradual de la arcilla por la cal como fué discutido bajo la formación del relieve gilgaî subterráneo. Así finalmente, en el nivel donde terminan todas las grietas se forma un horizonte cálcico blando y contínuo a partir de un horizonte descontínuo. Este horizonte inicia su hundimiento cuando la capa freática desciende en los paisajes sujetos a la erosión.

Para la formación de un 'horizonte cálcico incipiente' se consideran otras opciones como sedimentación geogenética, sustitución de material del suelo por calcita cristalizante y sustitución química de material por cal, como menos probables en este caso particular.

El proceso de sustitución mecanica descrita tiene implicaciones para un número de disciplinas en la siguiente forma:

1. Es un factor importante en la génesis de paisajes en los cuales los horizontes cálcicos blandos tienen una influencia aplanante sobre el relieve, pero cuando localmente están endurecidos causan el efecto contrario. El conocido 'caprock caliche' del Llano Estacado de Texas y Nuevo Mexico el cual consiste en varias capas blandas y duras puede explicarse como el resultado de varios ciclos de agradación y degradación.
2. Hay que dar la debida atención al proceso citado cuando se interpreten dataciones C14 de horizontes cálcicos. La aptitud del horizonte cálcico para emplazar objetos derivados de formaciones subyacentes en el suelo sobreyacente al horizonte sin que pueda considerarse el último como 'disturbado', tiene importancia para las dataciones basadas en éstos objetos (arqueología).
3. Es muy importante saber que la erosión en paisajes con horizontes cálcicos blandos se tornará muy perjudicial para la agricultura al exceder ciertos valores límites. Cuando la proporción de erosión se incrementa tanto que disturba el equilibrio del proceso, se presentará la exposición seguida por el endurecimiento irreversible.
4. El proceso debe incorporarse en la clasificación de suelos.

Esta publicación contiene también una reseña literaria sobre horizontes cálcicos la cual comprende fuera de nomenclatura y micromorfología, información sobre secuencias de horizontes, ocurencia en relación a ciertas zonas climaticas, aspectos genéticos y de la agricultura.

Resumé

Une étude de terrain fût exécutée dans une zone située dans les environs de la ville de Mérida dans le departement de Badajoz au sud ouest de l'Espagne dans le but d'expliquer la présence de differents types d'horizons calciques (croûtes calcaires) prés de-ou á-la surface de paysages sujet a l'erosion.

La zone fait partie du bassin versant de la rivière Guadiana constitué essentiellement de paysages ondulés sur granits, schistes et depôts tertiaires, sauf la vallée alluviale de la rivière. Les sols sont principalement classés en Inceptisols, Alfisols et Vertisols. Des horizons calciques friables de type continu et discontinu avec des parties superieures localement endurcies apparaissent fréquemment dans les sols sur les depôts tertiaires. Ils se présentent aussi sur les schistes et localement sur les granits. Dans cette région la végétation naturelle a en grande partie laissé la place à l'agriculture. Quelques zones sont maintenant irriguées. Le climat typiquement méditerranéen est 'semi-arid' avec une tendance 'sub-humid'.

Au début l'étude était concentrée spécifiquement sur un type de paysage d'argiles miocène ondulées, dont une coupe (Fig. 10) transversale a révélé que les horizons calciques suivent le relief et sont latéralement continus bien qu'ils présentent des formes différentes qui fusionnent peu à peu. Il y a essentiellement deux types de profils:

1. Les cîmes et les bords des plateaux ont un sol superficiel mince sous lequel se trouve un horizon calcique continu. La partie supérieure est durcie; elle fusionne via une limite irrégulière en un horizon calcique discontinu sous-jacent consistant en des amas de chaux friable dans de l'argile miocène. La zone de transition entre l'horizon calcique continu et discontinu est caractérisé par des surfaces de glissement qui se présentent à la fois dans l'argile et la chaux. Des nodules d'argile dont la partie interne est non calcarifère existent à la fois dans la chaux friable et dure.
2. Les sols des fonds des vallées diffèrent des types mentionnés ci-dessus en présence d'un sol superficiel colluvial épais et en l'absence de durcissement dans la chaux. Les autres phénomènes (limite irrégulière inférieure, surfaces de glissement et nodules d'argile) sont également présents dans ces profils.

Des échantillons des deux types de sols ont été relevés pour analyses et études micromorphologiques. Parallèlement aux analyses de routine d'autres tests ont été exécutés comme suit. La limite de liquidité de la chaux a été déterminée et sa valeur s'est avérée très basse. La densité de le masse a été déterminée sur des échantillons inaltérés à la fois de chaux et d'argile, alors que pour les échantillons d'argile on

a déterminé le coefficient d'extension linéaire (COLE). De plus pour certains échantillons de chaux on a déterminé la composition d'isotopes stables et recherché la présence de microfossiles. Le résultat de cette dernière étude était négatif. Le position des horizons calciques dans le paysage, les résultats des analyses et l'étude de la micromorphologie montrent que dans le cas présent ces horizons sont des phénomènes pédogénétiques. Il est montré que les sols superficiels et les nodules d'argile sont tous les deux derivés du matériau parental miocène sous-jacent.

Des essais de laboratoire ont été effectués avec des échantillons de chaux et de nodules d'argile pour étudier le comportement de ces matériaux entre eux dans des circonstances analogues à celles dans le sol et pour expliquer les phénomènes observés. Dans ce but des nodules d'argile, des pierres et des fragments pétrocalciques durs ont été enrobés dans de la chaux friable, puis alternativement séchée et humidifiée. Les résultats ont été enregistrés par stéréo-radiographie. Les radiographies ont montré que tous les objets montaient sous l'effet de l'humidification et descendaient sous l'effet du séchage. Dans un certain nombre de cas le résultat se traduit par une montée des objets. Il a été montré que la force agissante provoquant ces mouvements est due à la pression de l'air emprisonné dans la chaux cristalline sous l'effet de l'humidification. Il est clair que les objets de grande taille quelle que soit leur constitution ont davantage tendance à conserver leur composante ascendante que les particules fines. Par conséquent ils se déplacent vers le haut par rapport à la chaux fine environante.

Sur la base des observations de terrain et les résultats des essais, l'explication suivante a été donnée pour la genèse de la configuration des horizons observés. Quand de la chaux fine cristalline recouvre de l'argile qui gonfle et que le système est soumis à l'effet d'humidification et de séchage, une transition irrégulière se développe entre les deux matériaux qui peut être interprétée comme un microrelief gilgaî souterrain. En séchant il se formera des fissures dans l'argile dans lesquelles s'écoulera la chaux sous l'effet de réhumidification. Ce processus conduit à l'introduction d'argile dans l'horizon calcique friable, puisque la chaux qui s'écoule dans les fissures résiste à la pression exercée par l'argile qui gonfle. L'argile forme alors des protubérances dans la chaux. Ces protubérances ou 'piliers d'argile' cassent en fragments plus petits qui une fois présents sous forme isolée dans la chaux subissent l'influence du processus de montée recréé dans l'essai. Les nodules d'argile sont alors transportés vers le haut à travers l'horizon calcique et expulsés vers le haut de sorte qu'ils fusionnent avec le sol superficiel. Le résultat de ce processus de substitution mécanique est un mouvement descendant de l'horizon calcique entier (Fig. 5 et Fig. 38). Ce processus est fossile dans les horizons calciques avec des parties supérieures durcies qui ne s'humidifient plus du fait de leur imperméabilité. Dans les horizons calciques qui n'ont pas durcis le processus reste probablement actif. Des phénomènes semblables ont été observés localement dans des horizons calciques dans d'autres types de paysages.

Dans des conditions naturelles, un équilibre s'établit entre l'affaissement de l'horizon calcique et le transport simultané vers le haut de materiau du sol vers le sol superficiel d'un côté (les deux phénomènes étant liés) et l'érosion à laquelle ce sol superficiel est soumis d'autre part. Des perturbations de cet équilibre peuvent conduire à l'exposition de cet horizon dont le résultat est un durcissement et une fossilisation du système entier. (Cette dernière s'est produite dans les profils le long des bords de plateau du paysage d'argile miocène.) Une perturbation de l'équilibre peut aussi provoquer un changement de 'l'habitus' de l'horizon de continu vers discontinu. Si dans son mouvement vers le bas l'horizon rencontre un matériau non méteorisable ou difficilement méteorisable, l'équilibre est rompu et l'érosion provoque l'exposition qui est suivie par le durcissement. Des exemples d'horizons calciques qui ont 'coulé à fond' sur arkose ou granit ont été trouvés dans la région. Des 'dégats' locaux de l'horizon calcique dus à l'incision de ravines d'érosion ou à la rencontre de 'dikes' ou de filons non méteorisables sont 'réparés' par les horizons puisque la chaux est capable de subir une translation latérale tout en se déplaçant vers le bas.

Des comparaisons d'estimations de vitesses d'érosion dans la région avec celles de la vitesse de mouvement descendant de l'horizon calcique montrent que celles-ci sont du même ordre de grandeur. Il est probable que l'horizon calcique en forme discontinue est capable de développer des vitesses de mouvement descendant bien plus grandes et ainsi de supporter une érosion beaucoup plus forte. Dans un modèle alternatif où l'abaissement de l'horizon calcique était due entièrement à un lessivage (dissolution suivie d'une cristallisation à plus grande profondeur) on a pu calculer que le déplacement de l'horizon calcique ne pouvait pas du tout égaler les vitesses d'érosion estimées dans la région. Le modèle de dissolution est donc rejeté comme cause principale d'affaissement des horizons calciques de la région.

Comme l'horizon calcique peut accumuler de la chaux à partir des matériaux qu'il traverse au cours de son mouvement descendant, l'explication des horizons calciques continues épaisses s'écarte de l'hypothèse à savoir que leur existence a commencé il y a longtemps à partir d'horizons beaucoup plus minces. Pour la genèse de ces 'incipient calcic horizons' un nombre d'options sont discutées. L'explication la plus probable sur le développement est la suivante. Des cristaux de calcite qui se forment à chaque saison sèche comme des efflorescences dans les fissures de sols très argileux sont emportés vers le fond de ces fissures par les premières pluies de la saison humide suivante. Dilatation et retrait de l'argile en interaction avec la liquefaction de la chaux se traduit par un remplacement progressif de l'argile par la chaux, comme il a été discuté sous la formation du relief de gilgaî souterrain. Ainsi, au niveau où toutes les fissures se terminent, il se forme un horizon calcique continu friable à partir d'un horizon discontinu. Cet horizon commence son mouvement descendant quand la nappe phréatique baisse dans les paysages soumis à l'érosion. Pour la formation d'un 'incipient calcic horizon', d'autres options telles que le sédimentation géogénétique, la substitution du matériau du sol par de la chaux cristallisante et substitution chimique de materiau par la chaux sont considérées comme moins probables dans ce cas particulier.

Le processus de substitution mécanique décrit a des implications pour un certain nombre de disciplines comme suit:

1. C'est un facteur important dans la genèse des paysages dans lesquels les horizons calciques friables ont une influence aplanissante sur le relief mais lorsqu'ils sont localement durcis, ils produisent l'effect contraire. Le 'caprock caliche' bien connu dans le Llano Estacado du Texas et New Mexico composé de plusieurs couches de chaux friable et dure peut être expliqué comme résultant de plusieurs cycles d'accumulation et de dégradation.
2. Le processus devrait être pris en considération en interprétant les dates des horizons calciques par le procédé du C14. L'aptitude des horizons calciques de 'placer' des objets dérivés de formations sous-jacentes dans le sol couvrant l'horizon sans que ce dernier soit à considérer comme 'perturbé', a une importance quand il s'agit de déterminer les dates basées sur ces objets (archéologie).
3. Pour l'agriculture il est important de réaliser que l'érosion dans des paysages avec des horizons calciques friables devient très nocif si une certaine valeur limite est dépassée. Si la vitesse d'érosion devient si grande que l'équilibre dans le processus de substitution est perturbé, il se produit une exposition suivie par un durcissement irréversible du chaux.
4. Le processus doit être incorporé dans la classification des sols.

Cette publication comprend aussi une étude bibliographique sur les horizons calciques qui, en plus de la nomenclature de de la micromorphologie, contient une information sur les séquences des horizons, les circonstances dans lesquelles ils se produisent en relation des zones climatiques spécifiques des aspects génétiques et agricoles.

List of tables and figures

References

Abedi, M.J. and O. Talibudeen, 1974. The calcareous soils of Azerbaijan. I. Catena development related to the distribution and surface properties of soil carbonate. Soil Sci.25. (3): 357-372.

Adolphe, J.P., 1975. Role des microorganismes dans les concretionnements calcaires continentaux. Colloque; Types de croûtes calcaires et leur répartition régionale. Univ. Louis Pasteur, UER Géographie, Strasbourg: 71-75.

American Geological Institute, 1974. Glossary of Geology. Eds. M. Gary, R. Mac Afee Jr. and C.L. Wolf: 407.

Archer, D.R. and R. Mäckel, 1973. Calcrete deposits on the Lusaka Plateau of Zambia. Catena 1 (1-2): 19-30.

Aristarain, L.F., 1971. On the definition of caliche deposits. Z. Geomorph. N.F. 15 (3): 274-289.

Arkley, R.J., 1963. Calculation of carbonate and water movement in soil from climatic data. Soil Sci. 96: 239-248.

Artiola, J. and W.H. Fuller, 1980. Limestone liner for landfill leachates containing beryllium, cadmium, iron, nickel and zinc. Soil Sci. 129 (3): 167-179.

ASTM, 1954. Tentative method of test for liquid limit of soils. D423-54T, Issued by Amer. Soc. for Testing Materials, Philadelphia, USA, 5 pp.

Bal, L., 1975a. Carbonate in soil: A theoretical consideration on, and proposal for its fabric analysis. Neth. J. Agric. Sci. 23: 163-176.

Bal, L., 1975b. Carbonate in soil: A theoretical consideration on, and proposal for its fabric analysis. 1. Crystic, calcic and fibrous plasmic fabric. Neth. J. Agric. Sci. 23: 18-35.

Ballais, J.L. and T. Vogt, 1979. Croûtes calcaires quaternaires du piémont nord des Aurès (Algérie). Rech. Géograph. à Strasbourg - 12: 23-25.

Bales, J.T. Jr. and T.L. Péwé, 1979. Origin and rate of desert pavement formation - A progress report. J. of the Arizona-Nevada Acad. of Sci. 14: 84.

Bathurst, R.G.C., 1971. Carbonate sediments and their diagenesis. Elsevier, Amsterdam. 620 pp.

Bergsma, E., 1978. Method of a reconnaissance survey of erosion hazard near Mérida, Spain. In: Proc. workshop assessment of erosion in USA and Europe, Gent. Eds. M. de Boodt and D. Gabriels. John Wiley, New York: 55-66.

Bertouille, H., 1976. Contribution à l'étude des ferruginisations et encroûtements calcaires: rôle des thermomigrations. Revue de Géogr. de Montréal 30 (4): 327-338.

Bigham, J.M., W.F. Jaynes and B.L. Allen, 1980. Pedogenic degradation of sepiolite and palygorskite on the Texas High Plains. Soil Sci. Soc. Amer. 44 (1): 159-167.

Black, C.A. Ed., 1965. Methods of soil analysis part II. Amer. Soc. of Agron. Madison, Wisconsin, USA. 801 pp.

Blank, H.R. and E.W. Tynes, 1965. Formation of caliche in situ. Geol. Soc. Amer. Bull. 76: 1387-1392.

Blatt, H., G. Middleton and R. Murray, 1972. Origin of sedimentary rocks. Prentice Hall, Englewood Cliffs. 634 pp.

Blokhuis, W.A., Th. Pape and S. Slager, 1968. Morphology and distribution of pedogenic carbonate in some Vertisols of the Sudan. Geoderma 2: 173-200.

Blümel, W.D., 1979. Zur Struktur, Reliefgebundenheit und Genese südwestafrikanischer und südostspanischer Kalkkrusten. Z. Geomorph. N.F. Suppl. Bd.36: 154-167.

Bolt, G.H., 1963. Lecture notes on saline soils. Laboratorium voor Landbouwscheikunde, L.H. Wageningen.

Bolt, G.H. and F.F.R. Koenigs, 1972. Physical and chemical aspects of the stability of soil aggregates. Med. Fak. Landb. State Univ., Gent, Belgium. 37 (3): 955-973.

Boulaine, J., 1966. Sur les relations entre les carapaces calcaires et les sols isohumiques de climat xerotherique. Sci. du Sol 1 Numero special C.N.R.S.: 3-15.
Boulaine, J., 1978. Les sols Calfersiques. Cah. ORSTOM, Pédologie 16 (3): 265-291.
Boulet, R. and H. Paquet, 1972. Pédologie. Deux voies différentes de la pédogenèse en Haute-Volta. Convergence finale vers la montmorillonite. C. R. Acad. Sc. Paris, 275 serie D (12): 1203-1206.
Bouma, A.H., 1969. Methods for the study of sedimentary structures. John Wiley and Sons, New York, 458 pp.
Bouma, J., 1977. Soil survey and the study of water in unsaturated soil. Soil survey paper 13. Soil Survey Institute, Wageningen. 107 pp.
Bowler, J.M. and H.A. Polach, 1971. Radiocarbon analysis of soil carbonates: an evaluation from paleosols in southeastern Australia. In: Paleopedology origin, nature and dating of paleosols. Ed. D.H. Yaalon, I.S.S.S. and Isr. Univ. Press, Jerusalem: 97-108.
Brasher, B.R., D.P. Franzmeier, V. Valassis and S.E. Davidson, 1966. Use of Saran resin to coat natural soil clods for bulk-density and water measurements. Soil Sci. 101 (2): 108.
Bretz, J.H. and L. Horberg, 1949. Caliche in southeastern New Mexico. J. of Geol. 57: 491-511.
Brewer, R., 1972. The basis of interpretation of soil micromorphological data. Geoderma 8 (2): 81-95.
Brewer, R., 1976. Fabric and mineral analyses of soils. Wiley, New York. 470 pp.
Brown, C.N., 1956. The origin of caliche on the Northeastern Llano Estacado, Texas. The J. of Geol. 64 (1): 1-14.
Buckley, H.E., 1951. Crystal growth. John Wiley & Sons, New York. 586 pp.
Bureau of Reclamation, 1974. Eearth Manual. US Dept. of the Int., Gov. Pr. Off., Washington. 810 pp.
Buringh, P., 1960. Soils and soil conditions in Iraq. Min. of Agr. Baghdad. 322 pp., 2 maps.
Buringh, P., 1979. Introduction to the study of soils in tropical and subtropical regions. PUDOC, Wageningen. 99 pp.
Callot, G., H. Chamayou and M. Dupuis, 1978. Variations du pH de la solution de matériaux calcaires en relation avec la dynamique de l'eau. Eléments d'analyse d'un système carbonaté. Ann. Agron. 29 (1): 37-57.
Capolini, J. and M. Sary, 1975. Quelques aspects de la répartition des croûtes et encroûtements calcaires et calco-gypseux du piedmont sud du Hodna. Colloque; Types de croûtes calcaires et leur répartition régionale. Univ. Louis Pasteur, UER Géographie, Strasbourg: 133-139.
Castillo, E.C. and L.R. Beltrán, 1973. Clasificación agroclimática de España basada en la clasificación ecológica de Papadakis. Pub. A 53. Servicio Meteorologico Nacional, Madrid: 49.
Cooke, R.U. and A. Warren, 1973. Geomorphology in deserts. B.T. Batsford Ltd., London. 374 pp.
Coque, R., 1955. Morphologie et croûte dans le Sud-tunesien. A.G. 345: 367.
Coque, R., 1962. La Tunesie Présaharienne. Thèse C.N.R.S. Armand Colin, Paris. 476 pp.
Dapples, E.C., 1971. Physical classification of carbonate cement in quartzose sandstones. J. of Sedim. Petrol. 41 (1): 196-204.
Datiri, B.T., 1976. Characteristics and distribution pattern of sand in the lower Guadiana valley, Mérida area, Spain. M.Sc. thesis. ITC, Enschede. 161 pp., 5 maps.
Degens, E.T. and E. Rutte, 1960. Geochemische Untersuchungen eines Kalkkrustenprofils von Altkorinth - Griechenland. Neues Jahrb. Geol. u. Paleont.: 263-276.
Delwiche, C.C., 1975. The geobiology of calcium. Comm. in Soil Sci. and Plant Anal. 6 (3): 207-218.
Doorenbos, J. and W.O. Pruitt, 1977. Guidelines for predicting crop water requirements. Irrigation and Drainage Paper No. 24, FAO, Rome. 144 pp.
Doorenbos, J. and A.H. Kassam, 1979. Yield response to water. Irrigation and Drainage Paper No. 33, FAO, Rome. 193 pp.
Dorsser, H.J. van, 1974. A geomorphological map of a part of the lower Guadiana basin, the area south of the river Guadiana from the river Matachel to the Guadajira. Pub. B 55, Geogr. Inst. R.U. Utrecht. 19 pp.

Dudal, R., 1965. Dark clay soils of tropical and subtropical regions. FAO, Rome. 161 pp.
Dumas, M.B., 1969. Glacis et croûtes calcaires dans le Levant espagnol. Bull. Ass. Géogr. Fr. Vol. 375-379: 553-561.
Dumont, J.L., 1975. Les croûtes calcaires: Cimentation de sable par depôt de calcaire. Colloque; Types de croûtes calcaires et leur répartition régionale. Univ. Louis Pasteur, UER Géographie, Strasbourg: 65-70.
Durand, J.H., 1954. Les sols d'Algérie. Pedologie 2. Direction du service de la colonisation et de l'hydraulique. Birmandreis, Algérie. 244 pp.
Durand, J.H., 1959. Les sols rouges et les croûtes en Algérie. Etude generale no. 7. Direction de l'hydraulique et de l'equipement rural. Birmandreis, Algérie. 188 pp.
Evenari, M., D.H. Yaalon and Y. Gutterman, 1974. Note on soils with vesicular structure in deserts. Z. Geom. N.F. 18 (2): 162-172.
FAO, 1967. Guidelines for soil description. FAO, Rome. 76 pp.
FAO, 1973. Calcareous soils. Soils Bull. No. 21. FAO, Rome. 300 pp.
FAO-UNESCO, 1974. Soil map of the world. Vol. I legend. UNESCO, Paris. 59 pp.
FAO, 1976. A framework for land evaluation. ILRI, Wageningen. 87 pp.
Fedoroff, N., 1975. Classification micromorphologique des carbonates dans les sols. Colloque; Types de croûtes calcaires et leur répartition régionale. Univ. Louis Pasteur, UER Geographie, Strasbourg: 35-41.
Folk, R.L., 1965. Some aspects of recrystallisation in ancient limestones. In: Dolomitisation and limestone diagenesis; a symposium. Eds. L.C. Pray and R.C. Murray. Soc. Econ. Paleont. Min., Spec. Pub. 13: 14-48.
Franz, H. and G. Franz, 1969. Beitrag zur Kenntnis der Bildung von Kalkkrusten in Böden der warmen Trockengebiete. Z. Pflanzenern. Düng. 121: 34-42.
Franzmeier, D.P. and S.J. Ross Jr., 1968. Soil swelling: Laboratory measurement and relation to other soil properties. Soil Sci. Soc. Amer. Proc. 32: 573-577.
Frenzel, B., 1967. Die Klimaschwankungen des Eiszeitalters. Vieweg & Sohn, Braunschweig. 291 pp.
Fuehring, H.D., 1973. Response of crops grown on calcareous soils to fertilisation. In: Calcareous soils. FAO Soils Bull. 21: 53-71.
Gardner, L.R., 1972. Origin of the mormon mesa caliche, Clark County, Nevada. Geol. Soc. Amer. Bull. 83: 143-156.
Gazzolo, T. and G. Bassi, 1964. Le transport solide en suspension dans les bassins versants des cours d'eau Italiens. Ass. Int. d'Hyd. Sci. AIHS Pub. No. 65: 203-230.
Gehrenkemper, J., 1978. Rañas und Reliefgenerationen der Montes de Toledo in Zentral-Spanien. Berliner Geogr. Abh. Berlin. Heft 29: 79 pp.
Gehrenkemper, J., 1979. Sediment- und Bodendifferenzierung am mittleren Tajo (Zentralspanien). Z. Geomorph. N.F. Suppl. Bd. 33: 143-151.
Gigout, M., 1960. Sur le genèse des croûtes calcaires pleistocènes en Afrique du Nord. C.R. Somm. Soc. Géol. Fr.: 42-43.
Gile, L.H., 1961. A classification of ca horizons in soils of a desert region, Doña Ana County, New Mexico. Soil Sci. Soc. Amer. Proc. 25 (1): 52-61.
Gile, L.H., F.F. Peterson and R.B. Grossman, 1965. The K horizon: A master soil horizon of carbonate accumulation. Soil Sci. 99 (2): 74-82.
Gile, L.H., F.F. Peterson and R.B. Grossman, 1966. Morphological and genetic sequences of carbonate accumulation in desert soils. Soil Sci. 101 (5): 347-360.
Gile, L.H., 1977. Holocene soils and soil-geomorphic relations in a semi-arid region of southern New Mexico. Quat. Res. 7 (1): 112-132.
Goosen, D., E. Bisdom, A. Guerra Delgado and A. Jongerius, 1973. Soil survey and photo-interpretation in the Guadiana Valley, Spain. ITC Journal 1973-3: 449-463.
Goudie, A.S., 1972a. A regional bibliography of calcrete. In: Food, Fiber and the Arid Lands. Eds. W.G. McGinnies, B.J. Goldman and P. Paylore. Arizona: 421-437.
Goudie, A.S., 1972b. On the definition of calcrete deposits. Z. Geomorph. N.F. 16 (4): 464-468.
Goudie, A.S., 1973. Duricrusts in tropical and subtropical landscapes. Clarendon Press, Oxford. 174 pp.
Goudie, A.S., 1975. Petrographic characteristics of calcrete (caliche): modern analogues of ancient cornstones. Colloque; Types de croûtes calcaires et leur répartition régionale. Univ. Louis Pasteur, UER Geographie, Strasbourg: 3-6.

Gras, F., 1975. Les sols "a profil calcaire differencié" au Liban (Bekaa) - étude d'un toposequence. Colloque; Types de croûtes calcaires et leur répartition régionale. Univ. Louis Pasteur, UER Geographie, Strasbourg: 59-64.

Grossman, R.B., B.R. Brasher, D.P. Franzmeier and J.L. Walker, 1968. Linear extensibility as calculated from natural-clod bulk density measurements. Soil Sci. Soc. Amer. Proc. 32: 570-573.

Halasi-Kun, G.J., 1973. Improvement of runoff records in smaller watersheds based on permeability of the geological subsurface (I2). Unesco-WMO-IAHS Symposium on the design of water resources projects with inadequate data. Madrid: 131-145.

Hallsworth, E.G. and G.G. Beckman, 1969. Gilgaï in the Quaternary. Soil Sci. 107 (6): 409-420.

Harris, P.M., R.B. Halley and K.J. Lukas, 1979. Endolith microborings and their preservation in Holocene-Pleistocene (Bahama-Florida) oöids. Geology 7 (4): 216-220.

Hay, R.L. and R.J. Reeder, 1978. Calcretes of Olduvai Gorge and the Ndolanya Beds of northern Tanzania. Sedimentology 25 (5): 649-673.

Hay, R.L. and B. Wiggins, 1980. Pellets, oöids, sepiolite and silica in three calcretes of the southwestern United States. Sedimentology 27 (5): 559-576.

Heusch, B. and A. Milliès-Lacroix, 1971. Une méthode pour estimer l'écoulement et l'érosion dans un bassin; application au Maghreb. Mines et Géologie, Rabat 33: 21-39.

Hillel, D., 1980. Applications of soil physics. Academic Press, London-New York. 385 pp.

Holmes, A., 1970. Principles of physical geology. Thomas Nelson Ltd., London. 1288 pp.

Huizing, H.J.G., 1979. Examples of analysis of climatic data for agriculture, Mérida area, Spain. Unpublished preliminary data. Rural survey course ITC, Enschede. 3 pp.

IGME, 1950. Mapa geológico de España escala 1 : 50 000. Explicación de la Hoja No. 777. Mérida. Instituto Geológico y Minero de España (IGME). Eds. I. Roso de Luna and F. Hernández-Pacheco, Madrid. 99 pp., 1 map.

IGME, 1954a. Mapa geológico de España escala 1 : 50 000. Explicación de la Hoja No. 776. Montijo. Instituto Geológico y Minero de España (IGME). Eds. I. Roso de Luna and F. Hernández-Pacheco, Madrid. 66 pp., 1 map.

IGME, 1954b. Mapa geológico de España escala 1 : 50 000. Explicación de la Hoja No. 803. Almendralejo. Instituto Geológico y Minero de España (IGME). Eds. I. Roso de Luna and F. Hernández-Pacheco, Madrid. 119 pp., 1 map.

IGME, 1970. Mapa geológico de España escala 1 : 200 000. Sintesis de la cartografía existente Villareal-Badajoz. Hoja 58-59. Ed. Departamento de Publicaciones del Instituto Geológico y Minero de España (IGME), Madrid. 21 pp., 1 map.

Jacob, A. and H. v. Uexküll, 1963. Fertiliser use. Verlagsgesellschaft für Ackerbau mbh. Hannover. 617 pp.

James, N.P., 1972. Holocene and Pleistocene calcareous crust (caliche) profiles: criteria for subaerial exposure. J. of Sedim. Petrol. 42: 817-836.

Jansen, J.M.L. and R.B. Painter, 1974. Predicting sediment yield from climate and topography. J. Hydrol. 21: 371-380.

Jayaraman, M., 1974. Some aspects of calcic and petrocalcic horizons in the soils of the Mérida region (Spain). M.Sc. thesis, ITC, Enschede, 117 pp., 3 maps.

Jenny, H. and C.D. Leonard, 1939. Functionable relationships between soil properties and rainfall. Soil Sci. 38: 363-381.

Jenny, H., 1980. The soil resource (Origin and behaviour). Ecological Studies 37. Springer Verlag, New York. 377 pp.

Jessup, R.W., 1960. The stony tableland soils of the South-Eastern portion of the Australian arid zone and their evolutionary history. J. of Soil Sci. 11 (2): 189-196.

Jongerius, A. and G. Heintzberger, 1972. The preparation of Mammoth-sized thin sections. Soil survey paper no. 1. Neth. Soil Survey Inst., Wageningen. 37 pp.

Jung, Y.T., 1974. A study on the formation of broad, flat-bottomed valleys and depressions, in the Miocene clay area of Mérida region, Spain. M.Sc. thesis, ITC, Enschede. 144 pp., 1 map.

Kahle, C.F., 1977. Origin of subaerial Holocene calcareous crusts: role of algae, fungi and sparmicritisation. Sedimentology 24 (3): 413-436.

Kharaka, Y.K. and I. Barnes, 1973. SOLMNEQ: solution-mineral equilibrium computations. Rep. US. Geol. Survey, Water Res. Div., 74-002. 82 pp.
Knibbe, M., 1974a. Soil moisture regimes. Lecture Notes ITC Soils Department, Enschede. 15 pp.
Knibbe, M., 1974b. Genesis of landscape and soils of the Miocene area of Almendralejo. Unpublished notes. ITC, Enschede.
Knox, G.J., 1977. Caliche profile formation, Saldanha Bay (South Africa). Sedimentology 24 (5): 657-674.
Köppen, W. and R. Geiger, 1932. Handbuch der Klimatologie 3. Europa und Nordasien.
Krinitszky, E.L., 1970. Radiography in the earth sciences and soil mechanics. Plenum Press, New York. 163 pp.
Langbein, W.B. and S.A. Schumm, 1958. Yield of sediment in relation to mean annual precipitation. Trans. of the Amer. Geophys. U. 39: 1076-84.
Lattman, L.H., 1973. Calcium carbonate cementation of alluvial fans in Southern Nevada. Geol. Soc. Amer. Bull. 84: 3013-3028.
Lattman, L.H. and S.K. Lauffenburger, 1974. Proposed role of gypsum in the formation of caliche. Z. Geomorph. N.F. Suppl. Bd 20: 140-149.
Lattman, L.H., 1977. Weathering of caliche in Southern Nevada. In: Geomorphology in arid regions (D.O. Doehring, Ed.). Fort Collins, Colorado, USA: 221-231.
Leniger, H.A. and W.A. Beverloo, 1971. Inleiding in the technologie. Deel II 2e druk, L.H. Wageningen: 485 pp.
Leprun, J.C. and A. Blot, 1978. Sur la présence de sols bruns calcaires vertiques au Sénégal oriental. Science du Soil 1: 5-14.
Lindsay, L., 1979. Chemical equilibria in soils. John Wiley, New York: 100.
Macleod, D.A., 1980. The origin of the red Mediterranean soils in Epirus, Greece. J. of Soil Sci. 31 (1): 125-136.
Magaritz, M. and A.J. Amiel, 1980. Calcium carbonate in a calcareous soil from the Jordan Valley, Israel; its origin as revealed by the stable carbon isotope method. Soil Sci. Soc. Amer. J. 44 (5): 1059-1062.
Mahmood, N.N., 1979. On the origin of soil materials in the Proserpina-Trujillanos-Valverde de Mérida area, Extremadura, Spain. M.Sc. thesis ITC, Enschede. 162 pp, 1 map, 1 legend.
Manze, U. and K. Brunnacker, 1977. Ueber das Verhalten der Sauerstoff- und Kohlenstoff-Isotope in Kalkkrusten und Kalktuffen des mediterranen Raumes und der Sahara. Z. Geomorph. N.F. 21 (3): 343-353.
Margat, J., P. Taltasse and R. Raynal, 1954. Deux séries d'observations nouvelles sur les croûtes au Maroc (Couloir sudrifain et Maroc oriental). Notes Serv. géol. Maroc, t. 10 (122): 23-25.
Marsoedi, 1981. A semi-detailed soil survey and land evaluation study dealing with the usefulness of irrigation development for crop production in Guareña area, Badajoz, Spain. M.Sc. thesis ITC, Enschede. 121 pp., 1 map.
Massoud, F.I., 1973. Some physical properties of highly calcareous soils and the related management practices. In: Calcareous Soils. FAO Soils Bull. 21: 73-93.
Mathieu, I., 1974. Les croûtes et encroûtements calcaires: horizons de sol ou depôts? Etude bibliographique concernant l'Afrique du Nord. Sciences du Sol Doc. no. 175. 52 pp.
Mathieu, L., J. Thorez and C. Ek, 1975. Colloque; Types de croûtes calcaires et leur répartition régionale. Univ. Louis Pasteur, UER Geographie, Strasbourg: 114-120.
Meester, T. de. Highly calcareous lacustrine soils in the great Konya Basin, Turkey. Thesis L.H. Wageningen, also Agr. Res. Rep. 752, PUDOC, Wageningen. 169 pp., 1 map.
Meester, T. de, 1973. Morphology, mechanical composition and formation of highly calcareous, lacustrine soils in Turkey. In: Calcareous Soils. FAO Soils Bull. 21: 29-39.
Meigs, P., 1962. Classification and occurence of Mediterranean-type dry climates. In: UNESCO/IGU symposium, Landuse in semi-arid Mediterranean climates. Iraklion, Greece: 17-21.
Meijerink, A.M.J., 1977. Hydrological reconnaissance survey of the Serayu River basin. ITC Journal 1977-4: 646-674.

Menillet, F., 1975. Niveaux calcaires finement rubanés en milieu continental, hydromorphe et confiné a paleogeographie simple; l'exemple des calcaires de Beauce (Stampien Sup. - Aquitanien du bassin de Paris). Remarque de A. Ruellan dans la discussion. Colloque; Types de croûtes calcaires et leur répartition régionale. Univ. Louis Pasteur, UER Geographie, Strasbourg: 21.
Millot, G., D. Nahon, H. Paquet, A. Ruellan and Y. Tardy, 1977. L'épigénie calcaire des roches silicatées dans les encroûtements carbonatés en pays subaride, Antiatlas, Maroc. Sci. Géol. Bull. 30 (3): 129-152.
Millot, G., 1979. Les phénomènes d'épigénie calcaire et leur rôle dans l'altération. Science du Sol 2/3: 259-261.
Multer, H.G. and J.E. Hoffmeister, 1968. Subaerial laminated crusts of the Florida Keys. Geol. Soc. Amer. Bull. 79: 183-192.
Nagtegaal, P.J.C., 1969. Microtextures in recent and fossil caliche. Leidse Geol. Med. 42: 131-142.
Nahon, D. and A. Ruellan, 1975. Les accumulations de calcaire sur les Marnes eocènes de la falaise de Thiès (Senegal). Mise en evidence des phénomènes d'épigénie. Colloque; Types de croûtes calcaires et leur répartition régionale. Univ. Louis Pasteur, UER Geographie, Strasbourg: 7-11.
Nahon, D., G. Millot, H. Paquet, A. Ruellan and Y. Tardy, 1977. Géochimie de la surface et formes du relief. VII. Digestion et effacement des cuirasses ferrugineuses par les encroûtements calcaires en pays aride, Sahara de Mauritanie. Sci. Géol. Bull. 30 (4): 289-296.
Netterberg, F., 1969. The interpretation of some basic calcrete types. The South African Archeol. Bull. 24 (3/4): 117-122.
Netterberg, F., 1975. Self-stabilisation of road bases: fact or fiction? 6th Reg. Conf. for Africa on Soil Mech. and Found. Eng. RR.190: 115-119.
Netterberg, F., 1978a. Calcrete wearing courses for unpaved roads. The Civil Engineer in South Africa 20 (6): 129-138.
Netterberg, F., 1978b. Dating and correlation of calcretes and other pedocretes. Trans. Geol. Soc. S. Africa. 81 (3): 379-391.
Netterberg, F., 1980. Geology of Southern African calcretes: 1 Terminology, description, macrofeatures and classification. Trans. Geol. Soc. S. Africa. 83: 255-283.
Nieuwenhuis, E. and N.A. Trustrum, 1977. Gilgaï in Extremadura, Spain. Tech. Rep. 4, ITC, Enschede. 43 pp.
Noureddine, L., 1979. Remarques sur les croûtes calcaires dans la Beqa'a méridionale (Liban). Rech. Geograph. à Strasbourg 12: 5-13.
Olmstead, F.R., 1949. Suggested methods of test for securing the liquid limit of soils using one-point data. From: Waterways Experiment Station Tech. Mem. no. 3-286 report no. 1: 3 pp.
Paletskaya, L.N., A.P. Lavrov and Sh.I. Kogan, 1958. Pore formation in takyr crust. Sov. Soil Sci. 3: 245-250.
Pannekoek, A.J., 1968. Geomorphology of the Iberian Peninsula part I and II. Univ. of Leiden, Dept. of Geol. Lecture Notes. 31 + 39 pp.
Paton, T.R., 1974. Origin and terminology for gilgaï in Australia. Geoderma 11 (3): 221-242.
Pérez Mateos, J., 1955. Etude minéralogique comparée des formations sédimentaires du Tertiaire continental du bassin du Tage et du plateau de la Guadiana. Geol. Runds. 43: 357-362.
Price, W.A., 1933. The Reynosa problem of South Texas and the origin of caliche. Bull. Amer. Soc. of Pet. Geol. 17: 488-522.
Rao, K.V.S., 1975. The consequences of polycyclical soil development for taxonomic soil classification in Miocene clay, Mérida region, Spain. M.Sc. thesis, ITC, Enschede. 120 pp., 1 map.
Redondo, C.P., 1975. Croûtes calcaires dans les profils d'alteration des terraces de la Durance. Colloque; Types de croûtes calcaires et leur répartition régionale. Univ. Louis Pasteur, UER Geographie, Strasbourg: 55-58.
Reeves, C.C. Jr., 1970. Origin, classification and geologic history of caliche on the Southern high plains, Texas and Eastern New Mexico. J. of Geol. 78: 352-362.
Reeves, C.C. Jr., 1976. Caliche, origin, classification, morphology and uses. Estacado Books, Lubbock, Texas. 233 pp.

Richter, C., F. van der Pol and A. Marliere. A negative influence of manure on calcareous soils. Plant and Soil 50 (2): 515-520.
Rightmire, C., 1967. A radiocarbon study of the age and origin of caliche deposits. Unpub. M.Sc. thesis, Univ. Texas, Austin, Texas. 67 pp.
Rogaar, H., 1980. The morphology of burrow structures made by Tubificids. Hydrobiologia 71: 107-124.
Rogaar, H. and J.A. Boswinkel, 1978. Some soil morphological effects of earthworm activity; field data and X-ray radiography. Neth. J. Agric. Sci. 26: 145-160.
Roy, D.K., 1974. Soil patterns as related to some degradational processes in Miocene clays, Spain. M.Sc. thesis, ITC, Enschede. 112 pp., 1 map.
Ruellan, A., 1968. Les horizons d'individualisation et d'accumulation du calcaire dans les sols du Maroc. Trans. 9th Int. Conf. Soil Sci. Adelaide, Australia 4: 501-510.
Ruellan, A., 1970. Les sols a profil calcaire différencié des plaines de la basse Moulouya. Thèse Univ. de Strasbourg. 302 pp.
Ruellan, A., D. Nahon, H. Paquet and G. Millot, 1977. Géochimie de la surface et formes du relief. VI. Rôle des encroûtements et épigénies calcaires dans le façonnement du modelé en pays aride. Bull. Sci. Géol. 30 (4): 283-288.
Ruellan, A., 1980. L'accumulation du calcaire dans les sols. Reunion organisée par le groupe d'étude des systèmes carbonatées. Univ. de Bordeaux, Inst. de Geodynamique. INSA, Toulouse: 401-411.
Rural Survey Staff, 1973. Background information on land use and agriculture for fieldwork of the ITC rural survey course. Mérida, Spain. Internal publ. rural survey course ITC, Enschede. 11 pp.
Sabelberg, U. and H. Rohdenburg, 1975. Stratigrafische Stellung und klimatisch-geo-ökologischer Aussagewert der Kalkkrusten in Spanien und Marokko. Colloque; Types de croûtes calcaires et leur répartition régionale. Univ. Louis Pasteur, UER Géographie, Strasbourg: 120-128.
Salomons, W., 1975. Chemical and isotopic composition of carbonates in recent sediments and soils from Western Europe. J. of Sed. Petrol. 45 (2): 440-449.
Salomons, W. and W.G. Mook, 1976. Isotope geochemistry of carbonate dissolution and reprecipitation in soils. Soil Sci. 122 (1): 15-24.
Salomons, W., A. Goudie and W.G. Mook, 1978. Isotopic composition of calcrete deposits from Europe, Africa and India. Earth Surf. Processes 3: 43-57.
Scholz, H., 1972. Die ariden braunen Böden Südwestafrikas. Fortschr. Geol. Rheinlnd. u. Westf. 21: 101-108.
Segal, J.L. and G. Stoops, 1972. Pedogenetic calcite accumulation in arid and semi-arid regions of the Indo-Gangetic alluvial plain of erstwhile Punjab (India) - their morphology and origin. Geoderma 8: 59-72.
Sidhu, P.S., 1977. Aeolian additions to the soils of North-West India. Pedologie 27 (3): 323-336.
Siesser, W.G., 1973. Diagenetically formed oöids and intraclasts in South African calcretes. Sedimentology 20: 539-551.
Snedecor, G.W. and W.G. Cochran, 1974. Statistical methods. The Iowa State Univ. Press. Ames, Iowa, USA. 593 pp.
Spiers, B., 1981. Vegetation survey of semi-natural grazing lands (dehesas) near Mérida, South-West Spain, a basis for land use planning. Tech. Rep. 6, ITC, Enschede. 129 pp., 1 map.
Springer, M.E., 1958. Desert pavement and vesicular layer of some soils of the desert of the Lahontan Basin, Nevada. Soil Sci. Soc. Amer. Proc. 22 (1): 63-66.
Soil Survey Staff, 1951. Soil Survey Manual. US Dept. Agric. Handb. 18, Washington. 503 pp.
Soil Survey Staff, 1975. Soil taxonomy. A basic system of soil classification for making and interpreting soil surveys. US Dept. Agric. Handb. 436, Washington. 754 pp.
Thornthwaite, A.C., 1948. An approach towards a rational classification of climate. Geograph. Rev. 38: 55-94.
Tihay, J.P. and T. Vogt, 1979. Observations sur les croûtes calcaires dans le bassin de Bouira (vallée de l'Oued Soummam, Algérie). Rech. Géograph. à Strasbourg 12: 35-45.
Trewartha, G.T., 1943. An introduction to weather and climate. McGraw-Hill, New York. 545 pp.

Truc, G., 1975. Sols a profil calcaire differencié et pellicules rubanées dans le paleogene du sud et de la France. Colloque; Types de croûtes calcaires et leur répartition régionale. Univ. Louis Pasteur, UER Geographie, Strasbourg: 108-113.
UNESCO-FAO, 1963. Bioclimatic map of the Mediterranean zone. Arid Zone Research XXI, Ecological Study of the Mediterranean Zone. UNESCO, Paris. 58 pp., 6 maps.
UNESCO, 1970. Vegetation map of the Mediterranean zone. Map and explanatory notes. UNESCO SC.68/III.35/AF: 56-57.
Vadour, J. and G. Clauzon, 1976. Les croûtes calcaires ont-elles toutes une origine pédologique? Mediterranée 24: 71-81.
Visser, J., 1968. Textbook of photogrammetry. Vol. III.2. Radial triangulation. ITC, Enschede. 78 pp.
Vogt, T., 1979. Croûtes calcaires et sols rouges en France méditerranéenne: trois exemples. Rech. Géograph. à Strasbourg 12: 13-23.
Volk, O.H. and E. Geyer, 1970. "Schaumböden" als Ursache der Vegetationslosigkeit in ariden Gebieten. Z. Geomorph. N.F. 14: 79-95.
Watts, N.L., 1977. Pseudo-anticlines and other structures in some calcretes of Botswana and South Africa. Earth Surf. Processes 2 (1): 63-74.
Watts, N.L., 1980. Quaternary pedogenic calcretes from the Kalahari (southern Africa): mineralogy, genesis and diagenesis. Sedimentology 27 (6): 661-686.
Weast, R.C. (Ed.), 1974. Handbook of chemistry and physics. 55th Ed. CRC Press Cleveland, Ohio, USA. B77.
Wesemael, J.Ch. van, 1955. De bepaling van het calciumcarbonaatgehalte van gronden. Chem. Weekbl. 51: 35-36.
Wieder, M. and D.H. Yaalon, 1974. Effect of matrix composition on carbonate nodule crystallisation. Geoderma 11: 95-121.
Wilbert, J., 1962. Croûtes et encroûtements calcaires au Maroc. Al Awamia 3: 175-192.
Williams, G.E. and H.A. Polach, 1971. Radiocarbon dating of arid-zone calcareous paleosols. Geol. Soc. Amer. Bull. 82: 3069-3086.
Wilson, L., 1973. Variations in mean annual sediment yield as a function of mean annual precipitation. Amer. J. of Sci. 273: 335-349.
Wischmeier, W.H. and D.D. Smith, 1978. Predicting rainfall erosion losses. A guide to conservation planning. US Dept. Agric. Handb. 537, Washington. 66 pp.
Yaalon, D.H. and D. Kalmar, 1972. Vertical movement in a undisturbed soil: Continuous measurement of swelling and shrinkage with a sensitive apparatus. Geoderma 8: 231-240.
Yaalon, D.H. and E. Ganor, 1973. The influence of dust on soils during the Quaternary. Soil Sci. 116 (3): 146-155.
Yaalon, D.H. and S. Singer, 1974. Vertical variation in strength and porosity of calcrete (nari) on chalk, Shefela, Israel and interpretation of its origin. J. of Sedim. Petrol. 44 (4): 1016-1023.
Young, A., 1976. Tropical soils and soil survey. Cambridge Univ. Press. 468 pp.
Young, R.G., 1964. Fracturing of sandstone cobbles in caliche cemented terrace gravels. J. of Sedim. Petrol. 34: 886-887.
Zuidam, R.A. van, 1976. Geomorphological development of the Zaragoza region, Spain. Thesis R.U. Utrecht. 211 pp., 3 maps.