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Ferrolysis, a soil-forming process in hydromorphic conditions

Papers

This volume forms part of the doctoral thesis to be defended on 20 April 1979 in the Agricultural University, Wageningen.

Contents

The paper by Brammer and Brinkman is not claimed as part of this thesis, having been written mainly by the first author. It is bound in this volume to provide a clear context for its companion paper on genesis of surface-water gley soils in Bangladesh.

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FERROLYSIS, A HYDROMORPHIC SOIL FORMING PROCESS

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SUMMARY

Seasonally wet soils with grey, silty, surface or subsurface eluvial horizons occurring in East Pakistan and widely elsewhere have variously been recognized as pseudogleys, sod-podzolics, low humic gleis, solodized soils and planosols. On the basis mainly of extensive field work in East Pakistan, a hypothesis was made to explain the formation of these soils. The proposed mechanism comprises cation exchange reactions involving iron in an orderly sequence of reduction-oxidation cycles, leaching of displaced cations in the reduced phase and acid attack of clay minerals in the beginning of the oxidized phase of each cycle. Some published data are used to illustrate successive steps in the process. The term ferrolysis[1] is proposed for this hydromorphic soil forming process.

INTRODUCTION

A hypothesis is proposed for a hydromorphic soil forming process termed ferrolysis, in which a soil's cation exchange capacity (C.E.C.) is destroyed due to exchange reactions involving iron in seasonally alternating cycles of reduction and oxidation. This process is distinct from (but has often in the past been confused with) podzolization, argilluviation or gleization. Podzolization is not dependent upon seasonal reduction; argilluviation (Dudal, 1968) does not involve clay destruction; gleization does not require elimination of reaction products or clay destruction, and may in some cases involve the reverse.

The concept of ferrolysis would account for such diverse unresolved questions as the anomalously low cation exchange capacity of many topsoils under long-continued seasonal rice cultivation; the close similarity between solods and some planosols; the potassium fixing nature of some pseudogleys and the presence in them of Al-interlayered clays (soil chlorites); and the apparently greater speed of podzolization in seasonally wet conditions. It is amenable to experimental verification.

[1]The term ferrolysis, used first in this paper, is derived from ferro(us) and lysis, and has been coined as a short term for disintegration and solution in water by a process based upon the alternate reduction and oxidation of iron.

Papers containing more details, some practical implications of ferrolysis and descriptions of ferrolysed soils in East Pakistan are in preparation for publication by the FAO World Soil Science Resources Office.

CHARACTERISTICS OF FERROLYSED SOILS

Ferrolysed soils are characterised by a ferrolysed horizon or horizons overlying a slowly permeable or impervious horizon or layer.

Ferrolysed horizons in the main stage have grey (occasionally dark grey) colours with oxidized mottles, and generally with white or light grey pedotubules and/or cutans containing appreciably less clay than the adjacent soil matrix. These horizons have less clay and/or a lower cation exchange capacity of the clay fraction than the underlying material, which may or may not contain argillans or "flood coatings". Soils in the initial stage of ferrolysis have a seasonal variation in topsoil pH. Some are suspected to be potassium fixing.

Ferrolysed soils have formed under conditions of seasonally alternating reduction and oxidation (either past or present) with net excess of leaching. Where ferrolysis is active, the ferrolysed horizon is near neutral in reaction in the reduced condition but acid when oxidized. There is an appreciable content of exchangeable ferrous iron in the reduced phase and of exchangeable

Fig.1. Barind tract, East Pakistan. A nearly level clay landscape, seasonally shallowly flooded by rain water. Land use: transplanted rice in the monsoon season.

Fig.2. Barind tract, East Pakistan. Ferrolysed profile showing a white, silty, seasonally reduced, A_p horizon (to 15 cm), over a grey, mottled, fine-silty subsoil with many white silt specks (to 50 cm), grading into a grey, slickensided parent clay.

aluminium when the soil is oxidized. The conductivity of the soil solution is low at least in the oxidized phase.

The underlying horizon or layer impeding drainage may be a fine-textured parent material, as in the grey terrace soils of the Madhupur and Barind tracts of East Pakistan (Fig.1,2); or a fragipan or a textural B horizon, as in pseudogleys; or a solonetz horizon, as in solodized solonetz and solod soils; or a ploughpan in soils long used for rice cultivation, as in some parts of Southeast Asia. The excess water either moves laterally over, or slowly through the impeding layer or horizon. With lateral water movement, the lower layers may be acid or alkaline. Where water moves downward, the lower layers become acid as the upper horizon becomes ferrolysed.

DESCRIPTION OF FERROLYSIS

The following description is based upon extensive field observations, mainly in East Pakistan, and upon the physical, chemical and clay mineralogical data available for soils in East Pakistan. The complete process of ferrolysis - as proposed in this paper - is described here for the first time, but most of the postulated individual steps can be illustrated by published data, as shown in a next section. A complete sequence of experimental verification has so far not been carried out.

The proposed process of ferrolysis involves a sequence of repetitive cycles, each comprising an anaerobic and an aerobic phase. The oxidation of organic matter provides the energy to drive the whole ferrolysis cycle. (Clay destruction by ferrolysis is far more efficient - requires roughly ten times less organic matter - than by attack and complexing by organic acid).

During the anaerobic phase, free iron is reduced with concurrent oxidation of organic matter and formation of hydroxyl ions. The ferrous iron displaces exchangeable cations and the displaced cations are leached (or partly leached, only during the early part of the reduced phase, in the case of aluminium).

During the following aerobic phase, ferrous iron is oxidized producing ferric hydroxide and hydrogen ions. The hydrogen ions displace the exchangeable ferrous iron and corrode the octahedral layers of the clay minerals at their edges. At the same time, there is equivalent diffusion of hydrogen against aluminium, some magnesium and other ions released from the octahedral lattice edges.

Thus, in every cycle, cations are leached and a part of the clay lattice is destroyed. With continued ferrolysis a seasonally wet soil, even if originally base saturated, can eventually develop to a grey, unstable, silty or sandy soil with low clay content and very low cation exchange capacity.

Initial stage of ferrolysis

In the initial stage of ferrolysis, exchangeable bases are eliminated, to be eventually replaced by mainly aluminium from the lattice after oxidation, and the pH in the oxidized phase becomes lower; the pH in the reduced phase remains relatively high almost throughout the course of the process. Besides attacking lattice ions, the hydrogen also attacks slowly released (fixed) potassium in illite, thus forming swelling illite. Hydrolysis of easily weatherable minerals (for example, fine-grained biotite) in the silt and sand fractions, or capillary rise of part of the leached bases, during the oxidized phase may slow down ferrolysis and raise the measured percent base saturation.

Main stage of ferrolysis

In the main stage of ferrolysis, exchangeable aluminium and other ions originating from the clay lattice are eliminated, and the clay fraction is progressively destroyed. Silica goes into solution from the unsupported tetrahedral lattice edges and is also leached. The 2:1-type clay minerals with high cation exchange capacity are destroyed most quickly due to the large amount of ferrous iron which can be accommodated on their exchange positions. Clays with lower C.E.C. are destroyed more slowly, and 1:1-type clays, due to their low C.E.C. as well as their higher proportion of octahedral lattice ions compared with 2:1 clays, are least susceptible to ferrolysis. Depending upon the volume of leaching water passing through the soil in the early part of the reduced phase, a greater or lesser part of the aluminium displaced by the ferrous iron is leached out. The remainder is retained in the soil horizon and is precipitated when the pH rises above 5.5 due to formation of hydroxyl ions concurrently with reduction of iron. At the same time, further aluminium displaced by ferrous iron and neutralized by hydroxyl ions is precipitated. The aluminium is then in the form of octahedral interlayer fragments, consisting of $Al(OH)_3$ and some $Al(OH)_2$ H_2O which balances the layer charge, on and between the faces of 2:1-type clays. This fixes the layer thickness of the previously swelling clays at 14 Å (1.4 nm) and effectively blocks part of their cation exchange capacity. This is the mechanism of Al-interlayering or formation of soil chlorite (chloritization). Thus, depending upon the degree of leaching, either clay destruction or chloritization may be the dominant mechanism destroying the soil's cation exchange capacity.

Terminal stage of ferrolysis

In the terminal stage of ferrolysis the soil either has a very low clay content or most of the clay present has been converted into soil chlorite. The soil then has a very low cation exchange capacity and further degradation due to ferrolysis is slight and slow.

SOME EXAMPLES FROM PUBLISHED DATA

Many authors have reported data which can be used to illustrate parts of the ferrolysis process. For example, Ponnamperuma (1963) very clearly demonstrates the predominance of exchangeable ferrous iron, and the mainly cationic and some complexed ferrous iron in solution, in reduced paddy soils. Ponnamperuma (1964) mentions that acidification of the topsoil is probably caused by continual displacement by ferrous iron under anaerobic flooded conditions, but does not explain the source of the acidity. Siuta (1962) reports data on leaching of soil columns without and with reduction (by sugar addition). When the data are recalculated in milli-equivalents, it is clear that the composition of the succeeding leachate fractions are in agreement with the expected effects of ferrolysis. Cate and Sukhai (1964) give a good example of reduction and solubilization of iron by organic matter, and of the virtually complete displacement of exchangeable aluminium by ferrous iron, and show that the iron reduction process is reversible. (Their soils are not ferrolysed but are catclays.)

Nobody to our knowledge has so far reported what exactly happens first when a ferrous iron-saturated clay is reoxidized. Dr. P.R. Hesse at our request did some experiments and showed a sharp drop in pH upon oxidation of a reduced soil containing exchangeable ferrous iron, the final pH after oxidation being related to the proportion of exchangeable ferrous iron. If we assume that the exchangeable ferrous iron produces $Fe(OH)_3$ and exchangeable hydrogen ions upon oxidation, the next part of the process can again be found in the literature. For example, Eeckman and Laudelout (1961) have demonstrated that H-montmorillonite is unstable and is changed to an Al-montmorillonite by hydrogen ions liberating octahedral ions (mainly Al) from the clay lattice and equivalent diffusion of the hydrogen and aluminium ions over the plate surface to and from the crystal edge. Chernov (1959) also demonstrates the hydrogen–aluminium reaction which corrodes the edges of the clay minerals. Jackson (1960), too, discusses the structural role of hydrogen and different aluminium ions in clays, and describes, in detail, the nature of exchangeable and non-exchangeable interlayer Al compounds.

The work by Jackson (1960) demonstrates the nature of the Al-interlayering (chloritization) process, evidence for which is widespread in the literature. Reuter (1965) has published clay mineral data on two pseudogley soil profiles in northern Germany which are subject to seasonal saturation by rain water. The data very clearly show the expansion and subsequent chloritization of illite, with the accompanying slight transient rise and subsequent considerable drop in cation exchange capacity. (The mechanism making the aluminium available is not discussed in the paper, but is referred to as "hydrolytic weathering" of clay minerals). Other authors reporting chloritization under seasonally reducing conditions include Martin and Russell (1952), Martin (1954) and De Coninck et al. (1968).

Kawaguchi and Kyuma (1968) describe the soil forming process of Aquorizems in Southeast Asia only in terms of reductive eluviation of the plough layer and oxidative illuviation of iron in the subsoil. These authors mention, however, that the cation exchange capacity of the surface soil is often unusually lower than a value estimated by consideration of clay content, clay mineral composition and organic matter content, and that the subsoil rarely shows this bias. This we believe to be indicative of partial clay destruction and chloritization due to ferrolysis.

Thorp and Bellis (1960) describe planosols in the Kenya highlands with nearly white, silty, moderately to strongly acid A horizons. The B horizons are reported to contain a wide range of exchangeable sodium: from little in humid areas to considerably more than 12% in subhumid locations. Even if in the humid areas the B horizons contained more exchangeable sodium than at present during some (drier) time in the past, ferrolysis due to seasonal alternation of reduction and oxidation could explain the silty, acid A horizons.

The similarity of (some) planosols and solods is also recognized in the classification for the Soil Map of the World which places the solods and deeply solodized solonetz as "solodic planosols" (Dudal, 1969).

Zonn (1966) mentions two pathways of podzolization by organic acids: chloritization and breakdown of clay minerals. In view of the frequent references in the literature to seasonal hydromorphic conditions in podzolic soils (Soviet Soil Sci., passim) it is possible that many of the reported podzolic soils are influenced by ferrolysis, and that not all chloritization and breakdown of clay minerals in these soils is due to organic acids.

CORRELATION

It seems probable that ferrolysis is a major genetic process in many soils at present variously identified as pseudogley in Europe (Reuter, 1965); gley-podzolic in the northern U.S.S.R. (Zaboyeva, 1958); sod-podzolic in the podzolic zone (Dolgova, 1963); paragleys in the Carpathian foothills (Gerasimova, 1968); podbel and beidzhan-tu in Siberia (Liverovskiy and Roslikova, 1962); solodized soils and planosols in Australia (Oertel, 1968; Stace et al., 1968); leached pallid soils on the African plateau (Watson, 1962); planosols and planosol-solod intergrades in Kenya (Thorp and Bellis, 1960); degraded rice soils in Burma (Karmanov, 1960); low humic glei and soils with an anthraquic horizon in Southeast Asia (Dudal and Moormann, 1964); and Aquorizems in many countries of Southeast Asia (Kawaguchi and Kyuma, 1968).

The classification of ferrolysed soils in the U.S.D.A. 7th Approximation (Soil Survey Staff, 1960) is not clear. Some may be Albaqualfs; others (like the ferrolysed soils in East Pakistan) have presently to be classified as Aeric Haplaquepts, although this is inappropriate in view of the extreme nature of the changes that have taken place in them. In many instances, an Albic group or subgroup could be used to differentiate these soils, but in some cases, for example, where ferrolysed soils occur under permanent natural grassland, the organic matter in the topsoil masks the pallid nature of the mineral fraction.

Soils in which the topsoil and the upper subsoil are in the main stage of ferrolysis (mature ferrolysed soils) would be included in the planosols in the FAO-UNESCO soil units (Dudal, 1968), the group (Solodic, Dystric, Eutric) depending upon the nature of the underlying horizon. Soils in which only the topsoil is ferrolysed would be classified according to their subsoil characteristics, and not in one specific soil unit.

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CLAY DECOMPOSITION IN SEASONALLY WET, ACID SOILS: MICROMORPHOLOGICAL, CHEMICAL AND MINERALOGICAL EVIDENCE FROM INDIVIDUAL ARGILLANS

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ABSTRACT

Brinkman, R., Jongmans, A.G., Miedema, R. and Maaskant, P., 1973. Clay decomposition in seasonally wet, acid soils: Micromorphological, chemical and mineralogical evidence from individual argillans. *Geoderma*, 10: 259–270.

Individual argillans in thin sections from a seasonally wet, acid soil were studied by petrographic microscope, X-ray diffraction microcamera, and electron microprobe.

The data suggest that, under seasonally reducing and leaching conditions, free iron is reduced and partly leached; smectite and illite are decomposed while at least part of the aluminium, magnesium and potassium liberated is removed by leaching; silica liberated from the smectite and illite is reprecipitated as microcrystalline quartz; and the argillans are residually enriched in rutile and kandite.

Birefringent argillans are altered to isotropic, characteristically grainy cutans by this process. Strongly altered parts show a bright opalescent reflection in incident light.

INTRODUCTION

Many seasonally wet, acid soils have a considerably lower clay content in the upper horizons than in deeper horizons, as well as characteristic white or very light grey patches or tongues or "sprinkled" ped coverings* that contain much less clay than the surrounding material or ped interiors. The "silt sprinklings" are much better visible in the dry state than moist or wet.

Such soils are included, for example, in the Aqualfs and Aquults of the U.S.D.A. 7th Approximation (Soil Surv. Staff, 1973); the Planosols and Gleyic Podzoluvisols of the *Soil Units for the Soil Map of the World* (Dudal, 1970); and in the pseudogleys or hydromorphic soils of different European classifications, for example, C.P.C.S. (1967). The topsoils of Aquorizems in parts of Southeast Asia (Kawaguchi and Kyuma, 1968) show similar characteristics.

Mechanical analyses of a number of seasonally wet, acid soils from different parts of

*Similar "sprinkled" ped coverings were observed in some well-drained soils in midwestern U.S.A. (R.W. Simonson, personal communication, 1973).

the world confirmed the sedimentary homogeneity of most of the profiles studied, and confirmed but did not explain the lower clay contents in the upper horizons.

Micromorphological studies of thin sections taken from the same profiles have shown that in many cases the amount of clay illuviation cannot explain the differences in clay content between surface horizons and subsoil. A process of clay decomposition may therefore have taken place in these soils: a process by which clay disappears without corresponding illuviation. The process of ferrolysis (Brinkman, 1970; Dudal, 1973) was postulated to explain the nature of this process in seasonally wet, acid soils.

The presence of partly unaltered, partly altered argillans in such soils appeared to afford a possibility of studying in detail certain aspects of the process of clay decomposition.

Argillans in seasonally wet, acid soils (pseudogleys, planosols) from different parent materials and in tropical as well as temperate climates show characteristic micromorphological features: they range from "normal", birefringent to isotropic, grey and typically grainy. The grainy cutans tend to occur mainly in upper soil horizons, whereas the proportion of birefringent cutans is greater in the deeper horizons. Birefringent cutans may be preserved in ferric nodules or mottles in upper horizons.

Considerable concentrations of similar grainy material have also been observed in acid sulphate soils. So far, we have not observed grainy cutans in podzols. Grey, gel-like material with very low SiO_2/Al_2O_3 ratios was found in the B_3 horizons of tropical podzols by Veen and Maaskant (1971) and De Boer (1972), but this appears to be very different from the grainy cutans described in this paper.

MATERIALS

Samples from a well expressed pseudogley horizon in a coversand soil from the south of The Netherlands were used for this study.

This soil has strong pseudogley features, and is overlain by a plaggen epipedon. The A_2 horizon consists of bleached sand, tonguing into the brown, loamy sand B horizon. The difference in clay contents of the A and B horizons is sufficient for an argillic horizon, and the ratio of clay contents is quite high (4.8 against 1.4%). The A and B horizons both contain relatively large argillans, in different stages of alteration. The site and soil profile description, general micromorphological and analytical data are described and discussed elsewhere (Van Oosten et al., 1973).

METHODS

Undisturbed samples were impregnated with Synolith resin and acetone (method slightly modified from Fitzpatrick, 1970). After curing, sections were cut, ground, polished to a thickness of 20–30 μm and left uncovered. These thin sections were studied by petrographic microscope, and examples of different kinds of cutans were photographed under ordinary, polarized and reflected light.

X-ray diffraction microcamera exposures (Chesley, 1947) of some cutans were made to obtain an estimate of their relative clay and quartz contents. The kinds of clay minerals present cannot yet be determined from microcamera exposures of thin sections. Therefore, oriented aggregates of clay fractions from different horizons of the same profile were subjected to X-ray diffraction analysis (Mg-glycerol and K saturated).

Quantitative electron microprobe analyses were performed with a Cambridge Scientific Instruments Geoscan, using an accelerating potential of 20 kV and with reference to the following standards: diopside and kyanite for Si, kyanite for Al, olivine for Mg, Fe metal for Fe, TiO_2 for Ti and orthoclase for K. Apparent concentrations were corrected with a computer programme published by Springer (1967) with the following modifications: absorption coefficients from Heinrich (1966) and atomic number correction from Duncumb and Reed (1968).

Artificial "cutans" prepared from clay fractions with known compositions from the same profile were used for comparison: an average of mainly the B horizon (No.794), and the lower part of an A_2 tongue (No.795).

The hydrated character and the inevitably poor polishing quality of the investigated samples cause relative errors of 5–10%. Contents of constitution water in the two standard clay fractions analysed by wet-chemical methods being 10 and 10.3%, electron microprobe analyses of standard clay fractions and samples (assuming similar water contents in the samples) were recalculated to a sum of 90%. Except in the case of potassium, a reasonable agreement is obtained between the two analytical methods. (The reason for the discrepancy in K figures is not known, and the absolute illite percentages derived from the K contents by petrochemical calculation should therefore also be viewed with some reserve.)

X-ray emission pictures and scanning profiles for different elements were made with the same instrument, showing differences in Ti, Si, Al, Fe, Mg and K contents.

Contents of norm minerals in intact and altered parts of cutans were derived from the electron-microprobe data by a petrochemical calculation procedure adapted to soil clays (Van der Plas and Van Schuylenborgh, 1970). Minerals in this "goethite norm" include smectite, illite, kandite, quartz, rutile, goethite.

RESULTS AND DISCUSSION

Micromorphology. Normal, birefringent white to reddish-brown argillans or ferri-argillans (Fig.2A) predominate in lower horizons. Isotropic, grey cutans with a characteristic grainy pattern (Fig.2B) are common in upper horizons and bleached tongues. A range of transitions exists between these two forms. Such transitions may occur within one cutan (Fig.2C and D, outline sketch in Fig.3) and may cross the "shell" pattern boundaries indicative of stages in cutan formation (Fig.1). This shows that the grainy parts are due to alteration rather than to differences during deposition of the original cutans. Scattered fine black grains between "cleaned" silt and sand may indicate an extreme case: a former cutan almost completely disappeared. Isotropic, grainy parts of cutans exhibit a bright bluish white, "opalescent" reflection when viewed in incident mercury light (Fig.3A).

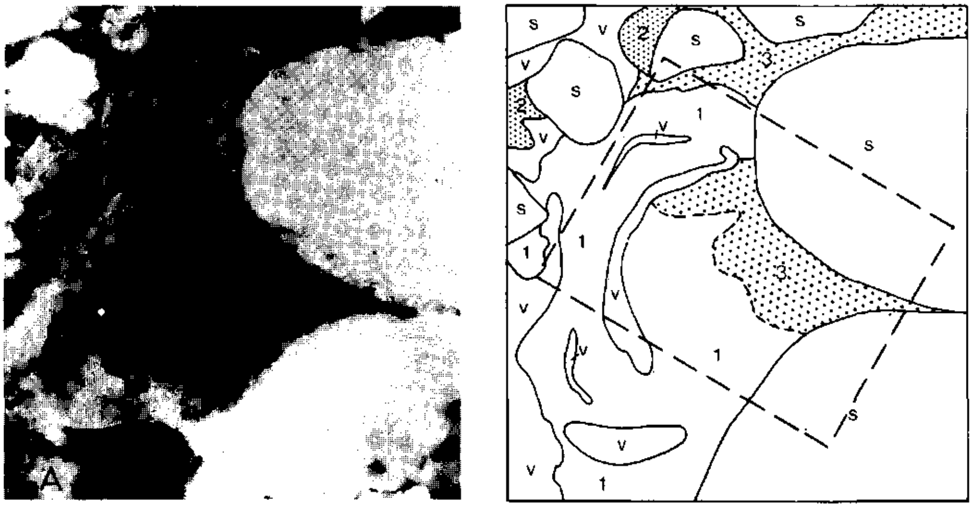

Fig.1. A. Partly altered cutan in polarized light. B
B. Outline sketch. Box shows approximate area covered by Fig.5. *v* = voids; *s* = skeleton grains; *1* = birefringent part of cutan; *2* = slightly birefringent parts of cutan and plasma; *3* = isotropic, grainy part of cutan. Width of figures represents approx. 200 μm.

X-ray diffraction microcamera exposures indicate a higher content of extremely fine-grained quartz and a lower content of clay minerals (020 line) in an isotropic, grainy cutan than in a birefringent cutan. Since approximately constant volumes of cutan in thin sections (about 20 μm thick and 50 μm diameter) were irradiated in the microcamera, this suggests that quartz is formed by crystallization (neoformation) during clay decomposition. The opalescent material described above is probably newly formed, microcrystalline quartz.

Neoformation of quartz within some weeks to 3 years at 20°C, 1 atm, pH 7 or 8, and silica concentration in solution about 5 mg/L was demonstrated by Harder and Flehmig (1970) in the presence of amorphous silica (+ Al or Fe hydroxide) and by Mackenzie and Gees (1971) in the presence of freshly ground quartz. The unsupported edges of silica sheets produced by clay decomposition are in an intermediate condition between quartz and amorphous silica, and presumably give rise to similar rates of quartz formation as these two solid phases.

X-ray diffractograms of clay fractions from the A_2 and B horizons of the same profile showed a considerable decrease in smectite and an increase in quartz content from B to A_2, and the appearance of incompletely aluminium interlayered material (soil chlorite) in the upper horizons. The latter mineral showed a sharp, well-defined 14 Å peak after Mg saturation and glycerolation, and partial collapse with a small 14 Å "shoulder" remaining after K saturation. Kandite and illite peak heights also increased somewhat toward the A_2 horizon.

X-ray emission pictures (Fig.4 and 5) show higher Ti and Si, and lower Al, Fe, Mg and K concentrations in the strongly altered part than in the remainder of a cutan (compare

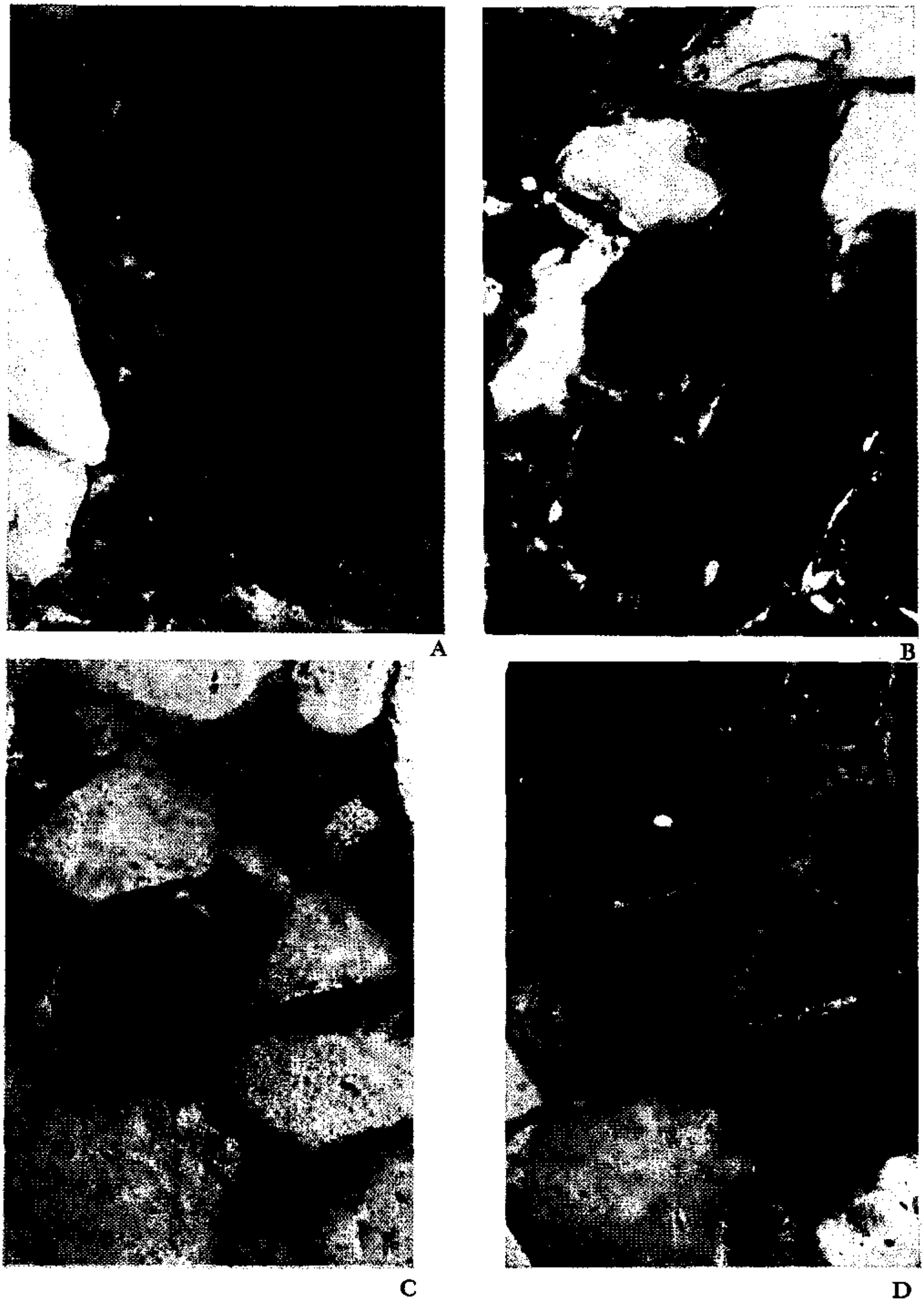

Fig. 2. A. Fresh cutan, birefringent, in polarized light. B. Altered cutan, isotropic, grainy, in polarized light. C. Partly altered cutan in transmitted light. D. Partly altered cutan in polarized light. Outline sketch of C and D in Fig. 3. Width of figures represents approx. 190 μm.

TABLE II

SiO_2/Al_2O_3 ratio and norm mineral composition of cutans

	Standard clay fractions*[1]		Standard clay fractions*[2]		Fresh cutan, birefringent*[2] (Fig. 2A)	Partly altered cutan*[2] (Fig. 2C,D)		Partly altered cutan*[2] (Fig. 1)		Altered cutan, isotropic, grainy*[2] (Fig. 2B)
	794	795	794	795		birefringent part	isotropic, grainy part	birefringent part	isotropic, grainy part	
Ratio:										
SiO_2/Al_2O_3 (weight)	2.2	2.4	2.4	2.3	2.0	2.1	2.4	2.2	2.5	3.8
SiO_2/Al_2O_3 (mol.)	3.6	4.1	4.1	3.9	3.4	3.6	4.1	3.7	4.3	6.5
Norm mineral composition (%):										
quartz	7.4	13.6	13	14	6	13	24	10	20	37
rutile	0.8	0.9	0.8	0.9	0.8	2.0	2.0	1.2	2.7	1.9
goethite	11.8	8.0	12.5	8.4	15.5	8.3	8.9	9.2	6.3	3.5
kandite	19.9	18.4	8	22	26	29	42	18	20	10
illite	20.2	19.4	30	23	18	20	12	26	24	24
smectite	34.6	29.7	32	28	32	25	9	30	21	18
H_2O^+	3.3	4.5	5	4	2	3	2	4	4	6
albite	1.8	1.7						~2	~2	
strengite	0.8	0.4								

*[1] Analysed by wet methods.

*[2] Analysed by microprobe.

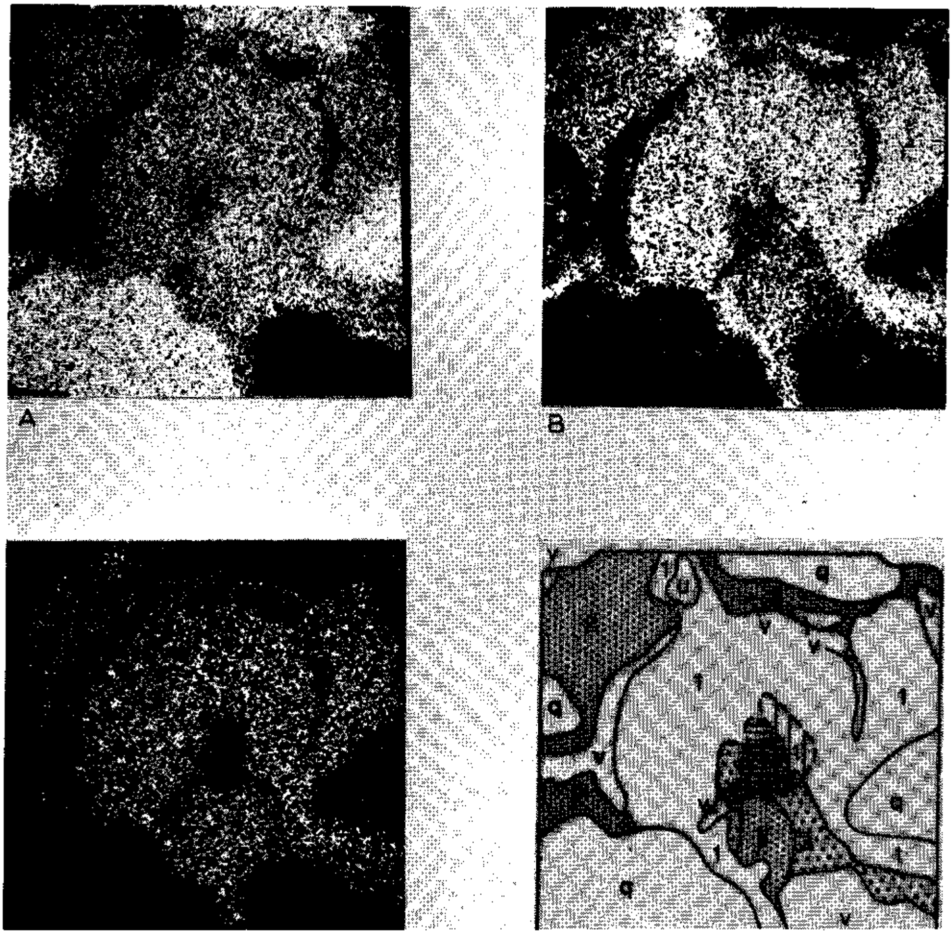

Fig.4. X-ray emission pictures of a partly altered cutan. A. SiK_α; B. AlK_α; C. KK_α; D. Outline sketch (compare Fig.3): v = voids; q = quartz grains; u = unknown spot (high Al, low Si and K: probably polishing compound); 1 = area with high Al content; 2 = moderate Al content; 3 = low Al content. Horizontal hatching: area with lower K content than surroundings; vertical hatching: area with slightly higher Si content than surroundings (compare Fig.3A). Width of figures represents approx. 140 μm.

The data are in agreement with the concept of ferrolysis, the proposed process of clay decomposition in pseudogleys and planosols described by Brinkman (1970). The neoformation of quartz in the presence of the presumably dissolving, unsupported tetrahedral clay lattice edges associated with this process is reported here for the first time.

CONCLUSION

The data suggest that, under seasonally reducing and leaching conditions, free iron is reduced and partly leached; smectite and illite are decomposed while at least part of the

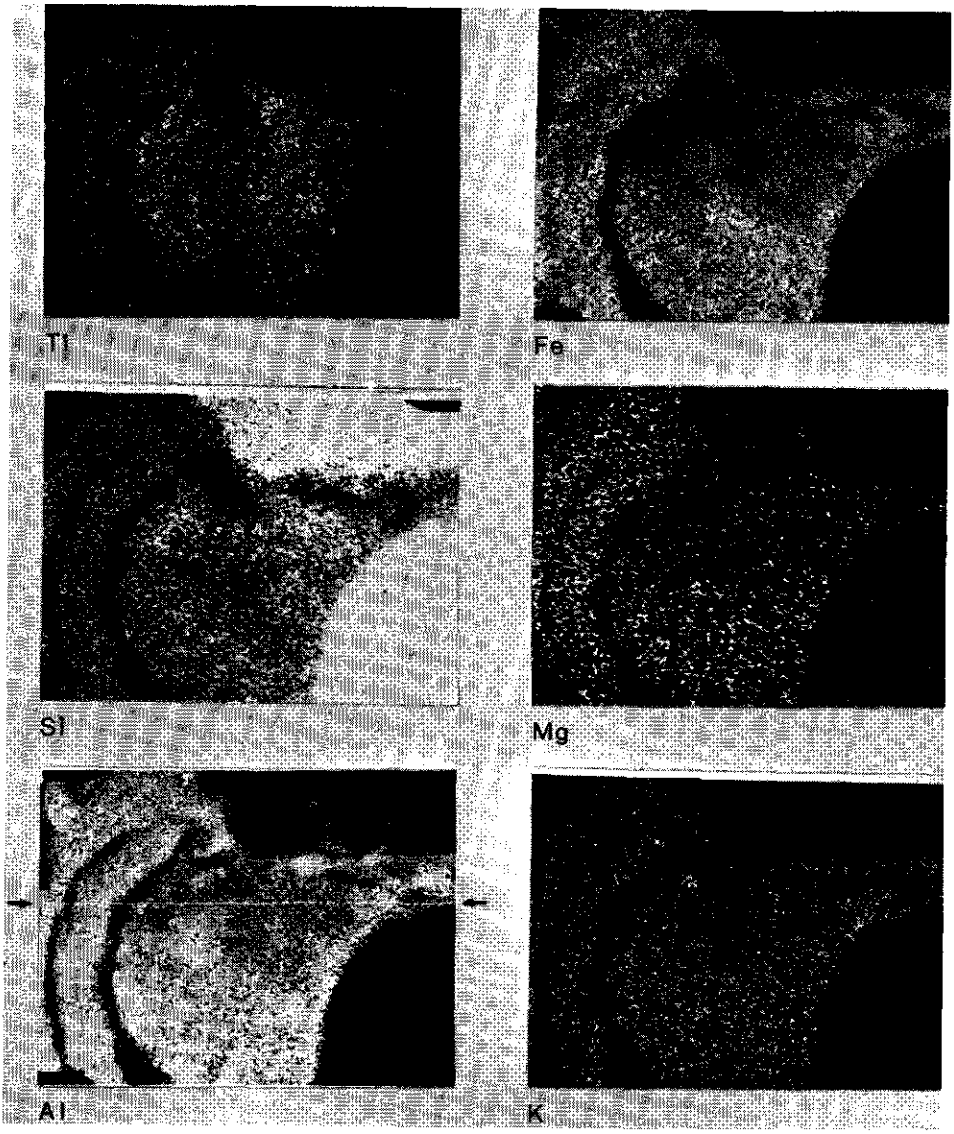

Fig.5. X-ray emission pictures of a partly altered cutan. K_{α} radiation. Area of pictures shown by box in Fig.1B. Arrows and line across Al emission picture show approximate position of scanning profiles (Fig.6). Width of figures represents approx. 150 μm.

aluminium, magnesium and potassium liberated is removed by leaching; silica liberated from the smectite and illite is precipitated as microcrystalline quartz; and argillans are residually enriched in rutile and kandite.

Isotropic, grainy material is produced from birefringent clay by this process. The bright, opalescent reflection of strongly altered parts in incident light may be caused by the secondary microcrystalline quartz.

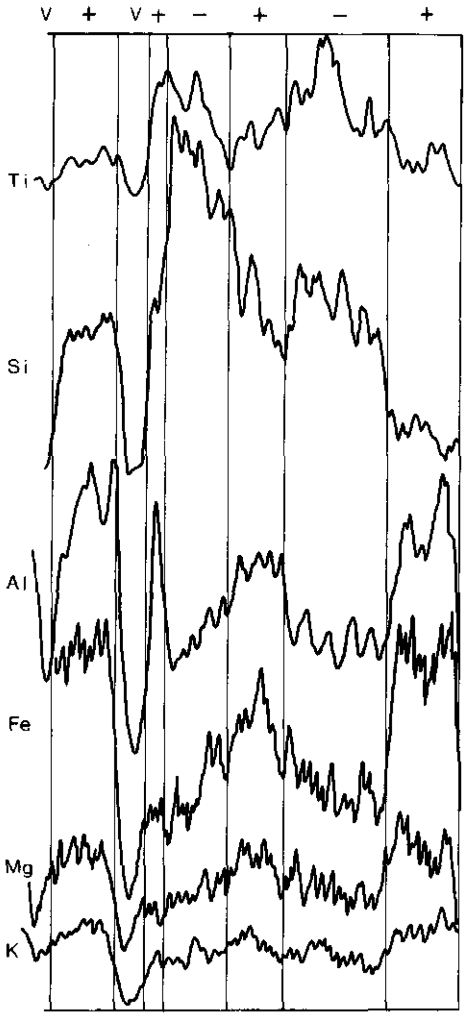

Fig.6. Scanning profiles across a partly altered cutan. Approximate position of scan lines shown by arrows in Fig.5. ν = voids; + = not or slightly altered parts; − = strongly altered parts.
Graphs indicate relative contents of elements in a narrow bundle of parallel scan lines. Base height to concentration ratios are different for different elements.
There may have been baseline drift during the Si scan. Profile length represents approx. 140 μm.

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Geoderma, 17 (1977) 91—109

SURFACE-WATER GLEY SOILS IN BANGLADESH: ENVIRONMENT, LANDFORMS AND SOIL MORPHOLOGY

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ABSTRACT

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Most of Bangladesh is seasonally flooded or waterlogged, mainly by rain water. Surface-water gley soils are extensively developed on the seasonally wet landscapes. They are acid, hydromorphic soils with albic horizons containing less clay than the deeper horizons, and with a seasonally fluctuating pH in the surface horizon. Such soils with grey, porous, silty albic horizons to depths ranging from 0.3 to more than 1 m are extensive over clays on low, level, terrace-like Pleistocene landforms. The oldest of the Holocene floodplain landscapes have soils in which only the upper 10 or 15 cm have less clay and contain albic material. Soils on younger floodplains where alluvial sedimentation is insignificant have seasonally acid A horizons, without substantial loss of clay. On all landscapes, puddling for rice cultivation apparently accelerates the processes giving rise to the albic horizon and concentrates them in the ploughed layer and ploughpan. A correlation of these soils is proposed with, e.g., aquorizems, degraded paddy soils, low humic gley and grey hydromorphic soils elsewhere in southeast Asia.

A companion paper gives analytical data on a representative example of these soils and discusses their genesis and classification.

INTRODUCTION

Surface-water gley soils* are extensively developed on floodplain and older terrace-like landscapes in Bangladesh. The soils on terrace-like landscapes are characterized by pale-coloured (usually albic), mottled, porous, silty surface horizons 0.3—0.6 m thick with low clay content, overlying a clay substratum or a cambic or argillic B horizon (these and other terms from FAO, 1974) and by the seasonally fluctuating pH of the surface

* Surface-water gley soils are seasonally water-saturated at least in the upper horizons due to precipitation or flood-water low in electrolytes. They are subject to lateral or vertical leaching. There is no accumulation of, for example, iron oxides from elsewhere as occurs in some groundwater gley soils.

horizon. On relatively old floodplain landscapes, too, there are surface-water gley soils, but less clearly expressed than on the terraces: the clay contents in the surface horizons are anomalously low and there are light grey silt skins and pockets in the ubiquitous ploughpan and on ped surfaces in the upper part of the cambic horizon below. Even in the majority of young floodplain soils, where there is little or no continuing alluvial sedimentation, the seasonally acid, seasonally neutral, Apg or Ag horizon indicates that a process of soil formation is already taking place.

All these soils have in common their occurrence on almost level to very gently sloping sites which are seasonally flooded or waterlogged followed by a period of aeration. Many, but not all, have a layer impeding through drainage. This may be a clayey C (or B) horizon; in some soils, it is a dense ploughpan. The upper, weathered horizon is acid during the part of the year when it is aerobic. The less weathered layers below may be acid or alkaline.

Fig. 1 indicates the physiographic regions of Bangladesh. Of these, the Madhupur and Barind tracts contain a large proportion of surface-water gley soils, as do the northern and eastern piedmont plains. The Tista, Old Brahmaputra and the northeastern part of the Meghna river floodplains as well as the Old Meghna estuarine floodplain contain soils in which only the surface horizon has an anomalously low clay content and seasonally fluctuating pH. Other soils in these floodplains, older basin clays in the Ganges river and tidal floodplains and most soils in the Jamuna (Young Brahmaputra) floodplain have a seasonally fluctuating pH in the surface horizon but no evidence of clay loss.

The present paper describes the physical environment of the surface-water gley soils in Bangladesh and their distribution; gives short field descriptions of the different kinds that are recognized; and discusses their correlation with similar soils elsewhere. A full description of Chhiata series, a representative example, is given at the end.

A companion paper (Brinkman, 1977) presents data on micromorphology, physical and chemical characteristics and mineralogy mainly of the Chhiata profile described in detail below; discusses the placement of these surface-water gley soils in two world systems of soil classification; and describes a model of polygenetic development that can explain the features of these soils.

ENVIRONMENT

Bangladesh mainly comprises the meander, estuarine and tidal floodplains of the Ganges, Brahmaputra, Meghna and some lesser rivers. Low, nearly level, older terrace-like landforms occupy important areas in the centre and northwest, and strongly dissected hill ranges occur along the eastern border. Parent material and soil distribution have been complicated by major shifts in river courses and by tectonic movements continuing to the present.

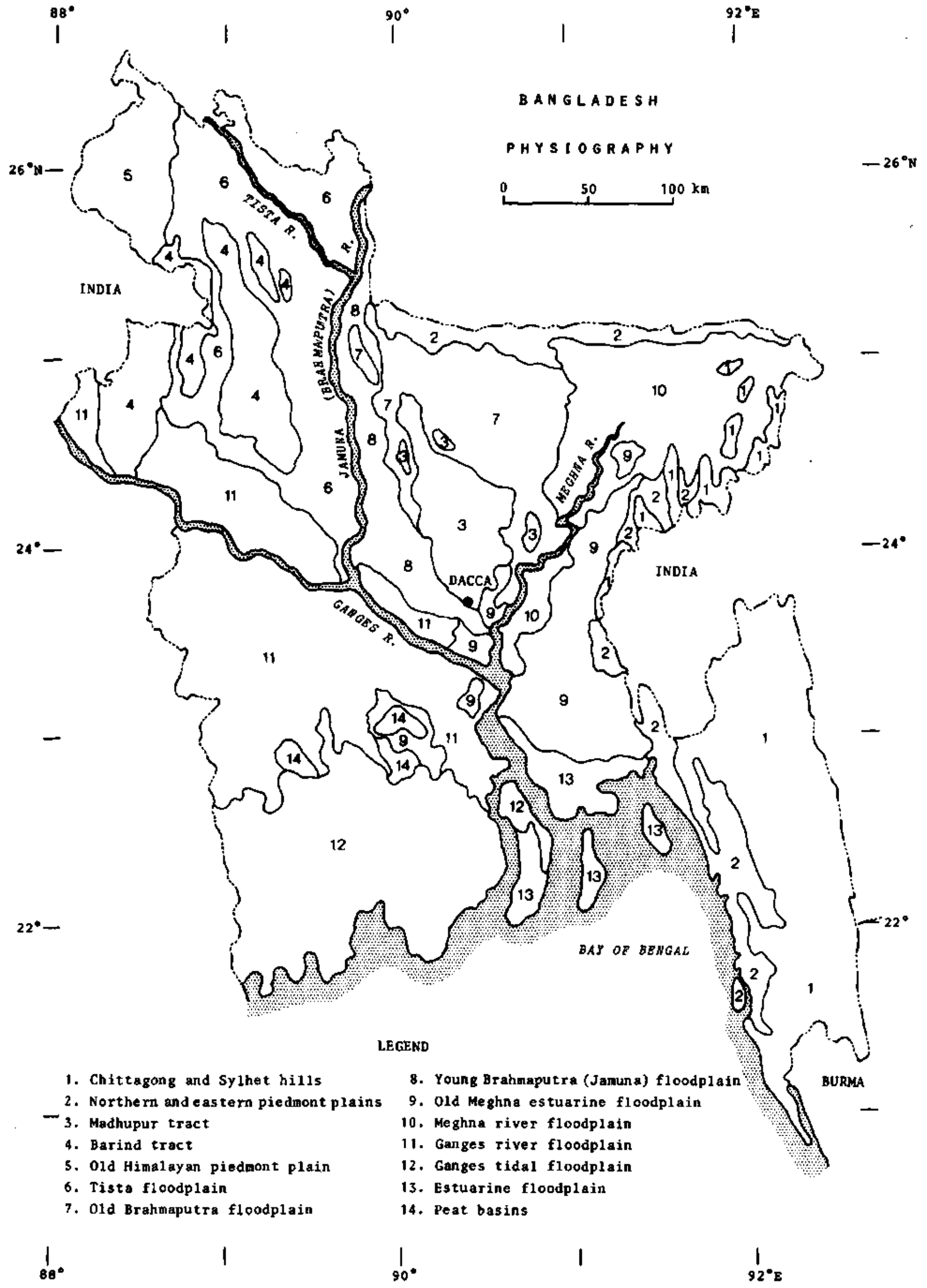

Fig. 1. Physiography of Bangladesh.

Climate

Bangladesh lies astride the tropic of Cancer and has a tropical monsoon climate. Monthly mean temperatures range from 18°C in winter to 30°C in summer (Table I). Rainfall is heavy and strongly seasonal, annual totals ranging from about 1,200 mm in the centre-west of the country to about 4,000 mm in the northeast. Most of the rain falls in the summer months between May and October. The winter season is almost rainless. Annual rainfall everywhere exceeds annual potential evapotranspiration, but potential evapotranspiration exceeds rainfall by about 200—400 mm in the dry season (Table I).

Hydrology

At the time of the heaviest rainfall (June—September), the main rivers entering Bangladesh are in flood, the combined peak flows of the Ganges and Brahmaputra rivers being of the order of 10^5 m^3 per second. Most of the country is seasonally flooded, therefore, by rain water unable to drain off the land until river levels fall in September—November. Depth of flooding ranges, in different places, from a few dm to locally more than 6 m.

Many terrace and piedmont areas that are above normal flood level mostly have such low slopes that they are waterlogged by rain water for several weeks during the monsoon season. Part of the soils have slowly permeable substrata that prolong flooding or waterlogging, but many do not. On such land, and on relatively higher floodplain land, farmers prolong the period of surface waterlogging by constructing low bunds round their fields and by puddling the ploughed layer for rice cultivation.

Vegetation and land use

The older soils appear to have developed under swamp, grassland or reed

TABLE I

Mean monthly temperature, rainfall and evaporation, Dacca (IECo, 1964)

	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.	Year
Temperature (°C)	18	21	26	30	29	28	28	28	28	27	23	19	26
Rainfall (mm)	10	26	55	148	239	343	323	342	232	141	18	4	1881
Evaporation (mm)	49	68	122	142	130	105	101	92	89	80	55	54	1087
Excess rainf. (mm)	—	—	—	7	109	237	222	249	143	61	—	—	summe 1028
Excess evap. (mm)	38	42	67	—	—	—	—	—	—	—	37	50	winter 234

vegetation. Only minor areas of surface-water gley soils remain under such vegetation. Most of the older floodplain and terrace soils have probably been cultivated for several centuries. Younger soils have been cultivated since their parent material was deposited. Rice is the major crop, together with some jute early in the wet season. A wide variety of dry-land crops such as mustard, pulses and wheat is grown on some of the younger floodplain soils in the dry season, but most older soils remain fallow during this period. However, during the past decade, substantial acreages have been brought under small-scale pump or tube-well irrigation, mainly to produce an additional rice crop.

Soil parent materials

The soils are developed in terrace material and floodplain alluvium. The terrace soils are developed over Madhupur clay, probably a marine deposit, equivalent to the Miocene—Pliocene Dupi Tila formation of Assam (Khan et al., 1964). This formation underlies the Madhupur and Barind tracts and appears remarkably homogeneous both vertically and throughout its lateral extent. The Madhupur and Barind tracts have been subjected to block faulting and may only have been uplifted in the Late Pleistocene, inasmuch as the oldest deposits found in valleys crossing them have a radiocarbon age of 5300—6700 years (FAO, 1971). Morgan and McIntire (1959) give more details on the geological structure and tectonics of Bangladesh. They consider the terrace areas as Pleistocene floodplain sediments. Later work on sand mineralogy by Huizing (1971), however, confirms their similarity with the Dupi Tila deposits and suggests that they are derived from a rather level, pre-weathered hinterland pre-dating the time when the present Bangladesh became a part of the Himalayan drainage system.

The floodplain alluvium is mainly of Himalayan origin, brought down by the Brahmaputra, Tista and other rivers. Ganges alluvium also includes material from the peninsular Indian shield and from eroding calcareous terrace soils in its upper course. Sediments of Himalayan origin are rich in weatherable minerals, especially biotite, and Ganges alluvium is calcareous. Upper Meghna (Surma—Kusiyara) alluvium and piedmont sediments derived from the Tertiary hill ranges in the east and northeast generally have low contents of weatherable minerals. The lowest buried layer recognized in floodplains, about 3 m below the surface near Dacca, was dated 5300—6700 years before present. This includes tree trunks and roots, probably of mangrove species, indicating estuarine conditions about that time. The oldest surface sediments in the floodplains (parts of the Old Brahmaputra and Old Meghna floodplains) may be about 2000 or more years old, as indicated by a few radiocarbon datings (FAO, 1971). Large areas of surface sediments, for example on the Young Brahmaputra (Jamuna) floodplain, are known from historic sources to be less than about 200 years old.

The surface-water gley soils are most easily recognized in the field when they are dry. They then typically comprise an almost white, very silty, anthraquic epipedon* overlying an almost white, variably mottled, highly porous, silty, albic E horizon with white silt specks and coatings in cracks and pores. This layer overlies a more clayey B or C horizon at about 25—60 cm, often with white silty specks or coatings in cracks and pores in the transition zone. The E horizon is slightly hard when dry and the mottles are sometimes weakly indurated. When wet, the A horizon becomes strongly reduced, as seen by $K_3Fe(CN)_6$ test; the E horizon becomes grey, slightly sticky and non-plastic, and the white silt segregations are not readily apparent.

These characteristics of surface-water gley soils are present to varying degrees in different floodplains and terraces. Simplified profile descriptions illustrating the major kinds of surface-water gley soils occurring in Bangladesh are given in the text below. A full description of one representative soil is given at the end of this paper. Soil horizon designations are according to FAO (1974); soil descriptions according to FAO (undated).

For practical purposes, the surface-water gley soils of Bangladesh are grouped as follows: mature without through drainage; mature with through drainage; immature; incipient. The four terms are defined below.

Mature surface-water gley soils have albic horizons extending to depths greater than the Ap horizons (Ap—Eg—B or C profiles). In immature soils, the albic horizon is restricted to the Ap horizon. Incipient soils have Ap horizons with a seasonally fluctuating pH and without evidence of clay loss.

Mature surface-water gley soils without through drainage

Profiles are developed on poorly drained level terrace landscapes over Madhupur clay. Each has a grey silty Ap horizon and a grey, mottled, porous, silty clay loam E horizon overlying grey, compact clay parent material which usually has tiny silt pockets and ped coatings in a transitional EC horizon. The Ap and E horizons appear almost white when dry. An example of these soils, Chhiata series, is fully described at the end of this paper. Its genesis was studied in detail by Brinkman (1977). A summary field description follows.

Soils of Chhiata series are developed over shallowly weathered Madhupur

* The anthraquic epipedon (Dudal and Moormann, 1964) is the surface soil layer altered by ploughing in soils used for wet-land crops, especially rice. It comprises both the cultivated layer and the underlying ploughpan. Both layers are in a puddled state, have grey base colours and are strongly iron-stained along root channels. At least the cultivated layer is strongly reduced when waterlogged or flooded. In Bangladesh, there is commonly a strongly oxidized layer and in places a coating of iron oxides, but no iron pan, at the base of the ploughpan.

clay on small, level, watershed sites of the Madhupur tract (Fig. 2). Seasonally flooded by rain water within field bunds for about 4—5 months. Used for a transplanted rice crop, sometimes preceded by a broadcast dryland rice crop; where irrigated, for two transplanted rice crops per year.

0—15 cm Apg	Grey (light grey dry) (5Y 6/1, 7/1) silt or silt loam with iron-stained root channels; strongly reduced* in monsoon season; compact ploughpan in lower 5 cm; pH 5—6 dry (7 reduced).
15—25 cm Eg	Grey (light grey dry) silt loam to silty clay loam with iron-stained root channels and fine to coarse reddish yellow (7.5YR 6/6) mottles increasing downward; not reduced in monsoon season; highly porous; pH 5—6 (wet and dry).
> 25 cm Cg	Grey (5Y 5—6/1) compact silty clay or clay, variably mottled red to yellow (5YR 4/8—10YR 5/8); strong blocky or wedge structure, with prominent intersecting slickensides; white silt specks and ped coatings present in variable amounts in the upper part; pH 5—6, gradually increasing downward to 7 or higher. This layer is the parent Madhupur clay which continues with little change to 6 metres or more. It may contain calcareous nodules below 50—100 cm.

Mature surface-water gley soils with through drainage

Profiles occur on poorly drained level terrace and piedmont landscapes. Each has a grey, silty, Al or Ap horizon and a grey, mottled, porous, silt loam to silty clay loam E horizon. The latter horizon is usually about 10—25 cm thick in terrace and piedmont soils but may extend below 1 m in some valley soils of the Madhupur tract. The underlying C horizon is a strongly mottled grey and red, friable clay in terrace soils and some piedmont soils. In the C horizons of most piedmont and valley soils, mottles are less abundant and brown rather than red, and textures range from silt loam to clay. Five examples are given below to illustrate the range of soils found in this group.

Soils of Chandra series, cultivated phase, are developed over deeply weathered Madhupur clay on extensive slightly concave sites of the Madhupur and Barind tracts (example in Fig. 2). Seasonally flooded by rain water up to about 1 metre deep for 4—5 months. Used mainly for a broadcast dryland rice crop followed by a transplanted rice crop; locally for deep-water broadcast rice intermixed with an early-maturing dryland rice.

0—15 cm Apg	Grey (light grey dry) (N 5—6, N 7) silt or silt loam with iron-stained root channels; strongly reduced in monsoon season; compact ploughpan in lower 5 cm; pH 5—6 dry (7 reduced).

* Strongly reduced conditions are indicated by the presence of ferrous iron, as shown by the dark blue stain on freshly broken surfaces in Ap material after treatment with a $K_3Fe(CN)_6$ solution.

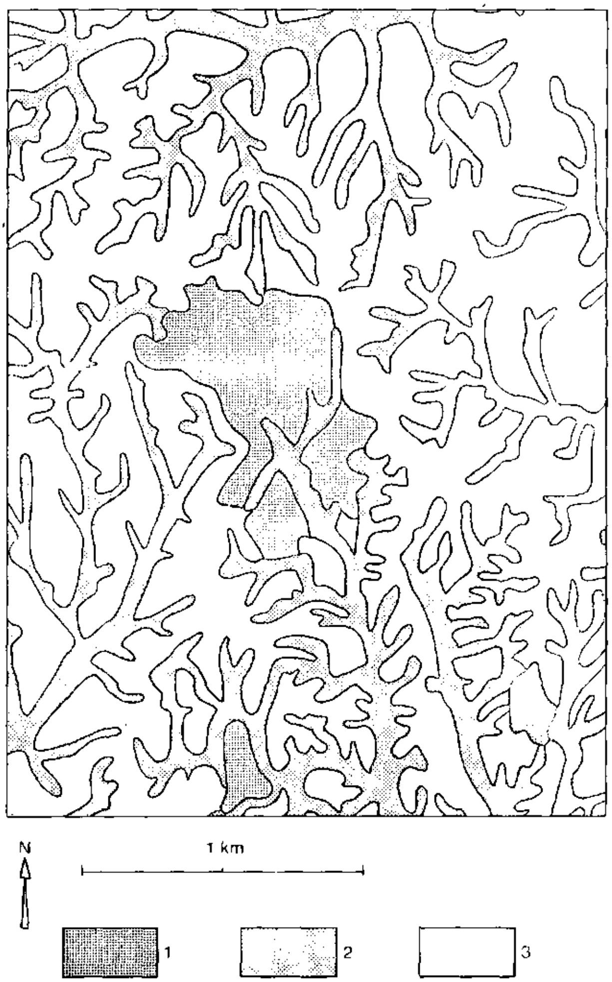

Fig. 2. Distribution of Chhiata and related soils in the Madhupur tract.
1 = Chhiata on shallowly dissected watershed sites.
2 = Chandra in valley heads, Kalma in main parts of valleys.
3 = Less poorly drained soils on more deeply dissected parts of the terrace.
Map by photo interpretation with limited ground data, location about 50 km NNW of Dacca.

15—25 cm Eg	Grey (light grey dry) silty clay loam with iron-stained root channels and medium to coarse reddish yellow (7.5YR 6/6) and black mottles increasing downward; mottles sometimes indurated; not reduced in monsoon season; highly porous; pH 5—6 (wet and dry).
> 25 cm Cg	Red and grey (2.5YR 3/6, 4/4, 5YR 5/6, and 5Y 6/1) reticulately mottled silty clay or clay; fine irregular blocky structure; rather friable moist; porous; pH 5—6. This layer

may continue to 6 m or more, the red mottles gradually becoming darker with depth. It is not indurated in the profile, nor does it indurate on exposure.

Soils of Chandra series, natural grassland phase are developed over deeply weathered Madhupur clay in a few concave shallow depression sites of the Madhupur tract. Seasonally flooded up to about 1 m deep by rain water (or a raised groundwater table) for 4—5 months. Under natural grassland, grazed and seasonally burned, but apparently never cultivated.

0—25 cm Ag	Dark greyish brown (2.5Y 4/2) friable clay loam; strongly reduced in monsoon season; pH 5—5.5 dry (7 reduced).
25—35 cm Eg	Grey (5Y 6/1) friable clay loam with many yellowish red (5YR 5/8) mottles; highly porous; white silt patches along pores; pH 5 (dry and wet, but higher in reduced parts).
35—100+cm Cg	Grey and red (5Y 6/2, 2.5YR 5/8) reticulately mottled, friable, porous clay; pH 5. This layer continues mottled to great depth. Tongues of E material may penetrate 25—50 cm into the upper part of this layer.

Fig. 3 is a horizontal section through the lower part of the E horizon, showing the considerable porosity and the white silt patches concentrated around pores.

Fig. 3. Horizontal section through the subsoil in a Chandra profile. Scale (black) 10 cm.

Soils of Amnura series are developed over deeply weathered Madhupur clay on extensive level sites of the Barind tract. The parent material is intermediate between those of Chhiata and Chandra soils in degree of alteration and permeability. Seasonally flooded within field bunds for about 4—5 months. Used for a transplanted rice crop, locally preceded by a broadcast dryland rice crop.

0—15 cm Apg	Grey (light grey dry) (5Y 5/1, 7/1) silt or silt loam with iron-stained root channels; strongly reduced in monsoon season; compact ploughpan in lower 5 cm; pH 5.5—6.5 dry (7 reduced).
15—30 cm Eg	Yellowish brown and grey (10YR 5/6, 5Y 6/2) mottled silt loam to silty clay loam; friable; highly porous; pH 6.5.
> 30 cm Cg	Grey and yellowish brown (5Y 5/1, 10YR 5/6) mottled silty clay or clay, becoming increasingly mottled yellowish red below about 1 metre; friable; porous; remnants of wedge-shaped peds with degraded slickensides sometimes visible; pH 6.5.

Soils of Kalma series are developed in narrow, gently sloping, streamless valleys in the Madhupur tract (Fig. 2). Seasonally flooded from 10 cm to more than 1 metre deep for 4—5 months. Used either for a broadcast dryland rice crop followed by a transplanted rice crop, or for deep-water broadcast rice intermixed with an early-maturing dryland rice.

0—15 cm Apg	Grey (light grey dry) (5Y 5/1, 7/1) silt loam to silty clay loam with iron-stained root channels; strongly reduced in monsoon season; compact ploughpan in lower 5 cm; pH 5—5.5 dry (7 reduced).
15—100+cm Eg	Grey (light grey dry) silt loam to silty clay loam with many strong brown (7.5YR 5/6) mottles; highly porous; white silt patches visible along cracks and pores in the dry soil; pH 5—5.5. This layer may continue to depths exceeding 3 m and overlies mottled, variably weathered Madhupur clay. The boundary as observed in excavations is clear to diffuse and generally tonguing, suggesting weathering, not a change in sediment.

Soils of Pritimpasa series are developed in piedmont plains at the foot of the Assam and Tripura (northern and eastern) hills. Flooded up to 30—60 cm for 2—3 days after heavy rain. Used for broadcast dryland rice followed by transplanted rice in fields bunded to retain water.

0—18 cm Apg	Grey (5Y 6/1) loam with iron-stained root channels; reduced during part of monsoon season; compact ploughpan in lower 8 cm; pH 4.8—5.3 dry.
18—60 cm Eg	Grey (5Y 5/1) clay loam with common dark greyish brown mottles; porous; thin patchy silt skins; pH 5—5.6.
60—117 cm	Grey clay loam with many yellowish brown mottles; weak

Bg	very coarse blocky structure; thin patchy gleyans*; pH 5.3—5.4.
117—137+ cm 2Cg	Grey fine sandy loam with few yellowish brown mottles; pH 5.5.

Immature surface-water gley soils

Profiles are developed on poorly drained level terrace and old floodplain landscapes. Each comprises an Ap horizon consisting partly or entirely of white (dry) silty material overlying a more clayey B or C horizon. Two examples are given, in terrace and in floodplain material.

Soils of Demra series are developed over very shallowly weathered Madhupur clay on level sites of the Madhupur tract. Seasonally flooded up to 3 m deep for about 4—6 months. Shallowly flooded soils used for a broadcast dryland rice crop followed by a transplanted rice crop. Deeply flooded soils formerly used for deep-water broadcast rice, now mainly for a transplanted winter rice crop with irrigation and for two transplanted rice crops where irrigated and pump-drained.

0—15 cm Apg	Grey (light grey dry) (N 5, N 7) silt or silt loam with iron-stained root channels; strongly reduced in monsoon season; compact ploughpan in lower 5 cm; pH 5—7 (7 reduced).
> 15 cm Cg	Grey (5Y 5/1) silty clay or clay, variably mottled yellowish brown to reddish brown (10YR 5/6, 7.5YR 5/8, 5YR 5/4); compact; strong wedge structure with intersecting slickensides; patches of white silt visible on ped faces and pores locally near top of layer in the dry soil; many large lime nodules met at a variable depth between 15 cm and more than 2 m; pH 7—8.5.

In several places the upper limit of the lime nodules and the boundary of the silt loam with the silty clay C horizon show a gilgai topography: undulating with a wavelength of several metres and an amplitude of about 1 m or less. The shallow soils belong to Demra series, the deepest soils in this complex to Chhiata series. Krotovinas occur both in the material with lime nodules and in the adjacent material without lime (Fig. 4). In the former, they consist of dark grey silty clay or clay, a colour not found elsewhere in the profile at present, presumably remnants of the dark grey A horizon of a former Vertisol (Fig. 4A). In the material that is free

* "Gleyans" is the name provisionally given to gleyed ped or pore coatings occurring in seasonally flooded soils (Brammer, 1971). The cutans are typically thicker than true argillans and comprise silt and mica as well as clay and humus. Their colour is that of the overlying surface horizon and it is assumed that they flow, or are injected, down voids from the puddled and reduced plough layer under conditions of seasonal flooding. Their presence is not diagnostic for an argillic horizon, though they may mask the presence of argillans.

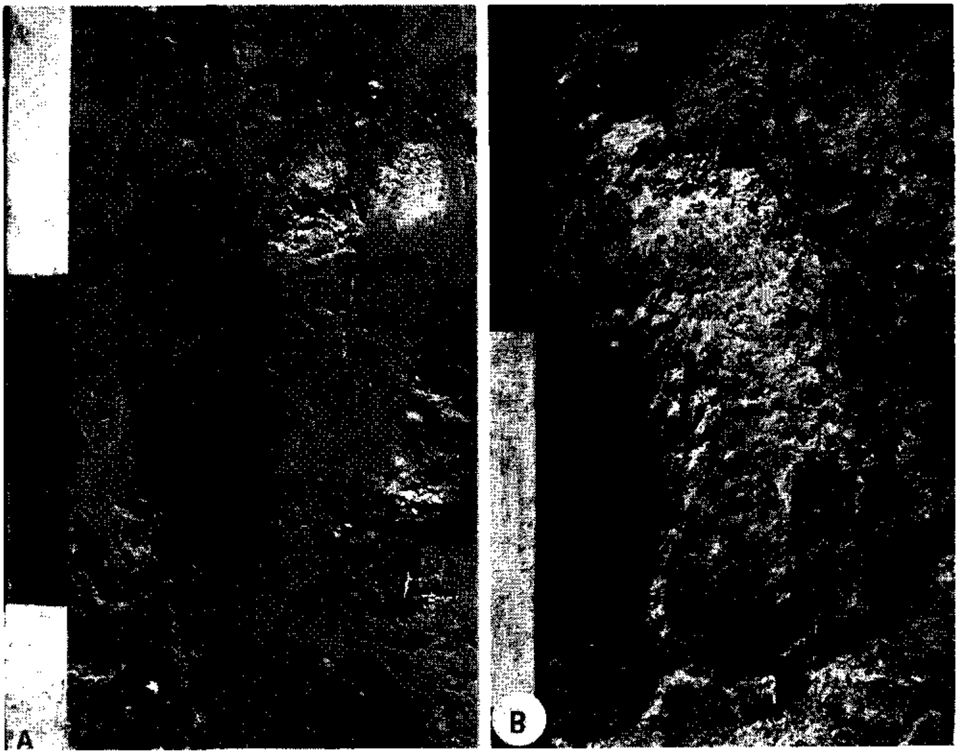

Fig. 4. Krotovinas in substratum of a Demra profile.
Scale division 10 cm. Vertical sections.
A. Krotovina of material from a former dark clayey A horizon in substratum containing (white) lime nodules.
B. Krotovina weathered to white silty material in substratum; white material tonguing down into surrounding clayey material.

of lime, the krotovinas consist of white silt loam or silt, and this fingers downward into the surrounding clayey material (Fig. 4B): a pattern very similar to that at the E—C boundary in, for example, soils of Kalma and Chhiata series.

Soils of Ghatail series are developed over old Brahmaputra alluvium in extensive basin and basin-margin sites. Seasonally flooded from 30 cm up to more than 3 m deep for 1—6 months. Mainly used for broadcast deep-water rice, locally for transplanted rice; part also used for an early dryland rice crop and for a dry-season fodder legume after the deep-water rice crop.

0—15 cm Apg	Very dark grey (2.5Y 3/1) silty clay loam to silty clay with iron-stained root channels; strongly reduced in monsoon season; compact ploughpan in lower 5 cm; white silt specks usually visible along cracks and in pores in ploughpan when dry; pH 5—5.5 dry (7 reduced).

15—50+ cm Bg	Dark grey (5Y 4/1) silty clay or clay with many fine dark brown to yellowish brown (10YR 4/3—5/8) mottles inside peds; strong coarse prismatic and blocky structure, locally wedge-shaped with pressure coatings; thick dark grey gleyans on ped faces and pores; white silt specks often seen along ped faces in upper 15 cm in the dry soil; pH 6.5—7.
> 50+ cm C or 2C	Grey, olive or brown sand to clay, sometimes stratified; dark grey gleyans often continue along vertical cracks and pores; pH 7—8.

Incipient surface-water gley soils

Profiles are developed in young alluvium on almost level floodplain sites. They have a marked seasonal change in reaction of the Ap horizon from acid dry to neutral when flooded. White silt segregations are not visible in the ploughpan or in voids below.

Soils of Dhamrai series are developed on floodplain ridges in young Brahmaputra alluvium (probably less than 200 years old). Seasonally flooded by river water 1—2 m deep for 1—5 months. Mainly used for jute or for deep-water broadcast rice intermixed with an early-maturing dryland rice in the wet season and followed by a dryland legume, cereal or vegetable crop in the dry season.

0—15 cm Apg	Olive-grey (5Y 4/2) silt loam to silty clay loam with iron-stained root channels; strongly reduced in monsoon season; compact ploughpan in lower 5 cm; pH 5—6 dry (7 reduced).
15—30+ cm Bg	Olive-grey (5Y 5/2) silty clay loam with many fine brown (2.5Y 5/4, 10YR 4/4) mottles in ped interiors; strong coarse prismatic structure; thick grey gleyans on ped faces and pores; pH 6.5—7.5.
> 30+ cm C or 2C	Grey, olive-grey or brown sand to clay, usually stratified; grey gleyans often continue along vertical cracks and pores; pH 7—8.

CORRELATION

Outside Asia, surface-water gley soils are known under many names, as mentioned earlier (Brinkman, 1970). These include pseudogley, gley-podzolic, sod-podzolic, paragley, podbel and beidzhan-tu, leached pallid soils, solodized soils and solods, planosols and planosol—solod intergrades. These soils may also be found under unexpected names. For example, Wharekohe and Tokomaru soils seen by one of us (H.B.) in New Zealand, described in the Northern Tour guide (Staff of Soil Bureau, 1968) as podzols and grey-brown podzolic soils(?) respectively, correlate satisfactorily with the mature surface-water gley soils in Bangladesh.

Soils of Chandra series, and related soils in the northern piedmont plains of Bangladesh, show affinities with Groundwater Laterites (Plinthic Ferralsols and Plinthic Acrisols, FAO, 1974). However, iron segregation has probably not advanced sufficiently nor do the coarse iron-manganese mottles indurate sufficiently upon exposure to recognize these soils as more than incipient Groundwater Laterites. They are, in any case, apparently dominated at present by the formation of a hydromorphic albic E horizon, and are better regarded as mature surface-water gley soils. In some mature (not fossil) Groundwater Laterites, formation of an albic E horizon may be subordinate to the process of iron segregation: the two processes are not mutually exclusive.

The most direct correlation of the surface-water gley soils in Bangladesh is with hydromorphic soils on terrace landforms occurring widely in southeast Asia (e.g., Moormann, 1961; Van der Kevie, 1972). Soils in Burma described as degraded rice soils (Karmanov, 1960, 1968) seem to have the white silt segregations; and profiles of "Low Humic Gley" soils seen by us in Thailand have the white silt specks and coatings, high porosity and ferruginous mottling characteristic of E horizons in the surface-water gley soils of Bangladesh. These soils are extensively developed on terraces and pediment slopes. They have profile forms resembling Chandra and Kalma series, although developed in quite different parent materials. Soils on the "low terrace" in northeast Thailand (Roi Et series, unpubl. data, R.B.) have a similar appearance, but these soils have a very low cation exchange capacity and a clay fraction consisting of kaolinite and quartz with small proportions of Al-interlayered (inactive) 2:1 clay minerals. Such "senile" surface-water gley soils are not known to occur in Bangladesh.

Soils long used for seasonal wet-land rice cultivation have anthraquic epipedons (Dudal and Moormann, 1964). Various workers in southeast Asia have suggested classifying such man-made surface-water gley soils as "paddy soils" or Aquorizems: e.g., Kyuma and Kawaguchi, 1966. Although such soils are probably closely similar, without more detailed descriptions and analyses their correlation with possible equivalents in Bangladesh is uncertain. Irrigated or alluvial soils may be preserved as incipient surface-water gley soils by regular small additions of base-rich sediment. Rainfed soils with less clay and lower C.E.C./clay ratios in the ploughed layer than in the lower horizons, as described by Kawaguchi and Kyuma (1968, 1969), are probably mature or immature in terms of Bangladesh soils: there is no indication whether the E horizons extend below the Ap horizons.

Dudal and Moormann (1964) refer to paddy soils developed as a result of long-continued rice cultivation on soils that originally developed as Latosols, Andosols, Regosols, etc. Similar soils occur on some relatively well drained sites of the Madhupur and Barind tracts and locally on high floodplain ridges elsewhere. In these soils, an anthraquic epipedon directly overlies a yellow, brown or red subsoil which is not hydromorphic. Such soils are equivalent to immature surface-water gley soils, except where base-rich sediment brought in by irrigation water may have maintained the surface horizon in the incipient stage.

DESCRIPTION OF CHHIATA SERIES

Chhiata* series, highland phase (Bangladesh). Profile 1/2-23 DAC. FAO soil units (FAO, 1974): Eutric Planosols, but see discussion under Soil Classification in Brinkman, 1977.
Examined 3.5.1965 by S.M. Saheed and 30.3.1966 by H. Brammer, R. Brinkman and M.M. Hassan.

The site

Location. Near village Dakshin Salna, Joydebpur P.S., Dacca district, Bangladesh. About 1 km north of Joydebpur road junction, 3.5 km northwest of Joydebpur, 30 km north of Dacca. About 24°2'40"N 90°30'7"E. Topographic map sheet 78L8 (1958). Aerial photo Dacca 2-23.

Elevation. About 10 m above mean sea level.

Landform and slope. Level summit of closely and shallowly dissected terrace. Fields with bunds about 20—30 cm high.

Vegetation/land use. Broadcast dryland rice in early rainy season; locally, a little mesta (Hibiscus sabdariffa, a fibre); followed by transplanted rice from middle of rainy season. All without irrigation or fertilizer. Occasional trees on field bunds, common around house sites.

Climate. Tropical monsoon climate (Köppen Aw). Mean monthly temperatures 18 and 30°C in coldest and warmest month. Annual rainfall 1,900 mm, evapotranspiration 1,100 mm. Excess summer rainfall 1,100 mm; excess winter evapotranspiration >200 mm. Monthly data in Table I.

General information on the soil

Parent material. "Madhupur clay", probably a Tertiary marine deposit, block faulted and slightly uplifted; a large terrace-like area of uniformly clayey materials, 10 or more metres thick over older river sediments.

Drainage. Poor. Shallowly flooded within field bunds by rain water during rainy season. Dry in dry season. External drainage slow, internal drainage very slow due to very slow permeability of ploughpan and substratum.

Groundwater table. Not observed. Profile is water-saturated in the surface horizons or flooded during the rainy season. New excavations (up to 6 m deep) remain dry through the dry season, but retain ponded water following subsequent rainy seasons (unless artificially drained for irrigation).

Surface stones or rock outcrops. None.

Evidence of erosion. None at site, but see human influence, below.

Presence of salt or alkali. None.

Human influence. Bunded small rice fields made by slight levelling. Locally,

* sic. Approximate pronunciation: Siata.

margins of shallow drainageways steepened to extend level field area. Occasional breakdown of bund at such margins resulting in slight sheet erosion and deposition over a few square metres of adjacent lower field. Use of traditional steel tipped wooden plough has resulted in strong, dense ploughpan.

Brief general description of the profile

Grey (white when dry), highly porous silt loam to silty clay loam, variably mottled reddish yellow and with fine iron nodules, grading into little weathered, grey, compact, slickensided Madhupur clay at generally 25—60 cm. Reaction of surface horizon 4 to 6, but 6 to 7 when sampled wet (reduced).

Description of individual soil horizons

0—8 cm Apg1	Light grey (5Y 7/1) dry to grey (5Y 6/1) moist silt loam; common fine distinct strong brown (7.5YR 5/6, dry) mottles; massive; dry slightly hard and moist very friable; common very fine and fine tubular pores; common fine roots; pH 5.0; abrupt smooth boundary. Sample no. 67-66; thin section 67050 (5 cm).
8—13 cm Apg2	Ploughpan. Light grey (5Y 7/1) dry to grey (5Y 6/1) moist silt loam; many fine distinct strong brown (7.5YR 5/6, dry) mottles; massive; dry hard and moist friable; few very fine tubular pores; few fine roots; pH 5.5; abrupt smooth boundary. Sample 67-67; thin section 67051 (10 cm).
13—18 cm Eg1	Light grey (5Y 7/1) dry to grey (5Y 6/1) moist silty clay loam; many fine distinct strong brown (7.5YR 5/6, dry) mottles; massive, breaking into weak coarse angular blocky; dry slightly hard, moist friable; common very fine and fine tubular pores; few fine roots; pH 5.6; abrupt smooth boundary. Sample 67-68.
18—30 cm Eg2	Light grey (5Y 7/1) dry to grey (5Y 6/1) moist silty clay loam; many fine distinct reddish yellow (7.5YR 6/6, dry) mottles; strong coarse prismatic and coarse angular blocky with patchy thin white silt coatings on vertical and horizontal faces; dry slightly hard and moist friable; common fine and many very fine tubular pores; few fine roots; few fine iron nodules; pH 5.4; clear smooth boundary. Sample 67-69; thin sections 67052 (19 cm) and 67053 (25 cm).
30—41 cm Eg3	Light grey (5Y 7/1) dry and grey (5Y 6/1) moist silty clay loam; strong coarse prismatic and medium and coarse angular blocky with patchy thin white silt coatings on vertical and horizontal faces; dry hard and moist friable; common fine

	and many very fine tubular pores; few fine roots; common fine and medium iron nodules; pH 5.3; clear smooth boundary. Sample 67-70; thin sections 67054 (34 cm) and 67055 (40 cm).
41—58 cm ECg	Light grey (5Y 7/1) dry to grey (5Y 6/1) moist silty clay; common fine distinct yellow-red (5YR 4/8) mottles; strong coarse prismatic and coarse angular blocky; patchy thin white silt coatings on vertical and horizontal faces and in pores; dry very hard and moist very firm; many fine tubular pores; common fine and medium hard iron nodules; clear smooth boundary. Sample 67-71; thin section 67056 (46 cm).
58—97 cm Cg1	Light grey (N 7) dry to grey (5Y 6/1) moist silty clay; many fine distinct strong brown (7.5YR 5/8) mottles; strong coarse prismatic, strong very coarse and fine and moderate coarse angular blocky with very few faint white silt coatings on ped faces and in pores; dry very hard and moist very firm; many very fine tubular pores; common fine and medium hard iron nodules and few fine hard manganese nodules; pH 5.6; gradual smooth boundary. Sample 67-72; thin sections 67058 (64 cm), 67059 (70 cm), 67060 (84 cm) and 67061 (94 cm).
97—127 cm Cg2	Light grey (N 6.5) dry to grey (5Y 5/1) moist silty clay; many fine distinct yellow-brown (10YR 5/8) mottles; strong medium and very coarse angular blocky; dry very hard and moist very plastic and slightly sticky; many very fine and common fine tubular pores; common fine and medium hard iron and manganese nodules; slickensides present; pH 5.8; gradual smooth boundary. Sample 67-73; thin sections 67062 (110 cm) and 67063 (120 cm)
127—152 cm Cg3	Light grey (N 6.5) dry and grey (5Y 5/1) moist silty clay; many medium distinct yellow-brown (10YR 5/8) mottles; very coarse and coarse angular blocky; dry very hard and moist very plastic, slightly sticky; many very fine tubular pores; common fine and medium iron and manganese nodules; slickensides present; pH 5.9. Sample 67-74.

Note: pH (saturated paste) determined in Soil Survey laboratory, Dacca.

Range and occurrence

Range in characteristics. Depth to the C horizon ranges from 25 to 90 cm. Intermittently flooded (highland) and seasonally flooded (medium highland) phases occur. The substratum locally contains coarse lime nodules below about 1 m.

Occurrence and associated soils. Soils of Chhiata series cover relatively small, low, level summits, in association with more extensive, similar soils but over permeable substrata (Chandra and Kalma series) that occur in very shallow (0.3—1 m deep) drainageways radiating from the summits; and with successively deeper and better drained soils on the interfluves toward the more deeply dissected parts of the terrace. This interfluve sequence ends with the well-drained soils of Kashimpur series occurring on terrace margins. See also Fig. 2.

Chhiata soils also occur in some larger, level areas where they form a complex with soils of Demra series: very shallow, poorly drained soils over compact, slickensided Madhupur clay.

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SURFACE-WATER GLEY SOILS IN BANGLADESH : GENESIS

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ABSTRACT

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Extensive areas of periodically wet, acid soils in Bangladesh have a seasonally fluctuating pH of the surface horizon and evidence for net clay loss. Morphological, chemical, mineralogical and other data mainly on a typical profile of these surface-water gley soils indicate a clay loss of some 1.5 kg/dm^2 ; alteration of smectite to a "soil chlorite", interlayered material with trapped ferrous iron; the consequent drop in C.E.C. of the clay fraction; and the presence of amorphous silica. The data were used to reconstruct a sequence of three soil forming processes: Vertisol formation, then argilluviation, followed by ferrolysis.

Ferrolysis involves, in the wet season: reduction producing ferrous iron, which displaces part of the exchangeable basic cations and aluminium; leaching of bases and part of the aluminium; and interlayer formation by the remaining aluminium while some exchangeable ferrous iron is trapped in the interlayers. In the dry season, oxidation of exchangeable ferrous iron produces exchangeable hydrogen, part of which attacks the clay minerals and is neutralized by liberation of Al, Mg and other ions from the clay structure. Part of the silica remaining from the clay structure is leached out in the next wet season, part accumulates in amorphous form. In soils long used for paddy cultivation, man has concentrated the ferrolysis process in the ploughed layer by the formation of a slowly permeable ploughpan causing strong reduction only in the surface horizon.

The hydromorphic albic horizon over more clayey material is indicative of the dominant process in surface-water gley soils. This sequum could usefully have a more important place in soil classification than it has at present, e.g. at great group level.

INTRODUCTION

During field studies in Bangladesh, extensive areas of soils were found with grey or light grey, silty surface horizons with pH seasonally fluctuating between about 5 and 7, overlying more clayey material. In Holocene sediments, the light grey silty material is limited to the ploughed horizon (and, occasionally, patches in the upper part of the underlying ploughpan) in the older parts of the Tista, Brahmaputra and Meghna floodplains and does not occur in the Ganges floodplain. On older, level terrace-like areas of the Madhupur and Barind tracts, light grey silty superficial horizons with seasonally fluctuating pH occur extensively in landscapes that are seasonally inundated or waterlogged during the monsoon rainy season. In the terrace areas, the light grey horizons are very clearly expressed, and extend to depths ranging from some 0.3 to locally some 2.5 m. Whatever the depth, the boundary with the underlying more clayey material appears "etched" and is tongued in many cases. Environmental data and field relationships, soil descriptions and correlation are discussed in a companion paper (Brammer and Brinkman, 1977).

The present paper reports detailed data on a typical profile of Chhiata series and some information on related soils, confirming and extending the field observations. Changes in two soil classification systems are suggested to facilitate placement of Chhiata and related soils; a reconstruction of two prior soil-forming processes in Chhiata series is given; and ferrolysis, a model of the main current processes operating in surface-water gley soils, is discussed at some length.

METHODS

Morphology and physical methods

Soil horizon designations are according to FAO (1974). Thin sections from undisturbed blocks in a vertical plane were prepared according to Jongerius and Heintzberger (undated (1963)). Micromorphological terms are according to Brewer (1964) with minor additions. X-ray transmission stereo radiographs of thick (5 mm) sections were prepared according to Rogaar and Thiadens (1975). In these, the spatial arrangement of voids down to some 0.2 mm diameter is visible.

Scanning electron microscope observations were made on undisturbed samples (small clods with freshly broken surface), glued to aluminium carrier disks and thinly covered by C and Au vaporized in vacuo. Si/Al K_α fluorescence peak height ratios were estimated for parts of cutans. Instrument: Jeol JSM-U3.

Hydraulic conductivity of undisturbed cores was measured by the constant head method; moisture retention at pF 2 and 2.5 on undisturbed samples in pressure cookers, and at pF 4.2 on disturbed samples in pressure membrane apparatus; bulk density on undisturbed cores after drying at 105°C; particle density was assumed to be 2.70 on the basis of 12 measurements on a range of soils (anon. (Huizing), 1970).

Particle size distribution was measured by wet sieving over a 50 μm sieve and by pipette for silt and clay fractions, after destruction of organic matter by heating with 10% H_2O_2, rapid flocculation and leaching with cold 0.1 N HCl, and dispersion at pH 8 with 0.003 M $Na_4P_2O_7$ buffer.

General chemical methods

Soil pH (1:2.5 water and $CaCl_2$ 0.01M) was determined by glass electrode;

organic carbon by dichromate-sulfuric acid with external heating (Schollenberger, 1927), assuming 87% oxidation of soil organic carbon; free Fe_2O_3 by Na dithionite-EDTA at pH 4.5 (comparable with Tamm method within some 2% relative error, Begheyn, pers. comm.); exchangeable bases and C.E.C. by Li EDTA; Al and H by KCl extraction; soluble salts by 1:2 extract; Na and K by flame photometer; and Ca, Mg and Al by colorimeter. HCO_3 was estimated by titration as methyl orange alkalinity; SO_4 by turbidimetric observations with gum acacia; Cl titrated with $AgNO_3$ and K_2CrO_4. Methods are described by Begheyn and Van Schuylenborgh (1971).

Clay fraction pretreatment was the same as in particle-size analysis but with dispersion by NaOH at pH 7—8. After 2 successive decantations of the fraction $< 2\ \mu m$, flocculation was by HCl at pH 3 immediately followed by filtration and washing on Büchner funnels; Li saturation and dialysis. Exchangeable Li is equivalent to 0.3—0.5 % Li_2O in the clay fraction. Parallel pretreatments were used for duplicate X-ray diffraction and ferrous iron determinations without prior oxidation and with oxidation by H_2O_2—Na acetate buffer (pH 5), followed by flocculation of clay fractions by neutral $BaCl_2$ without acid treatment or dialysis. The clay was centrifuge-washed and freeze-dried. Total chemical analyses for most elements were made by X-ray fluorescence on $Li_2B_4O_7$ glass disks (Halma, 1973). Zr analyses were made by X-ray fluorescence on $Li_2B_4O_7$ glass disks: Ag tube 25 kV, 20 mA, LiF crystal, scintillation counter, ZrKα peak measured at 22.35° 2θ, background at 23.10 and 22.00, all counting times 100 sec.

Na was determined by flame photometer, ferric and ferrous iron by colorimeter after decomposition by HF.

Ferrous iron

In the extraction and determination of ferrous iron, three conditions should be satisfied: complete extraction, absence of oxidation, and absence of reduction by organic matter. In addition, the pre-treatments for separation of the clay fraction should not dissolve and remove ferrous iron. The following procedure appears to satisfy all these conditions, as discussed below.

Soil samples are treated with H_2O_2 buffered at pH 5 to remove (most of the) organic matter (Jackson, 1956) and are kept between pH 5 and 7.5 during later stages in separation of the clay fraction. Iron is extracted from 100 mg freeze-dried, powdered clay fraction in Pt crucibles by swirling with 3 ml HF 48% m/m and 1 ml H_2SO_4, 96% m/m. Heat of mixing quickly brings the temperature of the mixture to 60°—65° C. After 1 min the HF is neutralized in boric acid solution. Colorimetric determination of ferrous and total iron was according to Begheyn and Van Schuylenborgh (1971).

The pretreatment with buffered H_2O_2 results in consistent ferrous iron figures, in contrast to low and erratic figures found after routine, unbuffered H_2O_2 and HCl pretreatments. The latter apparently remove part of the ferrous iron, particularly from the clay fractions in the upper horizons.

TABLE I

Soil moisture data on some seasonally wet, acid soils of the Madhupur tract*

Series name	Hor.	Depth (cm)	Clay (%)	Hydr. cond. range (cm/day)	Bulk density (g/ml)	Total pores (vol. %)	Moisture vol. % at pF: 2.0	2.5	4.2
Chhiata	Ap2	8	23	<0.1	1.68	38	36	nd	15
	E	20	29	12–25	1.40	48	38	nd	17
	C	50	45	<0.1	1.55	43	40	nd	28
Demra	C	30	42	0–2	1.52	44	44	40	25
Chandra	Ap2	10	23	<0.1	1.56	42	37	32	11
	3**	20	28	110	1.34	50	33	27	12
	4	38	49	200—400	1.30	52	34	31	21
	5	55	52	150—1000	1.37	49	37	35	27
	6	105	56	150—1400	1.41	48	37	35	28
Kalma	Ap2	5	27	0—10	1.41	48	46	42	15
	3	15	28	25—40	1.40	48	36	31	13
	5	50	35	7—15	1.49	45	39	34	20

*Summarized from Anonymous (Huizing) 1970.
**No definite horizon identifications.

ranging from 1.3 to 1.5 and air capacities of the order of 10%. Available moisture decreases with depth, from 20—30 vol.% in upper horizons to values of the order of 10% in deeper subsoils.

During the wet season, these soils are flooded (some intermittently) by rain water. Some soil air, under slightly more than atmospheric pressure, is often trapped under the ploughpan in these conditions. (Gases such as CO_2 and possibly methane may replace oxygen in soil air after flooding.) Because the land surface is above river flood level, water movement during the wet season in the deeply weathered soils, for example those of Chandra or Kalma series, should be downward, whereas in the shallowly weathered soils such as those of Chhiata or Demra series, the water would move laterally through the upper horizons, over the very slowly permeable C horizon, toward the deeply weathered Kalma soils in valleys. The seasonal inundation and water saturation are only partly due to the very slowly permeable C horizons, which do not occur in all of the soils. The great seasonal excess of rainfall over evapotranspiration (of the order of 800 mm in 6 months), the generally flat topography and the low gradient of the landscape to river flood level are important causes as well.

DYNAMICS OF pH, IRON AND ALUMINIUM DURING SEASONAL REDUCTION AND OXIDATION

pH

On the basis of field estimation with indicators, pH is essentially constant in the lower horizons, below the ploughpan, under wet and dry conditions. In the ploughed horizon of Chhiata soil, field pH ranged from about 5 in the dry season to about 7 under flooded conditions (under paddy) in the rainy season. Ghatail series, a soil of seasonally inundated, Holocene non-calcareous basins in Old Brahmaputra sediments, showed similar but more extreme changes: the pH of reduced ploughed horizons dropped from 7.5 (glass electrode) to 4.0—4.5 after complete oxidation (after air drying of soil in small fragments) and to 5.5—6.5 in mixed bulk samples presumably still containing some reduced material. Subsoils did not show a seasonal change in pH.

A reduced suspension of Chhiata Apg material (pH 6.8, EH 150 mV) was oxidized by stirring in an open vessel as pH and EH were measured at frequent intervals. The pH steadily dropped to 5 after 2½ h and then remained stable; the potential slowly rose to about 300 mV in about 2 h, quickly rose to 550 mV within the next hour and then remained stable. To a parallel sample, $FeSO_4$ was added in an amount equivalent to the C.E.C. In this case, the pH dropped to 5 in half an hour and reached 3.9 in about 2 hours, stabilizing at about 4.1 after a day. EH rose to about 300 in half an hour, 650 after 2 hours, and stabilized at about 500 mV 4 days after cessation of stirring.

Iron and aluminium

Field tests with $K_3Fe(CN)_6$ solution showed a strong ferrous iron reaction in the Ap1 horizon of flooded Chhiata and similar soils under paddy cultivation; a patchy reaction in the ploughpan (Ap2); and no detectable ferrous iron in or below the E horizon. All Chhiata soils to our knowledge are used for paddy cultivation. An example of Chandra series without a ploughpan, in a closed depression under semi-natural grass vegetation, inundated by rain water in the wet season, showed a strong ferrous iron reaction in the upper 5—8 cm of the A1 horizon, diminishing but still conspicuous to about 30 cm depth. Lower down in the E horizon the reaction was slight and looalized. In the C horizon, no ferrous iron was detected.

Samples from the ploughed horizon of Chhiata soils were analyzed for salt-extractable (soluble plus exchangeable) ferrous iron and aluminium when air-dry and also after a period of submergence in the laboratory. In air-dry condition 2 me Al/100 g and no ferrous iron were present, and after flooding, between 3 and 8 me ferrous iron/100 g and no aluminium. Samples of soil material brought from a submerged field and analyzed before and after oxidation (Table II) show similar differences in exchangeable ferrous iron and aluminium contents in the Ap1 horizon but little change below.

TABLE II

pH, aluminium and ferrous iron (me/100 g) in water-saturated upper horizons before and after oxidation*

	pH	Exch. Al	Exch. Fe	Sol. Fe
Ap1	6.7	0.02	2.91	0.03
After oxidation	5.0	0.60	0.04	<0.01
Ap2	5.2	0.13	0.02	<0.01
After oxidation	5.1	0.31	0.01	<0.01
E	5.3	0.02	0.02	<0.01

*Samples taken from an inundated field under paddy, transported in completely filled plastic screw-top jars; analysed as delivered and after air oxidation.

In soils with a ploughpan, strong reduction and formation of ferrous iron appear to take place only in the ploughed horizon and part of the ploughpan, whereas in a soil without a ploughpan under semi-natural grass vegetation, the reduction and ferrous iron formation extend into the E horizon and diminish less abruptly with depth. This is probably due to the presence of easily decomposed organic matter to greater depth under natural vegetation than in soil with a ploughpan under paddy. The soils presently used for paddy probably were wet for shorter periods before they were bunded to retain monsoon rain water. At that time, the zone of maximum reduction may well have been at some depth in the profile and not in the surface horizon as at present.

MICROMORPHOLOGY

The skeleton grains in the samples of Chhiata soils are mainly quartz with some micas. They are mainly of silt size, many 10—30 μm. There are some coarser grains, up to 200 μm, which are locally corroded (with ragged edges). The skeleton grains occur in a random distribution pattern except in the upper 0.3 m, where they are clustered. In the upper 0.3 m there are occasional small (50—1,000 μm) rounded and angular pedorelics of strongly birefringent material with (shrinkage?) cracks, possibly weathered mica remnants.

The plasma consists of clay minerals. Its proportion increases with depth. In the upper 0.3 m it occurs in irregular bands or patches with a finer texture, locally containing some iron oxides and having abrupt boundaries against the silt clusters. From about 0.4 m down there is a gradually increasing proportion of masepic, skelsepic and glaesepic, with a little channel vosepic, plasmic fabric.

Biogenic voids (channels, vughs, interconnected vughs) occur throughout the profile, diminishing with depth. Physicogenic voids (craze planes and skew planes) are present from about 0.3 m and increase with depth.

There are thin (10—100 μm) argillans along channels and some vughs, as well as derived papules, between about 0.3 and 0.6 m depth (in the E2, E3 and EC horizons). Argillans occupy 0.5 and papules less than 0.5% of the area of solids, respectively (2150 points counted). They consist of fine clay low in iron oxides and have continuous to weak, discontinuous orientation. The latter locally have a grainy structure (Brinkman et al., 1973).

A soil profile of Chandra series, similar to Chhiata soils but over permeable, deeply weathered, strongly red-mottled Madhupur clay, has up to 3% total clay illuviation features (ferri-argillans, argillans and derived papules), and to depths much greater than in the profile of Chhiata series. The proportion of grainy cutans and papules diminishes with depth (not known in surface horizons; 1/3 of total cutans and papules at 0.6 m; 1/5 at 1.4 m). In this profile, many argillans have pale grey, ragged edges with low birefringence along the voids. Mica content increases with depth and partially weathered mica remnants are evident locally.

Iron segregations in the Chhiata profile occur in three forms: neoferrans and two kinds of glaebules. Channel neoferrans are common in the A and E horizons, gradually disappearing in the EC horizon at about 0.5 m. They have diffuse to abrupt edges and are 20—100 μm wide. Neoferrans around pedotubules were also observed. Locally, neoferrans cover argillans or papules. Irregular, generally compound, ferric nodules with diffuse to abrupt outlines increase with depth from 0.3 m down. With depth, they become more rounded and tend to be surrounded by a glaesepic plasmic fabric. These nodules have the strongest red colours and the clearest droplet structure (Hamilton, 1964) between 0.3 and 0.6 m (in the E3 and EC horizons). The other kind of ferric glaebules is round with abrupt outlines and generally concentric structure (concretions). These occur between 0.3 and about 1.1 m depth, occasionally contain manganese oxides, and do not contain any argillans or papules. In the upper horizons, they contain fewer skeleton grains (more plasma) than the surrounding ground mass. This, together with their abrupt outlines, suggests that they may date from an early stage of soil formation.

Pedotubules (aggro-isotubules) up to 1 mm diameter occur in considerable numbers in the A and E horizons, down to about 0.5 m.

Cloudy "efflorescences" were observed in the Cg1 and Cg2 horizons, from 0.8 to more than 1.2 m. Such concentrations are brightly opalescent in incident light (Brinkman et al., 1973), and are presumed to consist of secondary silica.

Field observations of these soils in the wet season (flooded and under paddy) showed gas present in the Ap horizon and especially under the ploughpan, bubbling up after disturbance. This could be trapped soil air somewhat compressed by sudden wetting of the surface and inundation, or gases formed by anaerobic decomposition of organic matter. If the latter were the case, the considerable porosity of shallow subsoil horizons in many of these soils could possibly be vesicular (formed by gas bubbles). However, X-ray transmission stereo radiographs (Rogaar and Thiadens, 1975) confirmed the impression gained from the thin sections that the considerable porosity of these horizons is dominantly biogenic: tubular voids are dominant, mainly fine (by root or insect action) and some medium and coarse (by earthworms, as indicated by local infillings).

ELECTRON MICROSCOPE OBSERVATIONS

A scanning electron micrograph of a strongly altered cutan in the Chhiata profile (Fig.2) shows dark dissolution pits and slits; and a light grey residue, partly in the form of "moth-eaten" sheets, dissolved at the edges, and partly in the form of small spherical bodies on planes and edges of the cutan. The

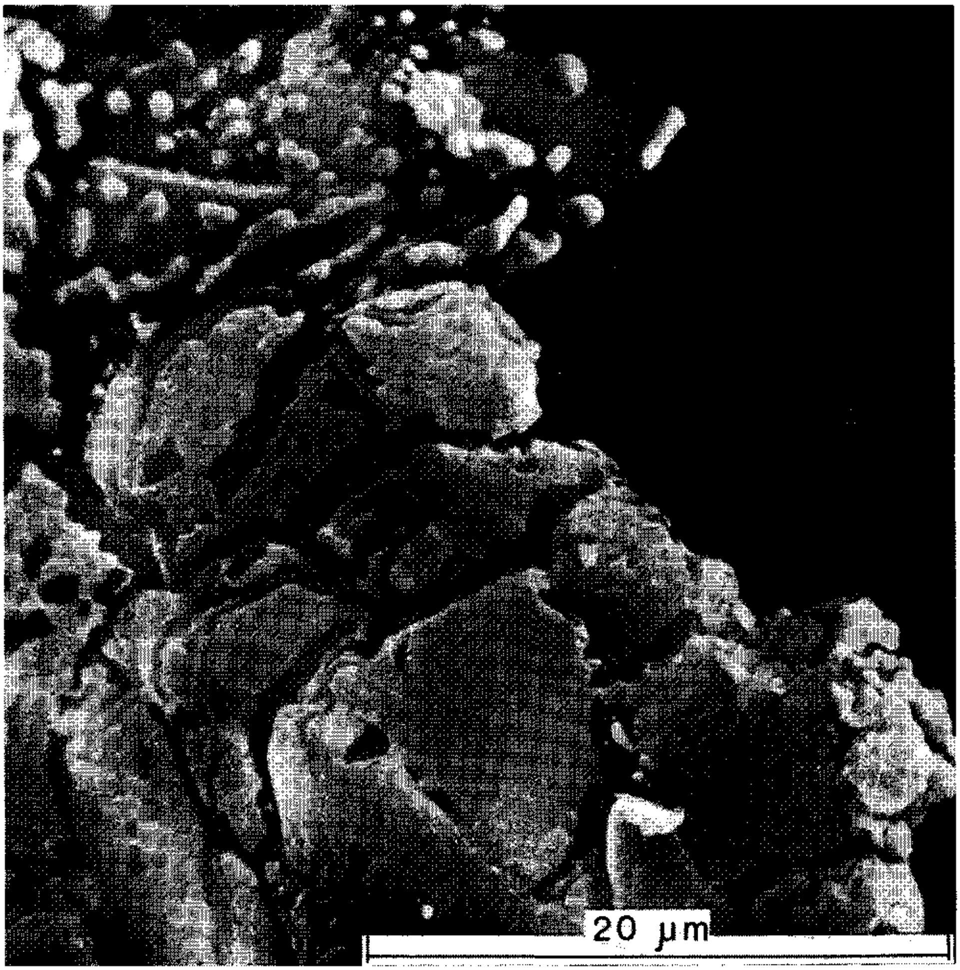

Fig. 2. Scanning electron micrograph of a strongly altered cutan in a sample of Chhiata series. Photo 316-3, Technical and Physical Engineering Research Service, Wageningen.

spherical shape was confirmed by stereoscopic observation. The graininess of strongly altered cutans observed in thin sections might be due to structures such as these. The Si/Al fluorescence peak height ratio of this strongly altered part of a cutan was estimated as about 8 or higher, whereas no potassium fluorescence peak was observed. An apparently less altered part of the same cutan had a Si/Al peak height ratio of about 6 and a small peak at the potassium K_α energy level. A cutan without clear signs of alteration in the same sample had a Si/Al peak height ratio of about 2.

These data suggest a decomposition process in two stages. First, removal of aluminium and other cations and reprecipitation of silica on the remaining clay, which may cause low birefringence and a grainy appearance of affected argillans in thin section. Next, dissolution and removal of the silica itself.

Transmission electron micrographs of the Chhiata clay fractions made by Habibullah et al. (1971) before and after selective dissolution by dithionite and carbonate also show gel-like material coating clay particles, which disappears with sodium carbonate treatment. Habibullah et al. (1971) estimate that the clay fractions in Chhiata surface and subsoil horizons contain about 12% of mixed silica-alumina gels, associated with amorphous iron hydroxides.

PARTICLE-SIZE DISTRIBUTION

Fig.3 shows clay percentages against depth for soils in different landscapes of Bangladesh. The young or perennially wet floodplain soils (A) show the usual sedimentary variation with the normal trend toward finer textures in surface horizons. Seasonally wet soils from old parts of the Ganges floodplain (B), developed in originally calcareous sediments, show the same trends. With increasing age, soils in these two groups tend to have thicker fine-textured layers over the subsoils with various textures which in their turn overlie generally sandy substrata. This, again, is in accordance with normal sedimentary patterns in meander and cover floodplains.

The soils in the old Brahmaputra floodplain (Fig.3C) have similar ages to those of the Gangetic floodplain shown in Fig. 3B but originated as noncalcareous sediments. These soils show the same sedimentary pattern as do those of the young and Gangetic floodplains, except for their strikingly lower clay contents in the surface horizons. This averages 34%, 9% lower than in the subsoils at 20 cm depth, whereas the surface horizons of the soils of the young and Gangetic floodplains have 48 and 50% clay, respectively, 7 and 2% higher than in the upper subsoils. The clay from the soils in the old Brahmaputra floodplain is not likely to have been removed by superficial erosion, because many of the soils occur in basin positions and the landforms of the floodplains with and without clay loss are very similar. Eluviation with illuviation is unlikely, too, because subsoil textures in the old Brahmaputra floodplain are not unusually fine and not finer than those in the old Gangetic floodplain. Eluviation cannot be ruled out on this basis alone. The profile of Ghatail series, discussed in later sections, is an example of soils in old Brahmaputra floodplain basins.

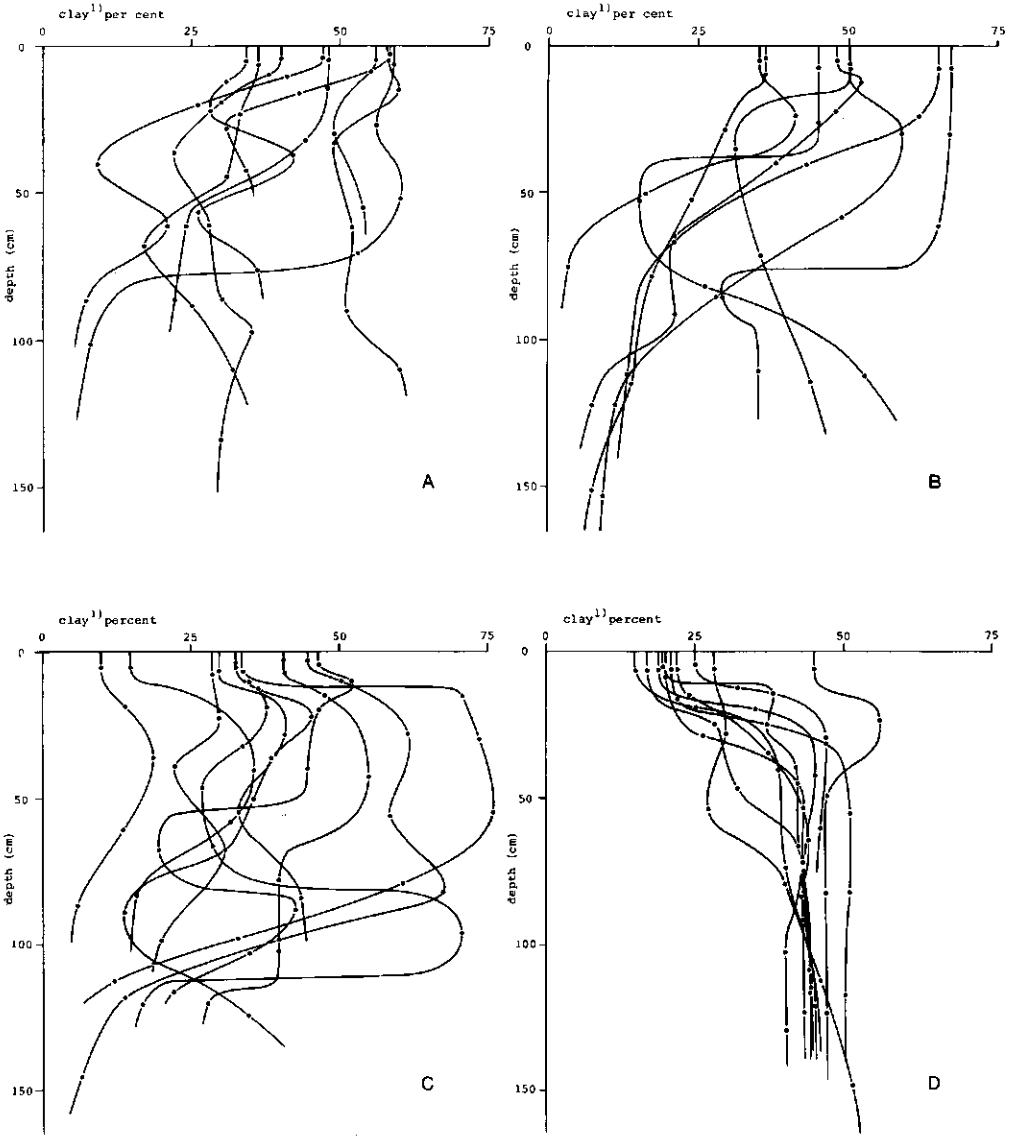

Fig. 3. Clay percentages[1] against depth for soils in different landscapes.
A. Young or perennially wet soils from several floodplains.
B. Seasonally wet soils from old parts of the Ganges floodplain.
C. Seasonally wet soils from the old Brahmaputra floodplain.
D. Seasonally wet soils from the Barind tract.

[1]Clay percentages by hydrometer (< 4 μm) from routine determinations in the Soil Survey laboratory, Dacca.

Fig.3D shows clay contents with depth for some soils of the Barind tract, the western part of the older terrace. The parent material (probably a marine under-water deposit) is constant, laterally and with depth. An occasional profile shows some indication of local erosion and deposition by an anomaly in the trend of the subsoil textures, but the striking aspect of the graphs is the great loss of clay apparent in the surface horizons and upper subsoils, to depths ranging from 0.1 to some 0,5 m, without indication of a clay increase at greater depth. In this landscape, again, general surface removal of clay is highly unlikely because slopes are very small over large distances and because soils of the occasional closed depressions also have silty upper horizons over clayey substrata. Even if there has been clay eluviation—illuviation in these profiles, that process cannot explain a clay loss averaging 22% from the surface horizons and 6% at about 0.3 m depth from parent material having some 45% clay. Sedimentation of a uniform silty cover over a clayey substratum is not likely but cannot be disproved by these data alone.

The clay content of a sample of very dark coloured surface soil, preserved in a krotovina in an area of Demra—Chhiata complex, is even higher than that of the present substratum. This supports the hypothesis that the original soil material was uniformly clayey.

The particle-size distribution of the described Chhiata profile from the Madhupur tract (Table III) shows the same trend as the soils shown in Fig.3D. The percentages of size fractions were recalculated to (sand + silt) = 100, in order to eliminate the influence of differences in clay percentages on coarser fractions. Fig.4 shows these (and further) data, which suggest that the non-clay fractions are homogeneous virtually throughout the profile. Only in the upper 8 cm, the ploughed horizon, is there an anomalously low content of all fractions less than 16 μm. At the time of sampling, we observed some local wash of fine material from this field into an adjacent lower one. If it is assumed that these fine fractions removed from the puddled surface horizon

TABLE III

Particle-size distribution, profile of Chhiata series

Horizon	Depth (cm)	Sample No.	Wt. % (size limits in μm)					
			2000—50	— 32	— 16	— 8	— 2	— 0
Apg1	0—8	66	4.9	21.1	41.4	11.7	8.4	12.5
Apg2	8—13	67	2.4	13.9	28.4	18.1	12.1	25.1
Eg1	13—18	68	1.5	12.9	26.6	18.1	13.2	27.7
Eg2	18—30	69	1.1	10.5	23.7	21.6	13.4	29.7
Eg3	30—41	70	2.3	12.6	21.3	16.8	13.7	33.3
ECg	41—58	71	2.8	11.4	19.8	13.3	11.1	41.6
Cg1	58—97	72	3.2	9.3	20.8	13.4	11.2	42.1
Cg2	97—127	73	2.9	14.5	16.4	13.1	10.2	42.9
Cg3	127—152	74	1.5	10.4	18.9	14.4	10.6	44.2

were originally present in proportion to the average for the remaining profile, and that material coarser than about 16 μm was not affected by the generally slow water movement over the soil, the composition of the surface horizon before this local erosion can be reconstructed as shown by the short dashed lines at the top of Fig.4. This corresponds to a loss of 2.4 g clay and 3.9 g fine silt per square cm at a bulk density of 1.5 for the ploughed layer.

On the assumptions that weathering has caused little change in the amounts of sand and silt (as discussed in later sections) and that the original clay content throughout the sediment was equal to that in the present C3 horizon, the total loss of clay from the profile due to possible clay decomposition can be calculated. For this purpose, bulk densities of the different horizons were estimated from Table I and from more data in Anonymous (Huizing), 1970, as follows: Apg1 1.5 g/cm^3, Apg2 1.7, Eg 1.4, ECg 1.5, Cg 1.55. On this basis, the amount of clay lost from the profile is 22 g/cm^2, apart from the 2.4 g calculated above.

Zr CONTENTS

In order to further test the homogeneity of the (sand + silt) fractions and the hypothesis of clay loss by decomposition, Zr contents were determined

TABLE IV

Zr contents (ppm) in fine earth, clay and (sand + silt) fractions

Sample No.	Fine earth	Clay	Sand + silt*[1]
66	792	78.5	894
67	629	73.5	815
68	540	77	717
69	596	73.5	817
70	499	85	706
71	454	71	727
72	434	69.5	699
73	418	61	686
74	416	57.4	700
Linear approximation of Zr contents with depth*[2]			
Mean content			733
At 0 cm depth		80	775
At 140 cm depth		58	674
Standard deviation*[3]		5	43

*[1] Calculated from clay percentage and Zr contents in fine earth and clay fractions.
*[2] Excluding sample 66 for Zr in (sand + silt) since this was probably affected by removal of fine silt from the ploughed layer. Differences with depth of Zr in (sand + silt) not significant at $P = 0.05$.
*[3] Of contents in individual horizons.

for the fine-earth and clay fractions and calculated by difference for the (sand + silt) fraction (Table IV). Zr contents of the (sand + silt) fractions are about 730 ppm, without a significant ($P = 0.05$) trend with depth and with a standard deviation of 43 ppm, if the surface horizon is not considered. The Zr content in (sand + silt) of the surface horizon is significantly higher than in the rest of the profile, presumably due to the preferential removal of fine silt from the surface, Zr being concentrated in the coarser fractions. Apart from the surface horizon, therefore, Zr contents in the (sand + silt) fractions appear to be constant with depth, with a coefficient of variation about 6%. This supports the hypotheses that the original sediment was homogeneous and that the bulk of the (sand + silt) fractions was relatively little affected by weathering.

Zr contents in the clay fractions can be used to reconstruct clay percentages before clay decomposition if three conditions are satisfied: the original Zr content of the clay fractions should be constant, Zr should not be removed in solution upon clay decomposition, and Zr in the clay fraction should move with the clay if argilluviation takes place. The first condition is most likely satisfied because the coarser fractions appear homogeneous; the second is likely because of the extremely low solubility of Zr compounds; and the third must be an assumption. If this last condition is not satisfied, the extent of clay eluviation and illuviation will be under- or over-estimated, but the total amount of "reconstructed" clay in the profile is affected little or not at all.

A clay distribution curve "before clay decomposition" has been reconstructed on the basis of Zr contents and is shown in Fig.4, recalculated to (sand + silt) fractions total 100%. A clay "bulge", absent in the present profile, is evident in the reconstruction. Apparently at some stage, sufficient argilluviation has taken place in this profile so that it would have been classified in the Alfisol (or Ultisol) order at that time, before destruction of sufficient total and oriented clay (cf. Micromorphology-section) to eliminate it from that order. Two findings from the thin sections support the hypothesis that the clay decomposition followed clay illuviation: very few argillans and papules were observed, virtually all between 0.3 and 0.6 m depth; and almost half of the clay illuviation features was grainy and had low birefringence, indicative of partial decomposition (Brinkman et al., 1973). If clay and Zr in that fraction have in fact moved together, a quantity of the order of 11 g clay/cm^2 was eluviated from the A and E horizons and about 5 g/cm^2 illuviated to depths between some 0.4 and 1.2 m.

The Zr contents of the clay fractions allow a separate estimate of the amount of clay removed by decomposition. This can be calculated from the difference between the reconstructed and present clay contents, under assumptions similar to those used earlier (cf. particle-size distribution). Clay loss on this basis totals about 15 g/cm^2. This calculation of clay loss has a coefficient of variation of the order of 12—15% due to the variability in subsampling and Zr determination alone. (In order to limit the error to this value, eight

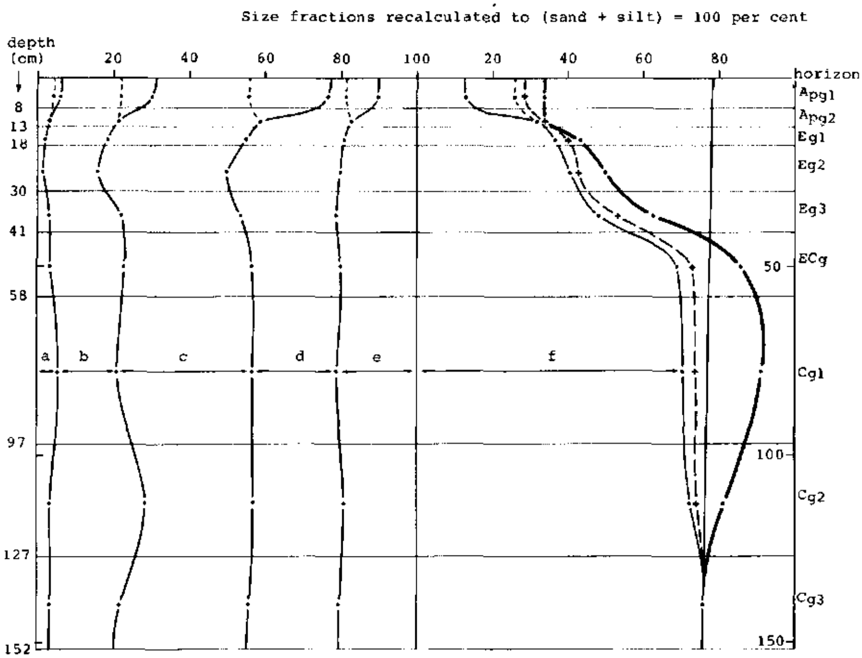

Fig.4. Particle distribution in a profile of Chhiata series, recalculated to a clay-free basis (sand + silt total 100). Size fractions (μm): a 2000—50; b 50—32; c 32—16; d 16—8; e 8—2; f <2. Dotted lines: reconstructed fractions in surface horizon before erosion. Heavy line: reconstructed clay fractions before clay decomposition, on the basis of constant Zr contents in original clay. Dashed line: reconstructed clay fractions on the basis of constant Ti in original clay (note apparent leaching of Ti compared with Zr).

counts were made on each of 2 subsamples per horizon. More subsamples of the parent material would have been used if more clay fraction had been available.) The figure for clay loss calculated from texture data is therefore thought more accurate than that calculated from Zr contents.

The dashed line in Fig.4 shows reconstructed clay contents on the basis of constant Ti in the clay fraction. It is clear that Ti in the clay fraction is not a dependable index element and that part of it has probably been leached out, together with decomposition products from the clay. (Ti in the (sand + silt) fractions appears stable, but cannot help to reconstruct clay contents). Mohr et al. (1972) point to the possibility that Ti may become mobile, for example under strongly reducing conditions. Sherman (1952) and Lotti and Averna (1968) also cast doubt on the validity of Ti as an index element.

GENERAL CHEMICAL AND CATION EXCHANGE DATA

The Chhiata profile has low pH values, pH in water increasing from 4.9 to 5.8 with depth and pH-$CaCl_2$ from 4.3 to 5.3. (Only in slightly weathered substratum material, near but above the first carbonate nodules, does the

TABLE V

General chemical data

Sample No.	pH water	pH 0.01 M $CaCl_2$	Org.C (%)	Free Fe_2O_3 (%)	Exch. cations (me/100 g) Ca	Mg	Na	K	Al	H	CEC (me/ 100 g)	Sol. salts* (me/100 g)
66	4.9	4.3	0.65	0.89	2.2	0.0	0.1	0.3	1.3	0.1	4.0	0.05
67	5.0	4.6	0.42	1.66	3.8	0.4	0.3	0.3	0.3	0.0	6.3	0.08
68	5.0	4.7	0.46	1.54	5.5	0.6	0.1	0.1	0.4	0.2	7.9	0.10
69	4.9	4.6	0.24	2.46	5.1	0.5	0.1	0.2	0.4	0.5	6.6	0.09
70	4.9	4.5	0.12	2.31	8.1	0.9	0.2	0.3	0.9	0.1	8.7	0.09
71	5.1	4.6	0.02	1.69	10.1	1.9	0.2	0.3	0.6	0.0	11.4	0.12
72	5.3	4.9	0.02	1.84	11.2	2.5	0.1	0.2	0.1	0.1	13.8	0.19
73	5.6	5.2	nd	1.50	13.0	3.0	0.3	0.3	0.1	0.1	15.6	0.23
74	5.8	5.3	0.18	1.55	14.1	3.1	0.2	0.3	0.0	0.0	17.3	0.05

*All bicarbonates; Ca 0.04—0.14, Na 0.02—0.08, Mg 0—0.04, K 0—0.01 me/100 g.

pH rise above 7.) Exchangeable bases, predominantly Ca, rise from less than 3 me/100 g soil material in the surface horizon to over 17 at depth, but base saturation is high throughout (65—100% with depth). Free iron is low, attaining a maximum of 2.5% in the E horizon. The soil is nonsaline. Data are listed in Table V.

The cation exchange capacity of the fine earth was recalculated to me/100 g clay and plotted against organic carbon, also recalculated to g/100 g clay fraction (Fig.5), in order to separate the contributions of clay and organic matter to the C.E.C. (method adapted from Bennema, 1966). The low exchange capacities of coarser mineral fractions are neglected in this approximation. Two conclusions may be drawn from the figure: the C.E.C. of or-

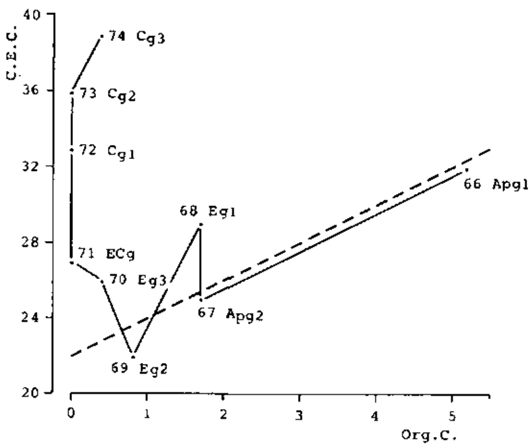

Fig.5. Cation exchange capacities of clay and organic carbon in a profile of Chhiata series. Ordinate: C.E.C. (soil) recalculated to me/100 g clay fraction. Abscissa: organic carbon, recalculated to g/100 g clay fraction. Sample numbers and horizons are indicated at data points.

ganic matter is of the order of 2 me/g carbon (dashed line); and the C.E.C. of the clay fraction is not constant with depth, but ranges about 22—26 me/ 100 g clay in the A and E horizons and steadily rises to about 38 me/100 g in the C3 horizon. The rise in cation exchange capacity of the clay fraction with depth is supported by two other sets of data. Crude, probably low, estimates on the basis of exchangeable Li retention after dialysis of the clay fraction yield C.E.C. values averaging 23 me/100 g in the upper 5 horizons and 29 me/100 g in the 4 lower ones. Cation exchange capacities of the clay fractions on the basis of Ca displacement by neutral K-EDTA are about 26 me/100 g for the upper 4 horizons, rising to 39 me/100 g in the lowest ones. A soil of the Ghatail series in Holocene sediments shows a similar trend; the cation exchange capacity of the clay fraction in the surface horizon is roughly half of that in the lowest one.

Clearly, destruction may not be the only process that has affected the clay fractions. Either the surface properties of the clay were modified in the upper horizons or clay minerals with a high C.E.C. were decomposed or eluviated preferentially.

TOTAL CHEMICAL COMPOSITION

General

The total chemical composition of the fine earth and of the clay fractions is listed in Table VI. Because the composition of the fine earth may be strongly dependent on the clay percentage, calculated compositions of (sand + silt) fractions are more informative. Table VII summarizes the figures for clay and (sand + silt) fractions in the form of linear approximations with depth. The bulk composition of the clay fraction is substantially constant, in contrast to its decreasing cation exchange capacity (Fig.5) and increasing zircon content (Table IV) toward the surface. According to Fig.4, less than a quarter of the clay fraction is lost from any horizon. The bulk composition of the remaining material is not a sensitive indicator of the nature of this loss. This is further discussed in the section on mineralogy.

In the (sand + silt) fraction, consisting mainly of SiO_2, contents of most other oxides decrease to half or less from the parent material toward the surface, with a corresponding relative increase of some 4% in the SiO_2 content. (The occasional small negative figures probably indicate random errors.) The increase in zircon content toward the surface is not significantly different from that of SiO_2. The weathering of minor constituents suggested by these figures has not appreciably changed the mass of the (sand + silt) fractions, apparently, which agrees with the results of the texture analysis.

Ferrous iron

Ferrous iron contents in clay fractions of the Chhiata profile are listed in

TABLE VI

Total chemical composition of fine earth and clay fractions

Sample No.	SiO_2	Al_2O_3	Fe_2O_3	MnO	MgO	CaO	Na_2O	K_2O	TiO_2	P_2O_5	Ign. loss
Fine earth (<2 mm):											
66	86.2	6.1	1.0	0.01	0.04	0.25	0.35	0.83	0.80	0.02	3.1
67	81.7	7.9	3.2	0.01	0.13	0.24	0.29	0.96	0.90	0.02	3.8
68	80.0	10.7	3.3	0.02	0.21	0.25	0.29	1.09	0.99	0.02	4.4
69	78.5	10.0	4.5	0.01	0.22	0.21	0.24	1.01	0.90	0.02	4.2
70	77.2	12.3	4.5	0.01	0.24	0.24	0.24	1.10	0.99	0.02	4.8
71	72.6	13.7	5.0	0.01	0.34	0.31	0.26	1.35	0.99	0.02	5.2
72	71.8	14.8	5.6	0.02	0.41	0.41	0.28	1.31	0.98	0.02	5.5
73	70.5	14.8	nd	0.03	0.44	0.50	0.32	1.37	0.98	0.01	5.6
74	71.7	14.2	4.7	0.11	0.51	0.65	0.50	1.62	0.96	0.01	5.0
Clay fraction (<2 μm):											
66	48.7	28.3	7.5	0.00	0.89	0.03	0.24	2.07	1.21	0.13	10.1
67	46.8	28.8	8.5	0.00	0.87	0.03	0.22	2.07	1.19	0.09	10.2
68	48.0	29.0	7.5	0.00	0.82	0.02	0.21	2.13	1.22	0.07	9.9
69	47.6	28.6	8.0	0.00	0.81	0.03	0.23	2.13	1.15	0.08	10.1
70	49.5	29.2	6.7	0.00	0.81	0.03	0.22	2.19	1.20	0.05	9.9
71	48.6	29.1	6.7	0.00	0.84	0.03	0.24	2.10	1.16	0.05	10.2
72	48.3	28.5	6.9	0.00	0.86	0.03	0.22	2.20	1.15	0.04	10.2
73	48.2	28.1	7.8	0.00	0.91	0.03	0.21	2.09	1.14	0.06	10.3
74	48.4	26.8	8.4	0.00	0.94	0.02	0.22	2.10	1.10	0.06	10.3

TABLE VII

Linear approximation to total chemical composition of clay and (sand + silt) fractions with depth

	Clay fraction (<2 μm): SiO_2	Al_2O_3	Fe_2O_3	MnO	MgO	CaO	Na_2O	K_2O	TiO_2	P_2O_5	ign. loss
Mean*[1]	48.3		7.5	.00		.03	.22	2.12		.07	
At 0 cm		29.1			.83				1.21		10.0
At 140 cm		27.5			.91				1.11		10.3
s*[2]	0.7	0.5	0.8	.00	.04	.004	.01	0.05	0.02	.03	0.1
(Sand + silt) fraction (2 000—2 μm):	SiO_2	Al_2O_3	Fe_2O_3	MnO	MgO	CaO	Na_2O	K_2O	TiO_2	P_2O_5	ign. loss
Mean*[1]			2.5			.15			0.84		1.9
At 0 cm	92.2	2.3		.00	−.10[3)]	.07	.24	0.53		.01	2.1
At 140 cm	88.4	5.0		.13	.17	.31	.55	1.05		−.02*[3]	1.4
s*[2]	1.3	1.0	1.6	.04	.03	.11	.11	0.13	0.05	.01	0.4

*[1] Mean quoted when slope of regression line is not significant ($P = 0.05$).

*[2] Standard deviation of contents in individual horizons. Contents at 0 and 140 cm depth listed where the regression line decreases the standard deviation.

*[3] Negative figures probably due to errors in (low) percentages in fine earth.

TABLE VIII

Iron contents* in clay fractions of Chhiata and Ghatail profiles

Chhiata sample No.	FeO (%)	Fe_2O_3 (%)	Ghatail sample No.	FeO (%)	Fe_2O_3 (%)
66	0.36	7.1	473	2.02	8.1
68	0.36	7.1	474	1.19	8.4
71	0.11	6.6	475	1.12	8.3
73	0.18	7.6	476	0.94	7.5

*Pretreatment before clay separation: H_2O_2 oxidation buffered at pH 5 with Na acetate; HF destruction with heat of mixing only, HF neutralized after 1 min.

Table VIII. The ferrous iron content in the clay of the surface horizon is about twice that in lower horizons. This "excess ferrous iron" is not exchangeable, because the original exchangeable cations were displaced and removed during pretreatment and separation of the clay fractions. The excess ferrous iron is easily removed by mild acid treatment, however: ferrous iron contents determined in clay fractions of the Chhiata profile after H_2O_2 and HCl treatments were 0.19% (s = 0.06%) without a significant trend throughout the profile.

In the profile of the younger Ghatail soil, FeO contents of the clay fraction rise from less than 1% at depth to about 2% in the surface horizon (Table VIII): a trend similar to but more clearly expressed than in the Chhiata profile.

MÖSSBAUER DATA ON IRON IN CLAY FRACTIONS

As an independent test on the differences in ferrous iron contents of clay fractions in surface and deeper horizons, Mr. C. Boekema, Lab. for Physics of Solids, Groningen University, recorded and interpreted two Mössbauer spectra at room temperature, of the top and bottom samples (473 and 476) in the Ghatail profile. Chemical data on these samples are listed in Table VIII; Mössbauer data in Table IX.

TABLE IX

Mössbauer data on two clay fractions of the Ghatail profile

Sample Nr.	Ferric iron*				Ferrous iron			
	Q	IS	LW	A	Q	IS	LW	A
473	0.72	0.25	0.52	9.9	2.60	0.99	0.40	3.4
476	0.69	0.25	0.52	6.7	2.70	1.00	0.31	1.0

Q = quadrupole splitting; IS = isomer shift with respect to Fe; LW = line width, all in mm/sec; A = area of resonance peaks, arbitrary units (ferrous iron in 476 = 1).

The ratio of Fe(II) resonance peak areas between top and bottom samples is 3.4; the ratio of the FeO percentages determined chemically is 2.15. Under the assumption that the recoilless fractions of Fe(II) are similar in both samples, the Mössbauer data thus confirm the interpretation that the clay fraction in the surface horizon contains more than twice the FeO percentage of the clay in the lowest horizon.

Besides Fe(II), only superparamagnetic Fe(III) is present: extremely finely distributed ferric oxides, with particle size less than 5 nm. This is in accord with the hypothesis that during ferrolysis, there is oxidation of exchangeable ferrous iron to ferric oxides, seasonally alternating with their reduction to ferrous iron. The resonance peak areas of ferric iron are in semiquantitative agreement with the Fe_2O_3 contents determined chemically.

MINERALOGY

Sand and silt fractions

In his study of the sand fractions of soils in Bangladesh, Huizing (1971) found biotite to be the only mineral appreciably attacked during soil formation in the seasonally wet, acid soils. By his counts, muscovite and feldspars did not show clearly consistent changes with depth. Sand fractions of soils on Madhupur clay (e.g., Chhiata series) contain mainly quartz, with about 5—9% weatherable minerals, mainly feldspars. In soils on old Brahmaputra sediments (e.g., Ghatail series), easily weatherable minerals comprise about 30 per cent, a third of which is mica, mainly biotite.

X-ray diffraction photos by the Guinier—DeWolff camera of different sand fractions in the Chhiata parent material show quartz with some plagioclase feldspar, little muscovite and a trace of goethite in the fractions finer than 210 μm, and quartz with considerable goethite, little muscovite and a trace of plagioclase in the coarser fractions. Fine nodules (about 2—3 mm) in the E and EC horizons contain quartz, much goethite and little muscovite.

The sand fraction coarser than 210 μm in the plough layer and ploughpan (about 1 per cent of the fine earth) largely consists of aggregates. These are stable against the routine H_2O_2, HCl and dispersing pretreatments, but fall apart, yielding a small amount of silt-size quartz grains after 2 min. of boiling in NaOH. The cementing agent is isotropic, and opalescent in incident light, probably secondary silica.

Epinorm mineral compositions (Burri 1959, 1964) of the (sand + silt) fractions in the Chhiata profile were calculated from the total chemical compositions and are listed in Table X. In the (sand + silt) fractions, most minor norm minerals decrease in quantity toward the surface, whereas the dominant norm quartz increases.

clay fraction about 10 me/100 g less than observed. In this standard case, only smectites with octahedral (Mg, ferrous Fe) substitution are considered

TABLE X

(Table X). In the beidellite variant, the maximum possible beidellite (Al-substituted smectite) is calculated in addition to the smectites with Mg and Fe substitution. This would lead to a C.E.C. some 40 me/100 g more than observed. Smectite probably accounts for some 30% of the clay fraction in the parent material, therefore, and would have mainly octahedral and some tetrahedral (Al) substitution. The "norm illite" contains more than 11% K_2O (is in fact a muscovite), whereas most soil illites contain some 6—8% only (Weaver and Pollard, 1973). The actual illite content may be of the order of 30%, therefore, which is in accordance with its peak area percentage. Kaolinite would then account for some 25%, and goethite and quartz for the remainder. The small kaolinite reflection (about 2% peak area) suggests that 25% is still an over-estimate.

Some Al interlayering, not yet resulting in a clear 14 Å reflection, may already be present in the lowest horizon. This would account for the relatively high Al_2O_3 percentage that led to the high estimate for kaolinite in this sample and for the low peak area of the sharp 7 Å kaolinite reflection. If we take peak area percentages as a guide, kaolinite would rise from some 2% in the parent material to about 4% in the surface horizon. Presumably this represents a relative, not absolute, increase due to the dissolution of some 25% of the clay originally present in the upper horizons as discussed in earlier sections.

In the weathered horizons, the goethite norm calculation is not relevant because Al interlayering cannot be deduced from bulk compositions. On the basis of the decrease in C.E.C. toward the soil surface, about half of the exchange capacity of the smectite appears to have been blocked by Al interlayering. The capacity to swell with glycerol treatment was lost almost completely, as indicated by X-ray peak area percentages for the 18 Å reflection decreasing from about 30% in the parent material to less than 5% in the upper horizons.

Interstratification

Peak areas of the interlayered material (14—12 Å) in the upper horizons are anomalously low, compared with the relatively low C.E.C. of the clay fractions and the decrease in the smectite peak. The largest peak area in the Mg-glycerol diffractograms (Fig.6B) throughout the profile is of the broad reflection between about 7.5 and 9 Å, covering more than 35% in the parent material and steadily increasing to about 60—70% in the upper horizons.

In the parent material, this broad "bulge" is absent in the K-saturated sample (Fig.6C), and is replaced by a somewhat increased background on both sides of the 10 Å peak; here, it may therefore be assigned to the second-order reflection of smectite.

In the upper horizons, where smectite contents appear to be very low, the 7.5—9 Å reflection was also observed in several K-saturated samples, persisted after heating to 270°C but disappeared below 400°C. Mg-saturated samples equilibrated at about 50% relative humidity (Fig.6A) do not show the major 7.5—9 Å reflection, but only broad 7 and 14 Å peaks. These findings suggest interstratification of a soil chlorite with some smectite.

Analysis by a curve resolver of a diffractogram of K-saturated clay from the surface horizon confirmed this and explained the low first-order 14 Å reflection. The relative peak areas of all broad peaks and of the sharp reflections, inter alia, of illite and kaolinite, were listed against reciprocal spacings (100/d) in Table XI. The two quartz peaks, the sharp (001)—(004) peaks of illite and the (001) and (002) peaks of kaolinite clearly belong to distinct phases. The broad peaks remaining show a clear pattern: weak odd-order and strong even-order reflections of a 14 Å component, displaced toward the nearby peaks of a 10 Å component; and two small peaks which are probably 2nd and 4th order reflections of a 24 Å structure. This shows that interstratification is mainly random but partly ordered. The weakness of odd-order and strength of even-order reflections suggest that the electron density in the interlayer of the soil chlorite is not much less than in the original octahedral layer. This could well be due to the trapping of ferrous iron in the interlayer as discussed above: the ferrous iron content in the clays of the surface horizon is virtually double that in the parent material. (The other ions common to the original octahedral layer and the interlayer are much lighter, i.e. aluminium and magnesium.)

TABLE XI

Relative peak areas against reciprocal spacing: broad peaks and sharp reflections in a diffractogram of K-saturated clay from the surface horizon of the Chhiata profile (sample 66)

Broad peaks

Reciprocal spacing (100/d)*[1]	7	(8)	12	(20.5)	(25)	(29)	(34)	(41)
Nature of peak*[2]	B	VB	B	B	VB	B	B	VB
Relative area*[3]	13	(7)	54	10	(7)	100	(18)	(5)
Identification*[4]	*Y*		*Y*2*Z*1	*Y*3*Z*2		*Y*4*Z*3	*Y*5	*Y*6*Z*4

Sharp peaks

Reciprocal spacing	10	14	20	23.5	28	28.7	30	39
Relative area*[3]	24	2	10	< 1	(7)	(3)	25	2
Identification*[5]	I1	K1	I2	Q	K2	C	I3,Q	C,I4

*[1] Figures in brackets: values approximate.
*[2] B = broad; VB = very broad.
*[3] Area of largest broad peak set to 100. Figures in brackets: area estimate very crude.
*[4] *Y*: 14 Å component; *Z*: 10 Å component; e.g., *Y*4*Z*3: combined fourth- and third-order reflections of interstratified 14 and 10 Å components.
*[5] C = corundum reflection from the keramic carrier; Q = quartz; I1, K1 etc.: first- and higher-order reflections of illite and kaolinite.

Comparisons with other soils

The X-ray diffractograms of a profile of the younger Ghatail series (Fig.7) show a trend in soil development closely similar to that in the Chhiata profile in spite of the different parent material. On the basis of peak areas, vermiculite accounts for about 45% of the clay fraction in the lowest horizon; this is progressively replaced by soil chlorite, which rises to some 35% in the surface horizon. Rough estimates of other clay minerals present are illite 25%, kaolinite 20% and interstratified material 10—20% throughout the profile. In the Ghatail profile, excess ferrous iron was found in the clay fraction of the surface horizon, as is the case in Chhiata soils (Table VIII).

The chloritization (Al interlayering) observed in these seasonally wet soils appears to be specific for their hydrologic conditions. The B horizon of a profile of the well-drained Kashimpur series, occurring on terrace margins in the same parent material as Chhiata series, has a clay fraction containing roughly equal proportions of illite and kaolinite, with only traces of soil chlorite and goethite. The kaolinite in Kashimpur soils is relatively well or-

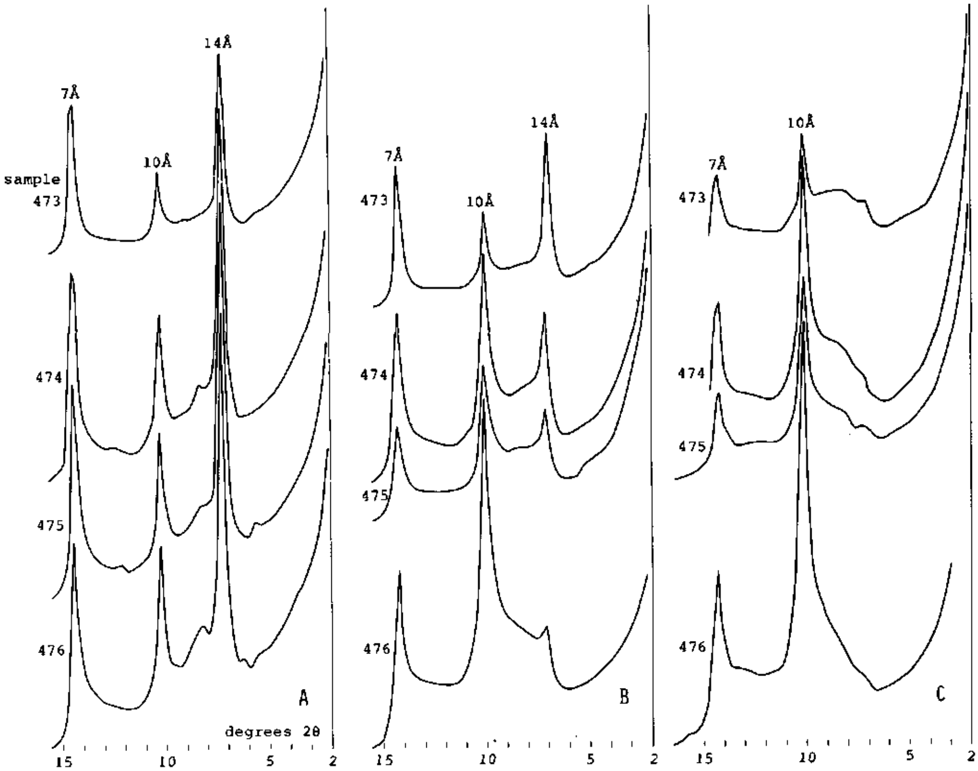

Fig.7. X-ray diffractograms of clay fractions in a profile of Ghatail series.
A. Mg-saturated, glycerol solvated. B. K-saturated. C. K-saturated, heated to 400° C.

dered (more than 70% of the 7 Å peak area changes to 10.4 Å with hydrazine treatment, cf. Alietti, 1970), but is dehydrated below about 475°C, which suggests a very small crystallite size.

SOIL CLASSIFICATION

FAO soil units

Soils of Chhiata and similar series characteristically have albic horizons, mottled at least in some subhorizons (hydromorphic E horizons) under ochric epipedons. The hydromorphic E horizons overlying slowly permeable C horizons with base saturation exceeding 50% are sufficient to place Chhiata series in the Eutric Planosols among the FAO soil units (FAO, 1974). The present definition does not require the transition from the E to the underlying horizon to be abrupt.

In the Madhupur and Barind tracts there are extensive areas of closely related soils with hydromorphic albic E horizons over permeable lower horizons, which are seasonally wet only because of climate and very slowly draining topography. These have no proper place among FAO soil units unless they have argillic horizons. Similar soils with argillic horizons and without slowly permeable layers within 125 cm of the surface, for example of Chandra series, would fall in the Gleyic Luvisols.

In soils of Chhiata and Chandra series (as well as in many surface-water gley soils elsewhere) the hydromorphic E horizons invade the underlying, degrading B or C horizons. In such cases, any argillic B horizon therefore appears to be fossil. Moreover, at least in Bangladesh the argillic horizons did not cause the hydromorphic conditions. If the albic horizon, which is the measurable expression of a recent soil forming process, should take precedence over a (generally fossil) argillic B horizon, all soils with hydromorphic E horizons and lacking a slowly permeable layer starting within 125 cm depth could be included in a new unit, proposed here as "Albic Gleysols". This would include Chandra series as well as several soil series occupying large areas in the Barind tract in Bangladesh.

USDA Soil Taxonomy

The horizon underlying the albic horizon in soils of Chhiata series has soil structure and chromas of 2 or less with strong to faint mottling. This horizon considered by itself, or compared only with the deeper substratum, would qualify as a cambic horizon. Because it does not directly underlie an epipedon and may start at depths exceeding 50 cm, however, it does not qualify as a cambic horizon in the USDA Soil Taxonomy (Soil Survey Staff, 1975). (The short definition in the FAO soil units does not exclude it from the cambic B horizons.) Therefore, the subsoil horizons have been designated as Cg horizons, although it is recognized that they have soil structure and that iron has been redistributed. Part of the soils in the terrace have strongly mottled non-calcareous horizons continuing to some 10 m — an additional reason for naming them C and not B horizons. The absence of a cambic horizon as defined eliminates these soils from the Inceptisol Order in the USDA Soil Taxonomy.

No clay skins were observed in the field in soils of Chhiata series, only silt skins in the upper part and occasional vertical pressure faces in the lower part of the Cg horizons. Thin-sections showed less than 1% oriented clay. Some slickensides are present in the lower part of the Cg horizon. Clay percentages increase from the surface down, and become uniform from 25—90 cm to great depth. Only by twisting the definition of the argillic horizon to (or beyond?) the limit of permissible interpretation could the Chhiata Cg horizon be termed argillic. In that case, these soils would be Ochraqualfs. Some soils with an abrupt textural change and some with tonguing of the E into the B horizon were also recognized on the terraces. If their B horizons are argillic horizons, these soils would be Albaqualfs and Glossaqualfs, respectively. If, as we believe, the Cg horizon in Chhiata and similar soils cannot be termed argillic, these soils with albic horizons overlying "Cg" horizons cannot properly be placed as Alfisols in the USDA Soil Taxonomy.

Recognition of a great group of "Albaquepts" would provide a place for these soils. This great group could be identified in the key after the Humaquepts, for example, by its albic horizon with mottles or fine nodules of iron or iron and manganese oxides starting within 50 cm of the surface. The definition of the Aquepts should then allow this mottled albic horizon, or the cambic horizon with dominant moist colours as in the existing version, to start within 50 cm of the surface. The definition of the cambic horizon might need to be widened to allow an overlying albic horizon.

RECONSTRUCTION OF TWO PRIOR SOIL FORMING PROCESSES

The parent material of the soils on the Madhupur and Barind tracts is a silty clay, quite homogeneous in composition, laterally over distances exceeding some 100 km and vertically over some 6—15 m.

The soils developed in this parent material appear to be polygenetic. Three main natural processes of soil formation are discussed below, which were probably sequential rather than concurrent. The findings reported here support the hypotheses that first, Vertisols appear to have been formed over much of the old terrace areas. In a second stage, clay eluviation and illuviation appear to have changed Vertisols into Luvisols (Alfisols). In the third stage, ferrolysis (clay dissolution and interlayering caused by seasonal reduction and reoxidation of ferrous iron in seasonally leaching conditions) produced the present grey, seasonally wet soils with low clay contents and low cation exchange capacities of the clay fraction. Finally, man has modified the surface horizon by centuries of paddy cultivation. All three processes of soil formation presumably took place in a climate with well-expressed wet and dry seasons, but each succeeding process under progressively wetter conditions in the rainy season.

Vertisol formation

As in many of the terrace soils, in the profile of Chhiata series there is evidence of former Vertisol formation. There are slickensides at depth as well as indications of pressure deformation (sepic fabric and skew planes) increasing with depth in thin sections. In some large pits in an area of Chhiata—Demra complex, about 1 km south of the Chhiata profile, there is evidence of a former gilgai topography. The upper boundary of the slickensided material is undulating with a wavelength of several metres and an amplitude of about 1 m or less, although the soil surface is level. Under the crests, the material contains coarse calcareous nodules at shallow depths (locally less than 1 m), whereas in the troughs, calcium carbonate is generally not present within about 2 m. In a few places, occasional gypsum crystals were seen in the compact material just above the calcareous nodules (H. Brammer, personal communication, 1976), indicative of a period with (seasonally) upward movement of moisture in the gilgai crests. Remnants of a former very dark, clayey surface soil containing smectite were observed "trapped" in the form of krotovinas in the upper part of the dense, calcareous material. Slickensides were most clearly visible at the inclined upper boundary of the dense material, running downward at an angle from the boundary to the region under the crest.

When these soils were formed, the climate must have been appreciably drier than at present, but with well-expressed seasonal differences in rainfall. This could have been in the Late Pleistocene.

Clay translocation

In soils on the presently well-drained terrace margins, field observations and descriptions suggest the presence of an argillic B horizon; ferri-argillans were observed in thin-section, and texture analyses have shown clay contents in the B horizons of the order of 5% higher than in the C and much higher than in the A horizons. Neither the Chhiata profile described nor a number of other seasonally wet terrace soils now show such a clay "bulge". Moreover, negligible percentages of argillans and ferri-argillans were observed in the thin sections of the Chhiata profile. Nevertheless, a reconstruction of clay percentages on the basis of a postulated uniform original Zr content of the clay fraction did show evidence for clay eluviation and illuviation: reconstructed clay percentages were 25—35, 49 and 44 from A to C horizons, directly comparable to the trend in the presently well-drained soils. The presence of ferri-argillans and papules and the occurrence of a clay "bulge" in the well-drained terrace soils (as well as in the Chhiata texture profile reconstructed on the basis of Zr contents) make it unlikely that any appreciable churning (Vertisol formation) would have occurred after the clay eluviation-illuviation. The clay translocation could have taken place during the early Holocene, in a period with less extreme wet seasons than at present. In soils of Holocene floodplains, which in Bangladesh are probably all less than some 2000 years old, no evidence for clay translocation was observed.

FERROLYSIS, A MODEL OF CURRENT SOIL FORMATION

During seasonal inundation, sufficient iron is reduced to the ferrous form in the upper horizons of Chhiata and similar soils to displace a considerable part of the exchangeable cations present before reduction started. The displaced cations come into the soil solution (probably as bicarbonates) and are free to leach out: laterally through the upper subsoil in Chhiata soils, laterally and down in soils with a higher permeability in deeper horizons, and possibly upward by diffusion into the inundation water. As discussed below in more detail, part of the exchangeable aluminium is displaced as well, mainly in the early stages of reduction when the pH is still low, as ions or polynuclear complexes. Another part of the aluminium is immobilized in place, mainly as interlayers and probably of the general form $(Al_6(OH)_{15})_n{}^{3n+}$ or of still lower charge, blocking exchange sites as well as trapping formerly exchangeable cations in the process. Some of the aluminium may form mixed gels with silica.

As shown in aqueous solution by Smith (1971), soluble polynuclear Al species with OH/Al ratios ranging about 2.3—2.5 (structures with 13 to 24 Al atoms, that could consist of 3 to 7 rings), are formed rather than solids if neutralization of trivalent aluminium is slow (as during reduction of iron in soil horizons, R.B.). Such "macro-ions" remain (meta)stable for periods of the order of a month or more and are slowly converted into solid colloidal gibbsite over several months while the bulk OH/Al ratio of the system remains stable. The total soluble Al concentration in solutions may appreciably exceed the equilibrium concentration for periods as long as 1—2 months and therefore allow ample time for them to be leached from the reduced horizon. More Al can also be in solution as macro-ions than as simple ions at limited anion concentrations because of their high Al/anion (HCO_3^-) ratio. Bache and Sharp (1976) demonstrated the existence of polynuclear Al ions in acid soils by extraction after shaking with $CaCl_2$ solutions: up to about 80% of total Al determined in solution was polynuclear. Direct evidence for considerable leaching of Al compounds during reduction of iron in the soil can be found by recalculation of Siuta's (1962) experiment on reductive eluviation. Even during the second reduction cycle of a loess that was originally Ca + Mg saturated, aluminium was removed from the soil column at rates of the order of 4—8 mmol/l, comparable to the rate for Mg and about half of the rate for Ca removed in the leachate.

The soil solution being leached out of the horizons in which reduction is active would contain aluminium species, ferrous iron and other cations. As soon as this solution reaches a horizon with a higher redox potential, ferric hydroxide (and CO_2) would form by oxidation of the ferrous iron, with some drop in pH. Accumulation of ferric iron oxides in a zone below or in the lower part of the ploughpan was indeed observed in several profiles of Chhiata and other seasonally wet, acid soils in Bangladesh and is described by several authors in paddy soils elsewhere in monsoonal S.E. Asia. Any aluminium ions would displace other exchangeable cations and polynuclear Al species would tend to form interlayers in the horizons traversed with a consequent decrease in C.E.C. This process could be inferred from a comparison of the deeper horizons in soils of Chhiata and Chandra series. In Chhiata soils, where water moves out laterally due to the very low permeability of deeper horizons, the pH and the cation exchange capacity rise with depth, and little or no interlayering of smectites was observed in the deep horizons. In soils of Chandra series, however, where permeability is no obstacle to vertical water movement, the pH remains low throughout the profile, as does the C.E.C. of the clay fraction, even though both soils have developed in Madhupur clay. It should be noted that this acidification and Al-interlayering in deeper horizons would proceed without clay dissolution: the only losses from these horizons would consist of exchangeable cations.

This is in contrast with the situation in the reduced horizon after the rainy season. During oxidation in the dry season, the soluble ferrous iron is oxidized to ferric hydroxide (plus CO_2) while the pH goes down somewhat, as in the case of ferrous iron moving into an oxidized horizon. However, the exchangeable ferrous iron upon oxidation produces ferric hydroxide plus exchangeable hydrogen. This unstable situation is changed in three ways. Any soluble bicarbonates not yet leached out may displace the hydrogen with formation of carbon dioxide. Aluminium in interlayers may increase in charge by dissociation of an OH group, thus neutralizing a hydrogen ion, and acid dissolution of part of the clay structure may produce Al, Mg or other metal cations that replace exchangeable hydrogen. This latter process gradually breaks down the octahedral layer of 2:1 clays. Particularly, smectites will be affected, because these have high C.E.C. liable to (partial) saturation with ferrous iron and subsequent acid formation.

Concurrently, the remaining tetrahedral silica layers (also weakened by dissolution of substituted Al) become unstable and give rise to soluble silica, part of which may be leached out in the next rainy season and part of which may accumulate in amorphous form. In horizons that remain moist during the dry season, much of the silica may be dissolved and removed during the next rainy season. In horizons that dry out, however, amorphous silica may become insoluble by dehydration. The mixed silica—alumina gels found in the clay fractions of Chhiata by Habibullah et al. (1971), as well as the silica-cemented aggregates observed by us in sand fractions of the upper horizons, appear to be the result of such dehydration.

Thus, within horizons subject to seasonal reduction and leaching, both clay dissolution and interlayering (formation of soil chlorite) take place in alternate seasons, upon oxidation and reduction, respectively, whereas clays in horizons traversed by the leaching products are interlayered (during the rainy season) but not dissolved.

The process of clay decomposition and aluminium interlayering caused by seasonal formation and reoxidation of ferrous iron in a seasonally leaching environment was first postulated in 1970 and termed ferrolysis (Brinkman, 1970). The regularly increasing "trapped" ferrous iron contents in clay fractions toward the surface are a mark of periodically reducing conditions especially in the surface horizon and to a lesser extent in the deeper horizons. Field observations showed that seasonally reducing conditions now prevail only above and in the upper part of the ploughpan produced by long-continued paddy cultivation. Below the ploughpan, seasonal reduction and hence also the clay alteration with "locking in" of ferrous iron are fossil, therefore, and must have taken place before the land was used for paddy cultivation. The considerable amount of medium and fine biopores down to several decimetres below the present ploughpan indicate the presence at that time of relatively deep-rooting grasses and herbs and, most probably, earthworms, which would have produced and redistributed sufficient fresh organic matter to serve as an energy source for seasonal reduction.

Besides the seasonally fluctuating pH and exchangeable cation population in surface horizons, the trends of trapped ferrous iron and C.E.C. of the clay fraction with depth, and the presence of amorphous silica in Chhiata series, other factors described in earlier sections support the ferrolysis model of soil formation. Anomalously low clay contents and low but seasonally rising pH occur in upper horizons of seasonally wet soils over large areas in Bangladesh, particularly in the older soils but also in the surface horizons of the soils of older Holocene floodplains with non-calcareous sediments. The Chhiata profile studied has a clay deficit between some 1.5 and 2 kg/dm^2 (not counting the slight loss by erosion from the surface horizon) and shows a clear alteration from smectite in the lowest horizon to soil chlorite, an Al-interlayered material with some trapped ferrous iron, in the upper horizons.

The data presented in this study suggest that the ferrolysis process now dominates soil formation in level areas of Bangladesh seasonally inundated by rain water. Human influence, in the form of the dense ploughpan produced by traditional land preparation for paddy, has restricted the process to the ploughed horizon and made the E horizon fossil in cultivated soils. Large areas elsewhere in monsoonal S.E. Asia have soils with similar morphology and presumably similar pedogenesis, particularly on river terraces but not restricted to those locations. Because parent materials may be different, however, the soils are not identical in all cases. In northeast Thailand, for example, we saw similar soils with far worse chemical characteristics due to the predominance of kaolinite and the very low proportions of other clay minerals in the preweathered sediment. Similar, but far less extreme, differences occur between soils in different clay mineral provinces within Bangladesh.

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Problem hydromorphic soils in north-east Thailand

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Problem hydromorphic soils in north-east Thailand. 1. Environment and soil morphology

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Summary

The Roi Et soil, a Gleyic Acrisol (FAO, 1974) is one of the main soils on the extensive seasonally wet, low terrace in north-east Thailand. The soil appeared poor in the field, producing traditionally low yields of one paddy rice crop per year. With fertilizers and dry-season irrigation, problems of water-logging, surface salinity and acidity caused poor germination and low yields of both rice and dry-season dryland crops.

X-ray stereo radiographs, macro- and micromorphological data indicate that a sequence of processes has taken place in this soil, including perforation and homogenization by roots and soil fauna; iron mobilization and redistribution; clay translocation; alteration of clay and formation of secondary silica; and surface slaking alternating with ploughing. The clay translocation appears to be fossil. Two stages of iron mobilization under (seasonally) wet conditions are indicated, the later one, with clay alteration, continuing to the present. The soil has a considerable macroporosity, due to worms and termites, mainly in the subsoil. The ploughpan and the deep subsoil have low porosity.

Introduction

There are large areas of seasonally wet, acid soils on low terrace landforms in south-east Asia, particularly in north-east Thailand (Fig. 1). These belong to the Gleyic Acrisols among the soil units of the Soil Map of the World (FAO, 1974 and 1976); the Aquults (part: Aqualfs) in the Soil Taxonomy (Soil Survey Staff, 1975); and the Low Humic Gley soils in older classifications (e.g. Moormann & Rojanasoonthon, 1968).

Most of this land is used for a single paddy rice crop per year, in the monsoon season. Generally, no fertilizers are used and yields are low (about 1 ton paddy per hectare). After provision of dry-season irrigation water in many locations, crop diversification is attempted and yield increases are expected, but problems of salinity, acidity and water saturation have limited the degree of success achieved.

The present paper deals with the environment and soil morphology of Roi Et series, a major soil on the low terrace. Subsequent papers will discuss physical and chemical aspects, mineralogy and genesis of the Roi Et soil (Brinkman, 1977), and the nature of the saline-acid conditions occurring on the low terrace, the possible mechanisms underlying them, and a set of proposals for reclamation, improvement and management of the soils for irrigated double cropping (Brinkman & Dieleman, 1977).

Methods

Soil description is according to FAO (undated); the horizon designations are according to FAO (1974). Thin sections from undisturbed blocks were prepared according to Fitz Patrick (1970). Micromorphological terms are according to Brewer (1964).

X-ray transmission stereo radiographs were prepared of 5-mm thick sections from plastic-impregnated undisturbed blocks according to Rogaar & Thiadens (1975). Voids and impregnating plastic are X-ray transparent and show dark on X-ray film; iron (as well as, for example, calcium in calcareous soils) strongly attenuate the radiation so that nodules are blank on the film image; silicon and aluminium cause moderate attenuation (grey tones). In contrast to thin sections or polished surfaces, which give information about a single plane, stereo radiographs allow direct three-dimensional observation of void patterns and concentrations of, for example, iron or calcium in a volume of soil.

Field data

Distribution, landforms and environment

Gleyic Acrisols (Roi Et and similar series) are the main soils on the extensive, nearly level, low terraces in south-east Asia (Fig. 1, map unit 2). Only where the terrace sediments are derived from adjacent calcareous or basic rocks, Gleyic Luvisols or Vertisols locally replace the Gleyic Acrisols. The low terraces also contain occasional long, narrow, shallow depressions (channel remnants?), and sandy outcrops of higher terrace material and levee remnants. The low terraces adjoin lower-lying, younger, less weathered hydromorphic soils (map unit 3) in generally narrow river plains and in the wide alluvial plain around Tonle Sap. The low terraces extend upstream between older, generally more sandy, well-drained terraces, hills and mountains (map unit 1).

North-east Thailand has a tropical monsoon climate, with annual rainfall about 1400 mm, more than 80 % of which falls in the months May through September. Potential evapotranspiration is about 1000-1300 mm, but the upper horizons dry out strongly and actual evapotranspiration is very low in the later part of the dry season without irrigation. During the rainy season, the soils on the low terrace are

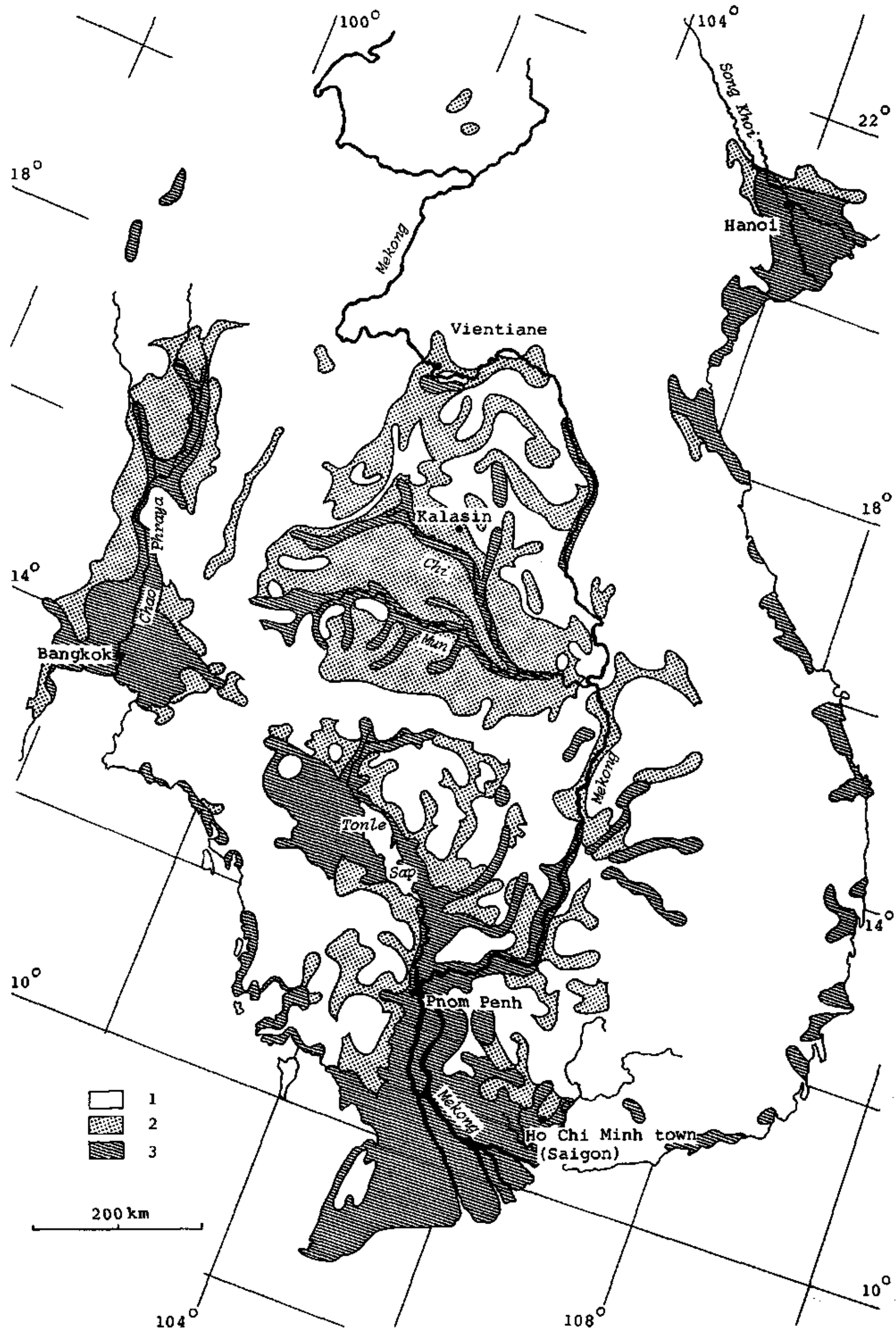

Fig. 1. Distribution of Gleyic Acrisols in the Mekong basin and surroundings. Simplified from FAO (1976), with some information from van der Kevie (1972) and Moormann & Rojanasoonthon (1968). Blank (map unit 1): mountains, hills and high, well-drained terraces; stippled (2): low terraces with Roi Et and similar weathered, acid hydromorphic soils (Gleyic Acrisols); hatched (3): younger alluvial plains.

Fig. 2. Worm casts in field margin adjoining bund (Pencil (right) 8 mm thick.)

inundated by (very slowly moving) rain water, part of which is retained by low bunds around the fields.

In spite of the inundation, the soils are apparently not reduced throughout their depth, because there are occasional small and larger trees in fields and frequent small ones on field bunds, as well as (rare) termite mounds in the fields and abundant small 'towers' of earthworm casts in the field margins, adjoining bunds (Fig. 2). Only where the soil is perennially saturated, for example by water leaking from irrigation field ditches, some dead and dying trees were observed. No trees were seen in the irregular, narrow, perennially wet seepage strips locally adjoining higher terraces.

Most of the low terrace (landscape Fig. 3) is used for a single crop of local long-grained paddy rice, as are the younger soils in the river plains. Forest covers part of the higher terraces and hills, as well as sandy outcrops in the low terrace and high levee remnants in the river plains. Part of the higher land is used for shifting or permanent cultivation of dryland crops.

The soil

A profile of Roi Et series is discussed, as an example of the main soils occurring in the low terrace of north-east Thailand and similar soils in other parts of the Mekong basin. A detailed description is given at the end of this paper.

The soil (Fig. 4) has a grey (light) silt loam plough layer and ploughpan (Apg) over a grey clay loam upper subsoil (Eg), all with fine mottles, overlying a grey loam deeper subsoil (Bg) with strong coarse mottles, extending beyond 2 m. The coarse mottling consists of soft nodules; few hard nodules occur in the upper Bg horizon.

The consistence is friable throughout, but ploughpan and substratum are firm in place. The structure is massive in the plough layer and ploughpan, and grades to very coarse prismatic and coarse angular blocky at depth.

Fine and medium tubular pores are common in most of the profile except for the ploughpan and the substratum below 1.4 m which have few pores. There are occasional coarse tubes and round and dome-shaped chambers, indicative of worm and termite activity. Roots extend to 0.6 m depth.

There are thin and, in the substratum, also medium and thick cutans on ped faces and in pores, and locally similar material filling the lower end of pores (Fig. 5). Cutan material is grey and appears silty or very fine-sandy to the touch.

X-ray stereo radiography

Stereo radiographs of vertical sections from different depths were used to obtain an insight into the spatial distribution of pores and of total iron in the profile. The

Fig. 3. Landscape of Roi Et series north-east of Kalasin; profile site and some excavated material in foreground.

Fig. 4. Soil profile, Roi Et series. Auger 1.2 m long. Profile described at end of paper.

information was checked by observation of polished surfaces of the same sections under incident light.

Pore structure

The Eg horizon (Fig. 6A) has abundant, mainly continuous, very fine random and fine mainly vertical tubes with twisting courses. Part of these are dendritically branching. The very fine tubes and at least the dendritic fine ones were probably produced by plant roots. There are also common medium (2-4 mm) simple or forking tubes in all directions. Part of the latter, and some coarse tubes (up to 8 mm) are filled with rather loosely packed fine granular material (aggrotubules). These coarse and medium tubes, and part of the fine ones, were probably produced by worms and termites.

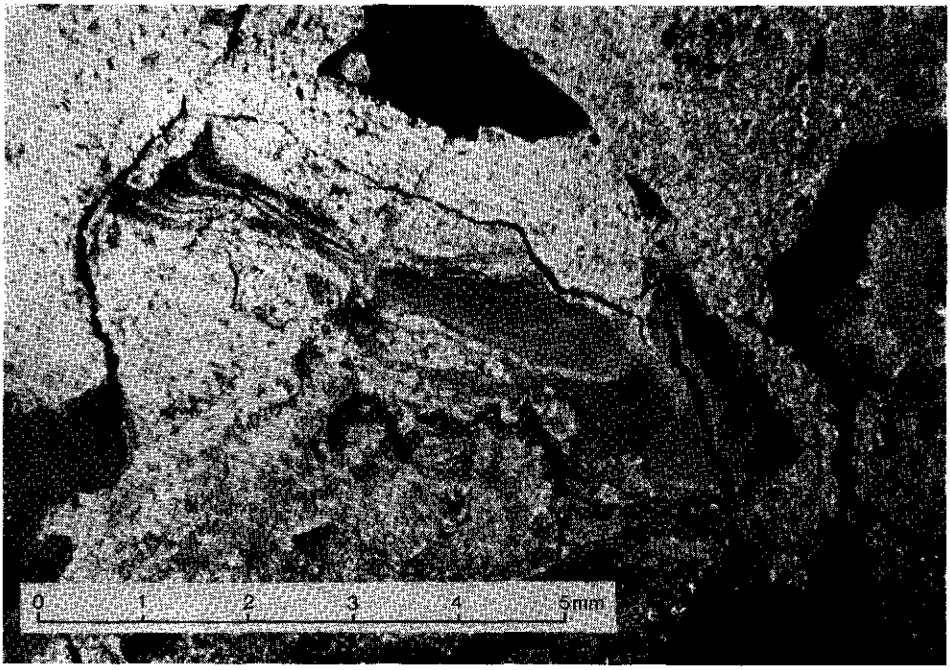

Fig. 5. Laminated infilling in bottom of former void. 185 cm depth. Impregnated section, 5 mm thick. Incident light. Fallen groundmass on top of the infilling. Remnant of void at top of figure.

Few continuous tubes are found in the Bg horizons (fig. 6B). In the upper Bg horizons, there are many vughs: discontinuous remnants of random very fine tubes, and of fine and medium tubes flattened into subhorizontal lenticular shapes. Common coarse (up to 8 mm) irregular voids each branch into several medium and fine tubes in all directions. Most pores occur in the parts low in iron; the iron-rich parts only contain occasional pores. Very few fine cracks (craze planes) are visible in the upper Bg horizons.

The lowest Bg horizon has generally common, mainly discontinuous, very fine random pores, and locally many in parts low in iron. There are common discontinuous fine and medium (1-4 mm) random tubes as well, but most of these are partly or completely filled by stratified or massive material and occasional aggregates. Most of these tubes in the material low in iron appear distorted. Few very fine and fine, and very few medium mainly vertical and some horizontal cracks (craze planes) were observed in the lowest horizon.

The predominance of vughs and distorted tubes in the B horizons shows that after a period in which mainly biotic activity influenced these lower horizons, physical processes have become dominant, presumably due to water saturation alternating with strong desiccation. Biotic activity has remained dominant in the Ag and Eg horizons.

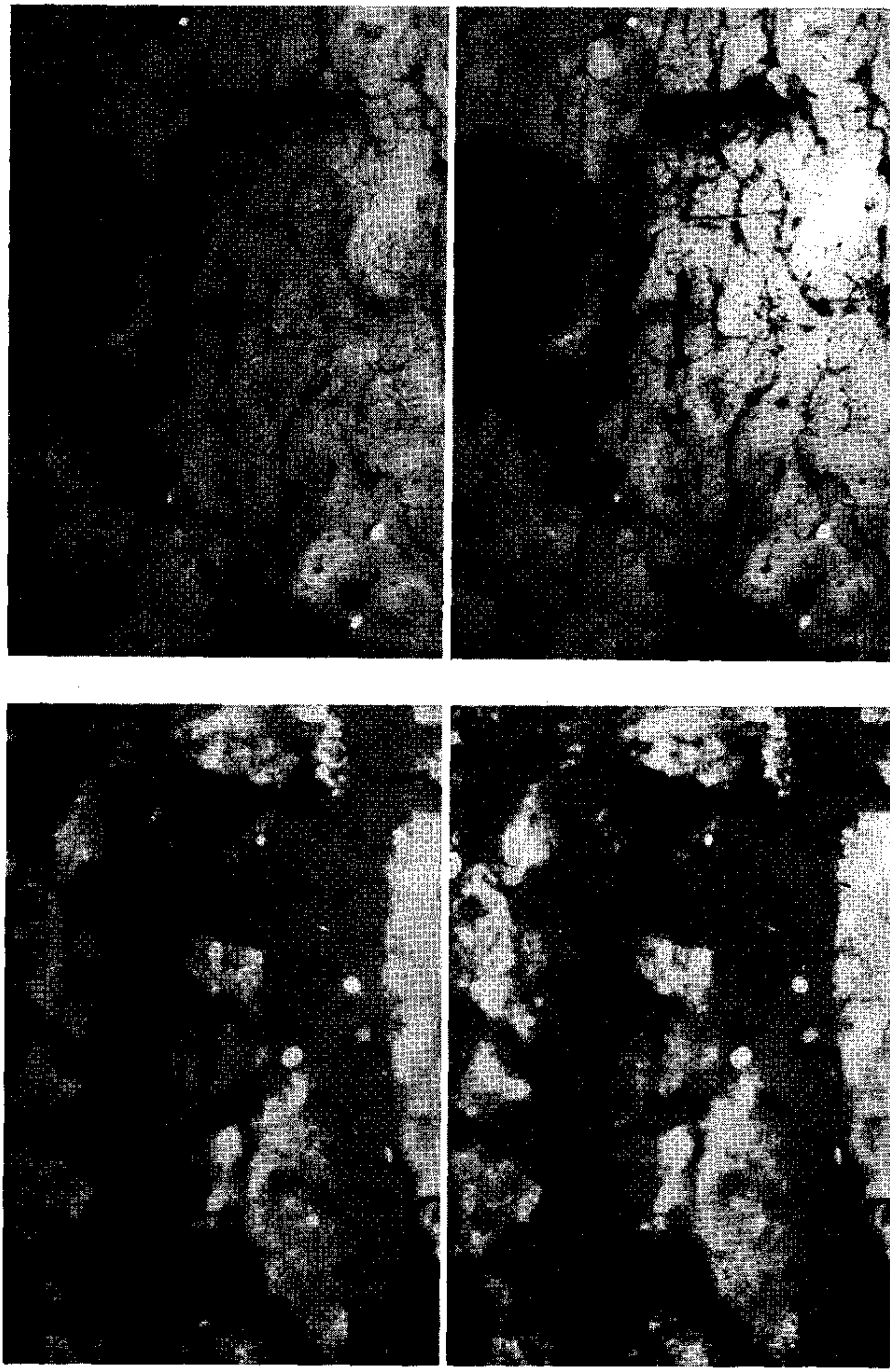

Fig. 6. X-ray stereo radiographs of 5 mm thick, vertical sections of the Eg and Bg horizons. A three-dimensional view may be obtained by use of a pocket stereoscope or a pair of lenses about +4 *diopters* (f = 25 cm) or stronger. Millimetre scale on left. Upper pair: Eg horizon, 50-59 cm depth; lower pair: Bg horizon, 96-105 cm depth. Black: voids; dark grey: soil material low in *iron*; light grey: soil material *higher* in *iron* (neoferrans in Eg, mottles and probably original soil material in Bg horizon); white: concentrated iron oxides (nodules).

Iron distribution

The Eg horizon contains common thin neoferrans along very fine pores, and common weakly expressed (iron content not very high) medium and coarse iron mottles with clear boundaries, increasing in the lower part of the horizon: probably remnants of the prismatic shapes observed further down. There are occasional fine and medium round ferric nodules with mainly sharp boundaries.

Many coarse, discontinuous prismatic shapes with clear, locally gradual boundaries occur in the upper Bg horizons. These have a higher iron content than the surrounding (more disturbed) material, and contain irregularly distributed concentrations of ferric oxides, less than one to several millimetres in size. There are few scattered ferric nodules (1-4 mm diameter) with sharp boundaries, both in the more disturbed material and in the prism remnants.

In the lowest B horizon, the prismatic shapes are larger still, about 5 cm wide. They contain mainly evenly distributed iron, and few medium concentrations with gradual boundaries. Occasional ferric nodules with sharp boundaries occur in the more disturbed material surrounding the prismatic shapes.

The occurrence of round ferric nodules with abrupt edges both in the disturbed material and in the prism remnants suggests that they may have been brought in with the sediment, or possibly that they were formed before a subsequent homogenization of the whole soil mass and before liberation of the iron oxides now present in the prismatic shapes.

The even distribution of iron in the prismatic shapes, without higher concentrations along the margins, suggests that the iron-rich areas are dissolution remnants from an originally ferruginous soil mass, and that iron redistribution played a minor part in their formation.

The presence of organic matter in the form of root remnants may have been the reason for activity of soil fauna, resulting in homogenization of part of the soil mass to a relatively great depth. This homogenized material containing some organic matter would then be far more liable to seasonal water saturation and to reduction and removal of iron oxides than the adjoining undisturbed parts.

Micromorphology

Skeleton grains throughout the profile consist of quartz, with sporadic heavy minerals. The quartz is corroded, and cracks in many grains contain iron oxides. The grain distribution pattern is mainly random, locally with clusters in the Bg horizons, and with a banded distribution pattern in the Apg horizons. The lowest horizon contains some angular, strongly birefringent grains 0.3-2 mm in size, locally covered by iron oxides, and showing exfoliation (fanning out) along their edges. These probably are pedorelics.

The plasma consists of clay minerals and a white opalescent material resembling secondary silica. In the Apg horizon, which contains some organic matter as well, there is less plasma than further down.

Biogenic voids throughout the profile consist of channels, vughs and interconnected vughs. Simple packing voids are found in the ploughed layer, and craze planes throughout the profile below the Apg horizons.

Common aggrotubules with diameters between 0.3 and 1 mm were observed in the Apg horizons, and few in the Eg. The latter contains occasional argillans and neoferrans. The upper 5 mm of the Apg1 largely consists of fecal pellets with a higher organic matter content than the rest of the horizon.

Redistributed iron oxides occur in two forms. Channel neoferrans, about 20-50 μm thick, occur in the Apg2, Eg and EBg horizons and in the lowest Bg horizon, at about 1.8 m depth. These locally cover argillans.

Orange to dark red ferric nodules with diffuse to abrupt boundaries are present throughout the EBg and Bg horizons, with a maximum about 1 m depth. Part of these have a droplet structure (Hamilton, 1964). The droplets are red, birefringent and of the order of 1-2 μm in size. These nodules generally contain illuviation cutans. A second type of dark red nodules up to several mm diameter, with abrupt boundaries and without illuviation cutans, occurs in the EBg and Bg1 horizons. These locally also have a droplet structure. Some cracks in the second type of nodules contain recrystallized iron oxides. Illuviated clay occurs in a shrinkage crack around one nodule.

Illuviation cutans and some papules occur throughout the profile below the Apg horizons, lining channels and, in the deeper horizons, cracks as well. Some cutans are covered by secondary iron oxides. The cutans are mainly argillans, low in iron, part with a continuous orientation (birefringent), part grainy and nearly isotropic. The ratio of birefringent to isotropic, grainy material decreases significantly ($P < 0.05$ one-sided) from 1.1 in the deepest horizons to 0.8 in the Apg and Eg horizons (Fig. 7). Argillans enclosed within ferric nodules tend to be more highly birefringent and less grainy than those occurring in the grey parts of the soil. Some cutans contain thinly stratified grainy material. Some cutans are partly birefringent, partly isotropic and grainy (Fig. 8), with gradual boundaries crossing the direction of stratification. Papules comprise 27 % of the grainy features and 16% of the birefringent ones. This suggests gradual conversion of birefringent into grainy material concurrent with continued clay illuviation.

The grainy material is strongly white opalescent in incident light (Fig. 8B) and dark in transmitted light (Fig. 8C); individual grains are of the order of 0.5 μm in size. When viewed at high magnifications ($\times 600$ to $\times 1000$) the grains are transparent and appear (weakly) birefringent. The grains may be clay-size quartz: see also the section on clay mineralogy in Brinkman (1977). The significance of birefringent and grainy argillans in a surface-water gley soil is discussed in Brinkman et al. (1973).

The Apg horizons contain a considerable proportion of stratified (banded) remnants of slaking crusts. The upper part of the pieces has the finest texture and generally contains much material that is white opalescent in incident light; the lower part is gradually coarser. The pieces contain occasional vesicular voids. In a few of the larger channels in deeper horizons there are cutans consisting of alternating silt and clay strata (Fig. 5): probably slaked material from the surface.

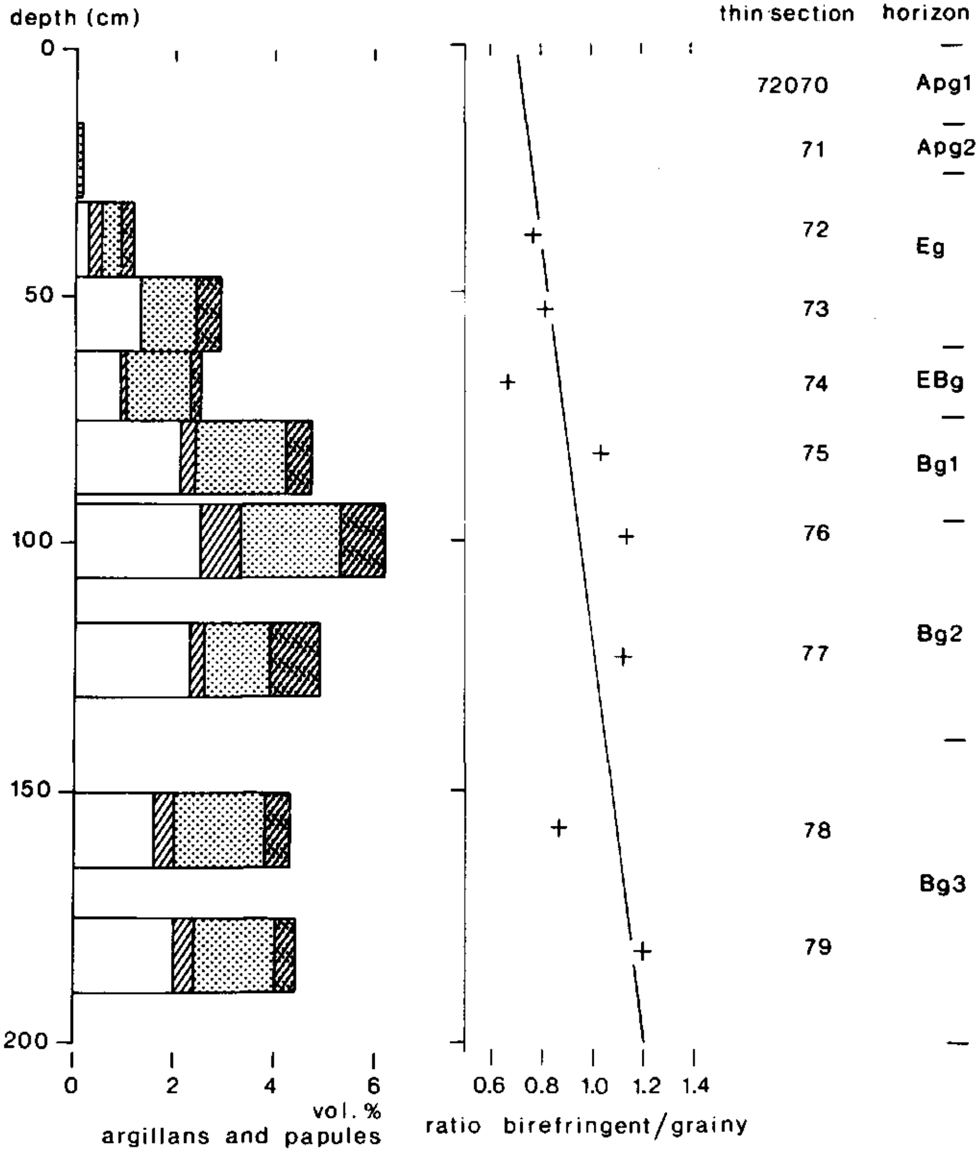

Fig. 7. Content of argillans and papules at different depths. Blank: birefringent argillans; hatched: birefringent papules; stippled: isotropic, grainy argillans; stippled and hatched: isotropic, grainy papules.

Possible sequence of processes

The observations indicate that several processes have taken place in this soil. These include corrosion of quartz grains and deposition of iron oxides in the cracks; perforation and homogenization by roots and soil fauna; iron redistribution; clay eluviation with illuviation over a considerable range of depths; alteration of clay and formation of secondary silica; and surface slaking alternating with ploughing. These processes have not all operated concurrently.

The corroded quartz grains with iron oxides in cracks are similar to the skeleton grains which we observed in well-drained Ferralsols (Oxisols), and unlike those in seasonally wet soils. They may have been brought in the sediment as pre-weathered material.

The iron nodules without enclosed argillans or papules are indicative of an early phase of alternating reduction and oxidation, before the start of clay translocation (possibly in a ground-water gley situation, shortly after deposition).

A considerable amount of perforation and homogenization must have taken place rather early during soil development, before and during the period of clay translocation. Most of the illuviated clay occurs as argillans on walls of channels and cracks, and occasionally in aggrotubules; relatively little has been reworked into papules. Biotic homogenization is continuing up to the present, as shown by the small towers of worm excreta (Fig. 2) along the field margins, and the occasional earthworms observed during excavation of the soil profile.

The presence of birefringent argillans in protected locations and partly birefringent, partly isotropic and grainy ones (Fig. 8) in other places indicates that clay translocation started before clay decomposition. Translocation must have continued while the decomposition process was active, because there are argillans with laminations of grainy material as well. The argillans (as well as the plasma) are increasingly grainy toward the surface, and few argillans or papules were observed in the Eg horizon, in spite of its maximal clay content. The Eg horizon in this profile may therefore have developed in the upper part of a former textural B horizon. The clay in the upper horizons is almost completely grainy, as clearly observed in the fine-textured parts of the slaking crusts. The features suggest that clay decomposition continued after the end of clay translocation, and occurred (or still occurs) mainly in the upper horizons.

Iron redistribution into nodules and occasional neoferrans due to seasonal reduction and oxidation probably started (again) at, or preceding, the beginning of clay decomposition, because illuviated clay enclosed in nodules is more birefringent and less grainy than that in the remainder of the thin sections. The occasional neoferrans around channels in the annually ploughed Apg1 show that the iron redistribution continues until the present.

The remnants of slaking crusts in the Apg horizons are recent and are produced by the annual ploughing and puddling for rice cultivation. The occasional cutans and channel infillings consisting of stratified silty and clayey material in deeper horizons (Fig. 5) are probably caused by sediment-laden water moving down large channels during the puddling operation.

Most of the biotic activity is presently concentrated in the Apg1, as shown by the abundant fecal pellets near the soil surface, probably due to the prevalence of recent rice roots in that horizon and the low porosity of the ploughpan.

Description of Roi Et series

Roi Et series (Thailand), FAO/Unesco Soil Units (FAO, 1974): Gleyic Acrisol; USDA Soil Taxonomy (Soil Survey Staff, 1975): Paleaquult. Profile KAL-1, examined 18 March 1972 by R. Brinkman.

The site
Location near Kalasin, north-east Thailand. About 5 km north-east of Kalasin town, along road to Thanon Thinanon, about 50 m east of road, about 1 km from the nearest large outcrops of higher terrace. Map reference Thailand 1:50 000 scale, sheet 5760-III (Changwat Kalasin), U.S. Army Map Service and Royal Thai Survey Dept. 1960. Km grid 1819.8 N, 345.1 E. About 16° 27′ N, 103° 33′ E. Elevation 145 m above mean sea level.

Landform and slope: level, low terrace, slope about 0.1 % to the east. Fields with bunds 30-40 cm high. Rare termite mounds, abandoned, about 0.8 m high. Occasional 'towers' of worm excreta, 5-10 cm wide and 5-20 cm high, in field margins immediately adjoining field bunds.

Vegetation/land use: transplanted rice (local long-grain variety), grown in the rainy season without fertilizers and without irrigation. Yields reported of the order of 1 ton/ha. Generally fallow in the dry season. Very locally, small patches of dry-season dryland crops near homesteads, irrigated by hand from wells. About 2 km west of this site, there is an experimental irrigation scheme of a few hundred hectares. Occasional, locally common trees on field bunds, very few in fields.

Climate: tropical monsoon climate (Köppen Aw). Mean annual temperature 27 °C, coldest month 22 °C, hottest month 30 °C. Precipitation 1370 mm/year, wettest month about 300 mm, driest month 1-3 mm. Potential evapotranspiration 1000-1300 mm/year (3 stations around Kalasin).

General information on the soil
Parent material: 'low terrace', a low, nearly level river terrace of uncertain age, late Pleistocene or older judging from soil development.

Drainage poor. Internal drainage slow due to low porosity of deep substratum (below about 1.5 metres); external drainage very slow due to the nearly level surface with field bunds. Seasonally flooded to shallow depth for 3-5 months. Moisture conditions in the soil: Apg1 dry, moist below.

Depth of ground water about 1.8 m at the site, but reported average below three metres at the end of the dry season. About 0.3 m (estimate) above ground level at the height of the rainy season. Ground water remains at or less than 0.5 m below the surface throughout the year in narrow strips along outcrops of a higher, sandy terrace and in places with excessive dry-season irrigation, as practised about 2 km west of this site.

No surface stones or rock outcrops are present; there is no evidence of erosion.

There is no salt or sodicity (alkali) or soluble acid at the site or in most of the area. In places with a permanently high water-table there is surface salinity. On slight elevations and on slightly higher marginal strips of the low terrace along outcrops of a higher, sandy terrace, the surface salinity is extreme and there are toxic concentrations of soluble aluminium and ferric iron in the surface soil and salt crust, with recorded local pH values about 3.

Human influence comprises low bunds, about 30-40 cm high, around rice fields, a ploughpan due to puddling for rice, and locally (not at this site) a permanently high water-table due to excessive dry-season irrigation water.

Brief general description of the profile

Deep, poorly drained, grey silt loam to loam with a distinctly mottled subsoil and strongly mottled substratum containing soft and hard ferric nodules. Structure is weak; the soil is porous to about 1.5 m depth but massive and apparently very slowly permeable below. Fine roots extend to about 0.6 m. Note: alteration under hydromorphic conditions (loss of iron) appears to be dominant in the present Eg horizon (probably a former part of a textural B) as well as in the Apg horizons.

Profile description

Apg1, 0-16 cm. Pinkish grey (7.5 YR 6/2) moist light silt loam; few fine distinct strong brown mottles mainly along pores; massive with bits, mainly lenticular, of grey slightly finer textured material (ploughed-in remnants of slaking crusts produced by puddling?); moist very friable; common, locally many fine roots; clear, wavy boundary. Sample No 72-119; thin sections 72070 (0-15 cm), 72080 (0-8 cm, 15 cm wide), 72081 (about 5 cm, horizontal plane).

Apg2, 16-26 cm. Pinkish grey (7.5 YR 6/2) moist light loam (very fine sandy); few fine distinct reddish yellow mottles mainly along pores; massive; moist very friable, slightly firm in place; few fine and very fine mainly vertical tubular pores; few, locally common, fine roots; clear, wavy boundary (24-28 cm). Sample No 72-120; thin sections 72071 (15-30 cm), 72082 (about 20 cm, horizontal plane).

Eg, 26-61 cm. Pinkish grey (10 YR 6/2) moist clay loam; common, locally few fine distinct strong brown mottles, mainly on pore faces; weak very coarse and coarse prismatic; moist friable; common medium and many fine mainly vertical tubular pores, locally scattered coarse tubular pores and dome-shaped chambers, about 5 cm wide and 3 cm high; broken thin cutans in tubes; locally fine granules (excreta) in pores; common fine mainly vertical roots; gradual smooth boundary. Samples No 72-121 (26-45 cm), 72-122 (45-61 cm); thin sections part of 72071 (15-30 cm), 72072 (31-46 cm), 72073 (46-61 cm).

EBg, 61-75 cm. Pinkish grey (7.5 YR 6/2) moist loam with very fine sand fraction; common fine distinct reddish yellow mottles; weak coarse subangular blocky; moist friable; few medium and common fine tubular pores in peds and on faces; generally broken but locally continuous medium and thin cutans in pores, locally cutans of fine sand, cutans are slightly greyer than mass; few medium and fine soft ferric nodules; common fine remnants of excreta, same colour as mass; no roots; gradual smooth boundary. Sample No 72-123; thin section 72074 (60-75 cm).

Btg1, 75-96 cm. Pinkish grey (10 YR 7/2) moist loam, ped faces with slightly less clay; many coarse prominent brownish yellow very soft ferric nodules with dark red to red (10 R 3/6-2.5 YR 4/6) centres and few medium dark reddish brown (2.5 YR 3/4) hard ferric nodules, all in peds, ped faces pinkish grey; moderate very coarse and coarse prismatic breaking into weak subangular blocky; moist friable, firm in place; few medium, common fine tubes in and on faces, common medium and fine tubes and few medium vughs in mass; continuous moderately thick cutans (gleyans[1] of material from the surface horizon?) on most vertical faces and tubes, broken thin cutans in vesicular pores, on horizontal and locally on vertical faces; few medium hard nodules; locally fine granular excreta; no roots; gradual wavy boundary. Sample No 72-124; thin sections 72075 (75-90 cm), part of 72076 (92-107 cm).

Btg2, 96-140 cm. Grey (10 YR 6/1) moist loam, ped faces with slightly less clay; many coarse prominent red and dark red (2.5 YR 4/8 and 10 R 3/6) soft nodules some with a reddish yellow rim or parts, and common coarse distinct reddish yellow soft nodules, all nodules in peds, ped faces pinkish grey (7.5 YR 7/2), locally grey; moderate coarse prismatic breaking into moderate coarse and weak medium subangular blocky; moist friable, firm in place; few medium, common fine tubes in ped faces, common medium and fine tubes and few fine to medium vughs in peds; continuous moderately thick cutans (gleyans) on faces and in tubes; many coarse soft nodules; locally in tubes fine and very fine excreta; no roots; diffuse boundary. Sample No 72-125; thin sections 72076 (92-107 cm), 72077 (116-131 cm).

Btg3, 140-200 cm. Pinkish grey 7.5 YR 7/2) moist loam; many coarse and medium distinct strong brown and reddish yellow mottles, in part soft nodules, locally mainly in lower part common medium and coarse prominent red soft nodules; moderate very coarse prismatic and very coarse and coarse angular blocky; moist friable, mottles and larger aggregates firm, very firm in place; few fine and very fine tubes in faces, few fine and common very fine tubes in peds, locally few medium and fine round chambers; continuous thin cutans on ped faces and pores, with mottles shining through; locally silty material accumulated in bottom of pores; no roots. Samples No 72-126 (140-170 cm), 72-127 (170-200 cm); thin sections 72078 (150-165 cm), 72079 (175-190 cm).

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[1] Gleyans is the name provisionally given to gleyed ped or pore cutans occurring in seasonally flooded soils (Brammer, 1971). The cutans are typically thicker than true argillans and comprise silt and mica as well as clay and humus. Their colour is that of the overlying surface horizon and it is assumed that they flow, or are injected, down voids from the puddled and reduced ploughed horizon under conditions of seasonal flooding. Their presence is not diagnostic for an argillic horizon, though they may mask the presence of true argillans.

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Problem hydromorphic soils in north-east Thailand.
2. Physical and chemical aspects, mineralogy and genesis

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Key words: paddy soils, interlayering, kaolinite dissolution

Summary

The genesis of one of the main soils on the extensive seasonally wet, low terrace in north-east Thailand was studied and its mineralogy and some physical and chemical aspects described.

The Roi Et soil is a silt loam with low clay contents in the surface horizon, increasing with depth. It is seasonally water-saturated, seasonally dry; has considerable porosity, but has a dense ploughpan at about 0.2 m and a dense substratum below 1.4 m depth. The soil is strongly acid with a low base saturation and a very low cation exchange capacity.

Silt and sand are 98 % quartz. Disordered kaolinite is the main clay mineral. About a fifth of the clay fraction is soil chlorite: a strongly Al-interlayered vermiculite in the upper horizons but partially Al-interlayered in the substratum. The interlayers contain a small amount of ferrous iron. Quartz contents in the clay fractions range from one tenth in most of the profile to about three tenths in the surface horizon, with a corresponding decrease in kaolinite. The kaolinite in the upper horizons shows signs of dissolution.

These data are in accordance with the hypotheses of clay eluviation-illuviation and long-continued iron redistribution and ferrolysis: clay alteration and dissolution under the influence of alternating reduction and oxidation of iron.

Introduction

The environment and the soil morphology of the Roi Et soil, one of the main soils on the extensive seasonally wet, low terrace in north-east Thailand, were described earlier (Brinkman et al., 1977). This paper deals with some physical and chemical aspects, mineralogy and genesis of the Roi Et soil. A subsequent paper (Brinkman & Dieleman, 1977) discusses the saline-acid conditions occurring on the low terrace, and possible ways of reclamation, improvement and management for irrigated double cropping.

Methods

Bulk density and field moisture content were measured on undisturbed cores; porosity was calculated assuming a particle density of 2.65 g/cm^3. Particle size distribution was determined by sieve and pipette. pH was measured by glass electrode in suspensions 1:2.5 in water and 0.01 *M* $CaCl_2$.

Organic carbon was estimated by heated dichromate-sulphuric acid, assuming 87 % recovery, according to Schollenberger (1927). Exchangeable bases and cation exchange capacity (CEC) were determined by Li EDTA (Begheyn & van Schuylenborgh, 1971); Al and H by KCl extraction. Na and K were measured by flame photometer and Ca, Mg and Al by colorimeter.

Clay fraction pretreatment was by hot 10 % H_2O_2 buffered at pH 5 with sodium acetate-acetic acid, followed by centrifuging and decantation of the clear supernatant. After dispersion by NaOH to pH 7, two decantations were made of the fraction <2 μm.

Suspensions with about 10 mg Na-clay were brought on porous tiles for X-ray diffraction by a suction technique according to van Reeuwijk (1976), modified from Dümmler & Schroeder (1965). The remainder of the clay was flocculated with $BaCl_2$, centrifuge-washed and freeze-dried for chemical analysis.

Total chemical analyses for most elements were made by X-ray fluorescence on $Li_2B_4O_7$ glass disks according to Halma (1973). Na was determined by flame photometer, ferric and ferrous iron by colorimeter after one minute decomposition by HF-H_2SO_4. This time suffices for complete dissolution of these elements from the clay fractions and avoids problems of iron reduction or oxidation (Brinkman, 1977).

Heavy minerals from sand fractions were separated by bromoform and identified by petrographic microscope; feldspar counts were made on 800-2000 grains after etching by HF vapour and staining according to van der Plas (1966). Epinorm mineral calculations were made by a computer programme based on Burri (1964). Diffractograms were produced of Mg-saturated oriented aggregates of clay fractions without and with glycerol solvation, and of K-saturated aggregates after drying and heating to different temperatures, on a Philips PW 1050 diffractometer with CoKα radiation, slits 1° - 0.2 mm - 1°, Fe filter, scanning speed 1° 2θ/min, scintillation counter, time constant 4 s, recorder range 1000 cycles/s, speed 10 mm/min. Transmission electron micrographs of clay fractions were made on a Philips EM 300 electron microscope.

Physical and chemical data

The bulk density of the ploughed layer and the Eg and Bg1 horizons ranges about 1.4 - 1.45 g/cm^3. The ploughpan and the Bg horizons below 1 m depth have bulk densities about 1.55 g/cm^3 (Table 1). These differences correlate with the amount of fine tubular pores estimated in the field, suggesting that the Apg2 and particularly the Bg3, from 1.4 m down, are the main horizons restricting permeability. USBR (Anon., 1971) lists permeabilities ranging between essentially zero and 36 mm/day

Table 1. General physical and chemical data.

Sample No 72/	Horizon	Depth (cm)	Bulk density (g/cm³)	2-50 μm fraction (%)	<2 μm fraction (%)	<0.2 μm / <2 μm	Org. C (%)	Total Fe_2O_3 (%)	pH H_2O	pH $CaCl_2$	Exchangeable cations (meq/100 g soil)						CEC*	Al sat. (%)
											Ca	Mg	Na	K	Al	H		
119	Apg1	0- 16	1.45	54.3	9.3	0.28	0.3	0.4	5.1	3.9	0.2	0.0	0.1	0.1	0.4	0.3	1.1	36
120	Apg2	16- 26	1.54	47.0	11.6		0.2	0.7	4.7	3.9	0.5	0.0	0.1	0.1	0.6	0.3	2.1	29
121	Eg	26- 45	1.37	38.9	28.3	0.29	0.3	1.6	4.9	3.7	1.0	0.0	0.1	0.1	3.0	0.3	4.6	65
122	Eg	45- 61	1.41	41.6	27.0		0.0	1.4	4.3	3.6	0.6	0.0	0.1	0.1	3.7	0.3	5.0	74
123	EBg	61- 75	1.43	44.0	24.7		0.1	1.8	4.7	3.7	0.4	0.0	0.1	0.1	3.4	0.3	4.9	70
124	Bg1	75- 96	1.47	45.5	21.2	0.29	0.0	3.3	4.6	3.7	0.5	0.0	0.1	0.1	3.0	0.4	5.0	60
125	Bg2	96-140	1.52	45.5	23.6		0.2	3.4	4.5	3.7	0.3	0.0	0.1	0.1	4.3	0.3	6.1	70
126	Bg3	140-170	1.60	48.3	18.7		0.0	1.4	4.5	3.7	0.2	0.0	0.2	0.0	3.1	0.3	5.0	62
127	Bg3	170-200	1.52	47.2	24.9	0.38	0.1	2.2	5.0	3.7	0.7	0.0	0.4	0.0	3.7	0.3	5.5	69

Soluble salts (1:2 extract): 0.1 mmol NaCl/100 g soil to 140 cm depth, decreasing to less than 0.01 mmol/100 g soil at 170-200 cm.
Ground water 1.1 mmol NaCl:1.
* CEC = cation exchange capacity.

below 2 m depth, and ranging up to about 150 mm/day at shallower depths in two profiles of Roi Et series.

The moisture distribution at the end of the dry season (Fig. 1) indicates that moisture contents are virtually constant throughout the Bg horizons and steadily decrease in the upper horizons toward the surface. Moisture depletion in the dry season apparently extends to about 0.7 m depth under one unirrigated rice crop per year.

The grain size distribution was recalculated to (sand + silt) fractions total 100 % (Fig. 2), in order to separate the possible effects of clay redistribution and decomposition from sedimentary differences. The homogeneity of the sand and silt fractions throughout the profile is evident. In contrast, the clay content is low in the Apg horizons, rises abruptly to a maximum in the upper Eg horizon and decreases slightly toward the Bg horizons. The low clay contents in the surface horizons appear systematic, but not the maximum in the Eg horizon: one of the two Roi Et profiles reported on by USBR (Anon., 1971) lacks this maximum and is homogeneous below the Ap horizons, the other has a maximum but has corre-

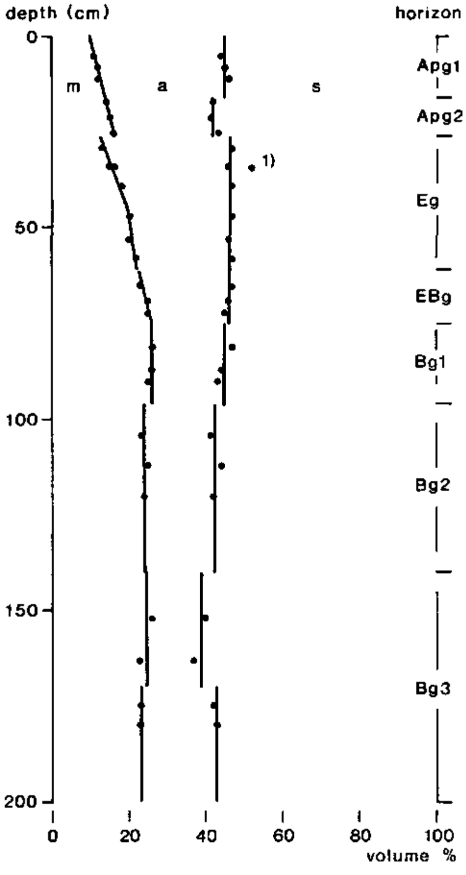

Fig. 1. Moisture distribution and total porosity. m = field moisture (February: late dry season); a = air; s = solids (density 2.65 g/ cm^3 assumed).

[1] Sample contains large pore.

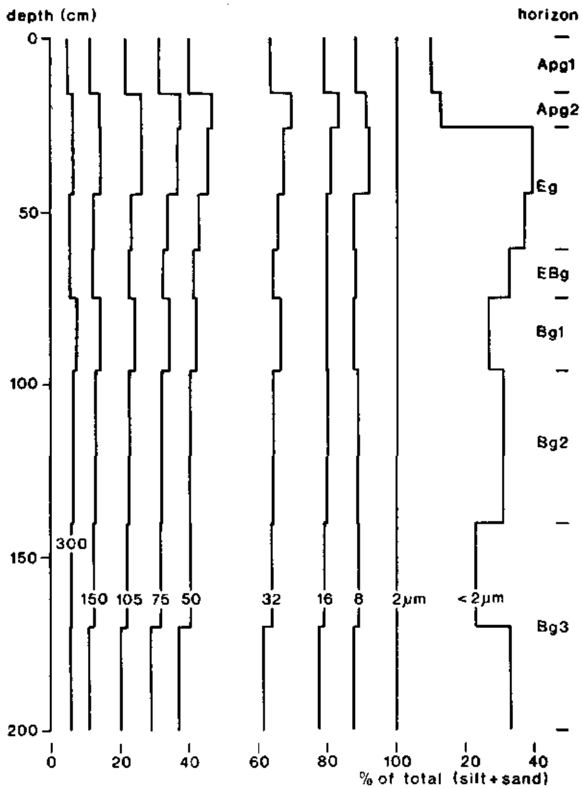

Fig. 2. Cumulative grain size distribution, recalculated to (sand + silt) fractions (total 100 %).

sponding variations in the coarse fractions with depth. The ratio of fine clay (<0.2 μm) to total clay is 0.38 in the lowest horizons and 0.29 - 0.28 in the remainder of the profile. This suggests that other soil forming processes may have superseded clay translocation, as also indicated by the micromorphological data.

The profile has a low organic matter content, a low pH, a very low cation exchange capacity particularly in the Apg horizons, and a high proportion of exchangeable aluminium especially in the Eg and Bg horizons (Table 1).

The variation in total chemical composition (not listed) is almost completely due to the variations in clay content and composition. The fraction coarser than 2 μm is 99 % SiO_2.

The chemical composition of the clay fraction (Table 2) is relatively constant in the Bg and Eg horizons, but SiO_2, TiO_2, FeO and P_2O_5 contents increase in the Apg horizons whereas Al_2O_3, Fe_2O_3, MgO and K_2O tend to decrease.

The cation exchange capacity of the clay fractions was estimated in several ways. For each sample, the CEC of the fine earth (includng organic matter) was recalculated on the basis of 100 g clay and plotted on the ordinate, and the organic carbon percentage, likewise recalculated per 100 g clay, on the abscissa (Fig. 3). If the clay and organic matter in a soil profile would have a constant CEC, such

Table 2. Total chemical composition of clay fractions (% w/w).

Sample No 72/	SiO_2	Al_2O_3	Fe_2O_3	FeO	MnO	MgO	CaO	Na_2O	K_2O	TiO_2	P_2O_5	BaO*	Ign. loss
119	61.6	21.7	2.32	0.12	0.01	0.21	0.08	0.09	0.31	2.31	0.12	1.39	9.9
121	50.1	30.5	3.27	0.10	0.01	0.22	0.07	0.09	0.29	1.63	0.05	1.67	12.1
124	49.1	30.2	4.74	0.09	0.00	0.25	0.07	0.09	0.44	1.53	0.05	1.77	12.0
127	48.7	29.9	5.53	0.08	0.00	0.22	0.07	0.09	0.41	1.50	0.05	1.85	11.8

* Clay fractions are Ba-saturated.

a diagram would consist of a straight line, the (positive) slope of which indicates the CEC per gramme organic carbon, and the intercept with the ordinate the CEC of the clay fraction. It is clear from Fig. 3 that the clay fractions of the upper horizons have a lower cation exchange capacity than those of the horizons at greater depths, regardless of the CEC ascribed to the organic matter. Data on clay fractions

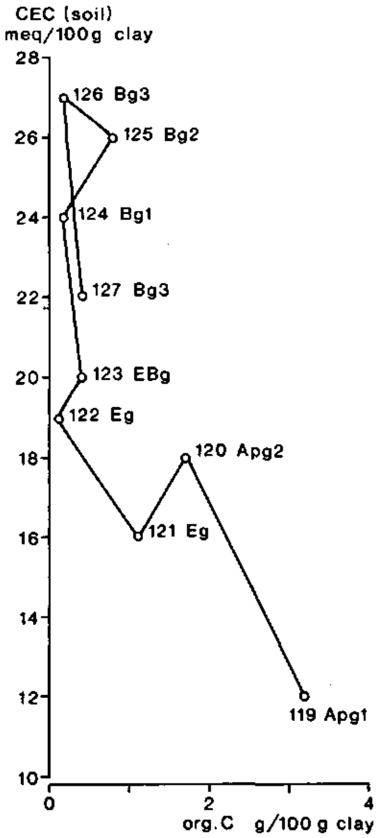

Fig. 3. Cation exchange capacity of soil, recalculated per 100 g clay. Abscissa: organic carbon, recalculated per 100 g clay.

saturated with Ba (Table 2) and Ca confirm this trend. The CEC of clay fractions Ca-saturated at pH 7 ranges from 20 meq/100 g clay in the surface horizon to 31 meq/100 g in the lowest horizons (Table 3).

Mineralogy

The silt and sand fractions

The silt fraction consists of mainly angular and subrounded quartz grains, with iron oxide specks on some of the grain surfaces. In the surface horizon about one per cent of the silt grains are amorphous silica as identified by their isotropism and low index of refraction (1.42 - 1.44). Most of these are strongly solution-pitted. Part are recognizable phytoliths (plant opal): colourless through pale pink to light brown rod-like and plate-like shapes, a few with identifiable pits, and an occasional diabolo (hour-glass) shape, sizes ranging from about 50 μm to fragments a few μm across. Some amorphous silica grains were seen in the Eg and EBg, and none in the Bg horizons.

The sand fraction throughout the profile is dominated by angular to subrounded detrital quartz grains, part locally encrusted with red iron oxides, and some grains containing very thin needle-shaped inclusions. The sand fraction from the Bg1 horizon (which has medium, hard ferric nodules), contains fine and very fine nodules as well. Feldspars are absent from the surface horizons, and account for varying proportions between 0.1 and 1 per cent of the fractions 50-420 μm in horizons below 0.5 m depth. Potassium feldspars are essentially absent throughout the profile.

Epinorm mineral calculations confirm that the (sand + silt) fractions essentially consist of quartz: 98 $\pm$ 2 %. Rutile contents are 0.4 %, decreasing in the upper three horizons to 0.2 %; hematite content is 0.6 % in the lowest horizon, 2.7 % in the Bg1 and Bg2, and steadily decreases to 0.1 % in the surface horizon.

Heavy minerals constitute about 0.04 % of the fraction 50-420 μm. Counts of 100 transparent grains per sample did not reveal significant trends with depth. The average composition is suggestive of strong weathering or preweathering: 51 zircon, 31 tourmaline, 10 rutile, 4 anatase, 4 others (including epidote, titanite, aggregates), and 38 opaque grains per 100 transparent grains.

The clay fraction

The main clay mineral is kaolinite, with soil chlorite and quartz, the latter increasing in the Apg horizons; a slight amount of feldspar; and a little goethite mainly in the Bg horizons. Kaolinite is dominant in the fine clay (less than 0.2 μm), and is the main component in the coarse clay. The kaolinite is b-axis disordered as indicated by the single X-ray diffraction peak about 0.445 nm tailing toward smaller spacings (index of crystallization zero).

The soil chlorite has a 1.4 nm basal spacing not expanding with Mg saturation and glycerol treatment, and only collapsing to 1.0 - 1.2 nm after K saturation upon heating to 400 °C (surface horizon: to 550 °C). Only the clay fraction in the lowest horizon shows an irregular diffraction band from 1.0 to 1.4 nm after K saturation,

PROBLEM HYDROMORPHIC SOILS IN NORTH-EAST THAILAND. 2

clay fraction would be 5 % for the lowest horizon, and 15 % for the surface horizon. This ratio is in good agreement with the estimates given above.

Ratios of the X-ray diffraction peak heights 0.7 nm/0.334 nm (kaolinite/quartz) decrease from more than 10 in the lowest horizon through 0.9 in most of the profile to 0.2 in the surface horizon. This difference cannot be explained by differences in contents alone, and part is probably due to the decreasing order and/or size of ordered domains in the clay minerals toward the surface.

Transmission electron micrographs of clay fractions (Fig. 4) also suggest pedogenic weathering of the dominant kaolinite. In the surface horizon this is 'pockmarked' with dissolution cavities and has rounded edges, whereas the micrograph from the lowest horizon shows angular hexagonal forms with little indication of dissolution.

Soil genesis

Hydrological aspects

The strongly seasonal rainfall distribution and the extensive, level surface of the low terrace give rise to seasonal water saturation and shallow flooding of Roi Et and similar soils. This is augmented by the very slow permeability of horizons below some 1 - 2 m depth and of the ploughpan. The ferric iron distribution in the soil, combined with observations under saturated conditions in similar soils elsewhere (Brinkman, 1977) indicates that in the upper horizons, iron is reduced and becomes mobile during the rainy season.

During the dry season, the water-table in non-irrigated areas slowly recedes to depths ranging from about 2 to more than 3 m. Capillary rise from the ground water into the root zone is probably negligible, therefore, as also suggested by the absence of unirrigated dry-season crops and by the virtual absence of weed growth between the rice stubble in the late dry season. These soils thus appear to be subject to seasonal water saturation, reduction and slow leaching by a solution containing ferrous iron, alternating with seasonal oxidation and, at least in the upper horizons, drying out.

Geogenesis

The parent material of the soils in the low terrace presumably was a preweathered sediment, the sand and silt fractions consisting essentially of quartz, with small to trace amounts of iron oxides, Na feldspars, zircon, tourmaline, rutile, anatase, etc.; and the clay fraction comprising mainly kaolinite with vermiculite, some quartz and goethite. (The clay fraction might originally have contained illite, that weathered to vermiculite by loss of K during an early phase of soil formation.)

The original soil material probably contained about 20 % clay, and had a cation exchange capacity of about 10 meq/100 g mineral soil (50 meq/100 g clay fraction).

Pedogenesis

Soil formation, particularly under the prevailing seasonally wet conditions, has caused drastic changes in the soil characteristics.

An early phase of hydromorphism appears at least to have redistributed iron oxides into (hard) nodules without enclosed argillans. Biotic perforation and homogenization by roots and, at least in part, by earthworms and termites produced a system of macropores to about 1.5 m depth. Clay translocation, which appears to have begun after the start of homogenization and ended during the present phase of hydromorphic weathering, has lowered the clay content of the surface horizons to about half of the presumed original figure, and caused maximal clay contents in the present Eg horizon (the upper part of a former textural B horizon). This may have taken place in a drier climate than at present, with little if any water saturation or reduction.

During the present phase of hydromorphism, biotic activity has continued, as shown by the presence of abundant worm casts in, and locally on, the annually ploughed surface. Iron mobilization (reduction) and redistribution has resulted in ferric nodules and mottles enclosing argillans. The greatest changes have occurred in the nature of the clay fraction.

Vermiculite has been aluminium-interlayered, resulting in the formation of a soil chlorite, with a little ferrous iron trapped in the interlayers; and part of the kaolinite and vermiculite has been decomposed. The consequent relative accumulation of clay-sized quartz was observed both in micromorphology and clay mineralogy. The low cation exchange capacity of the clay fraction caused by these changes has resulted in a cation exchange capacity of about 1 - 2 meq/100 g soil in the surface horizon, and about 5 meq/100 g in the deeper horizons. Also, the deeper horizons are about 70 % aluminium-saturated, the aluminium probably having originated from decomposition of the clay.

The clay mineralogy of this soil is in agreement with the hypothesis that long-continued ferrolysis (Brinkman, 1970, 1977) has dominated soil formation. The ferrolysis model postulates that during periodic reduction, in the rainy season, iron oxides are reduced by continuing microbial decomposition of organic matter; ferrous iron then displaces exchangeable cations, which are partly leached out. When air re-enters the soil in the dry season, exchangeable ferrous iron is reoxidized to ferric hydroxide and exchangeable hydrogen. This attacks the clay minerals, releasing aluminium and magnesium from the structure which then become exchangeable cations. Part of these are removed again in the next wet season, after displacement by newly formed ferrous iron. Silica from the weakened clay structure is partly dissolved and leached; and partly reprecipitated as amorphous silica, particularly in the surface horizons that dry out periodically. Possibly, some clay-sized secondary quartz may be formed as well. Part of the exchangeable aluminium displaced by ferrous iron is not leached out, but polymerized to macro-ions with low charge during iron reduction, and fixed as interlayer fragments in the vermiculite structure. This process traps some of the originally exchangeable cations, including ferrous iron, in the interior of the interlayers.

The low percentage as well as the inactive nature of the clay make the soil very susceptible to slaking and local surface wash. Puddling of this material for rice cultivation has produced a dense ploughpan, in spite of the continuing earthworm activity.

Consequences of this kind of soil development for use of the land include a hazard of aluminium toxicity for irrigated dryland crops with high fertilizer applications, or with rising ground water; a low buffering capacity for fertilizers and a narrow margin between aluminium toxicity and problems due to over-liming; and aeration problems in irrigated dry-season dryland crops.

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Problem hydromorphic soils in north-east Thailand. 3. Saline-acid conditions, reclamation, improvement and management

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Summary

Saline-acid conditions have developed in patches in the irrigated areas on the low terrace in north-east Thailand. There are also traditionally uncultivated, virtually barren, saline-acid strips adjoining higher terrace remnants, in spite of the excess of monsoon rainfall over evapotranspiration. Calculations show that the salts in the shallow groundwater of the low terrace may have originated from rainfall, but that salts in the main rivers are mainly derived from salt beds.

The local surface salinity, mainly of NaCl, is caused by continual evapotranspiration during the dry season and locally impeded leaching. The latter is due to a combination of a shallow water-table, slow vertical permeability and in some cases the slight elevation above the normal level of monsoon flooding.

The high salt concentrations in and on the soil surface bring originally exchangeable aluminium into solution, which lowers the pH. Soluble aluminium is toxic to plant roots even at low concentrations. In extreme cases even some ferric iron is dissolved at the soil surface.

Reclamation, improvement and management practices on these soils should include leaching, for example under two rice crops per year; judicious liming, to eliminate most of the exchangeable aluminium but not to exceed the small buffer capacity of these soils; and emphasis on paddy rice, both in the monsoon season and irrigated in the dry season.

If, however, dry-season dryland crops are to be grown, physical problems of different kinds may necessitate further land improvement and management practices. These include, principally, lowering and keeping down the water-table, for example by control of irrigation water losses from canals and ditches; ploughing or disking in chopped crop residues with added nitrogen; and locally, chiseling the upper part

of a dense subsurface horizon. Wherever salts and toxicity have not been eliminated by reclamation, the procedure of sowing in the sloping sides of ridges as early as possible in the dry season would protect the seedlings from salinity and aluminium toxicity, since irrigation would force the salts to the ridge tops, away from the young plants.

Introduction

In the rice-growing plains of north-east Thailand there are scattered small spots and strips of traditionally uncultivated, apparently saline, virtually barren land. In an experimental dry-season irrigation project in the area, extensive salinity and

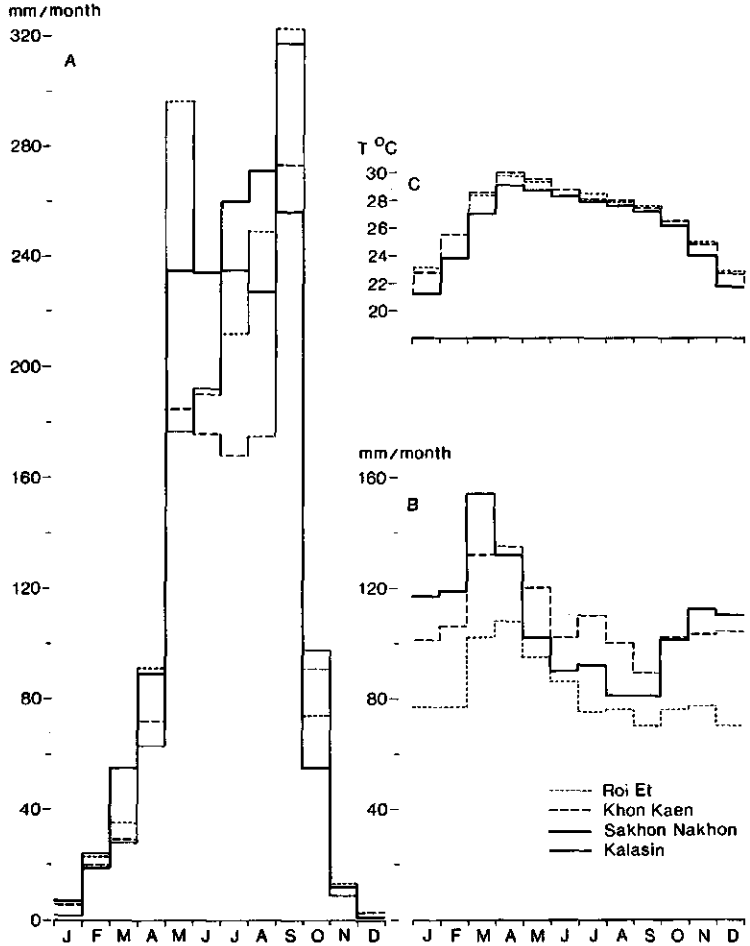

Fig. 1. A: monthly rainfall; B: potential evapotranspiration; C: temperature at three stations around Kalasin. Data recalculated from van den Eelaart (1972) and Wernstedt (1972).

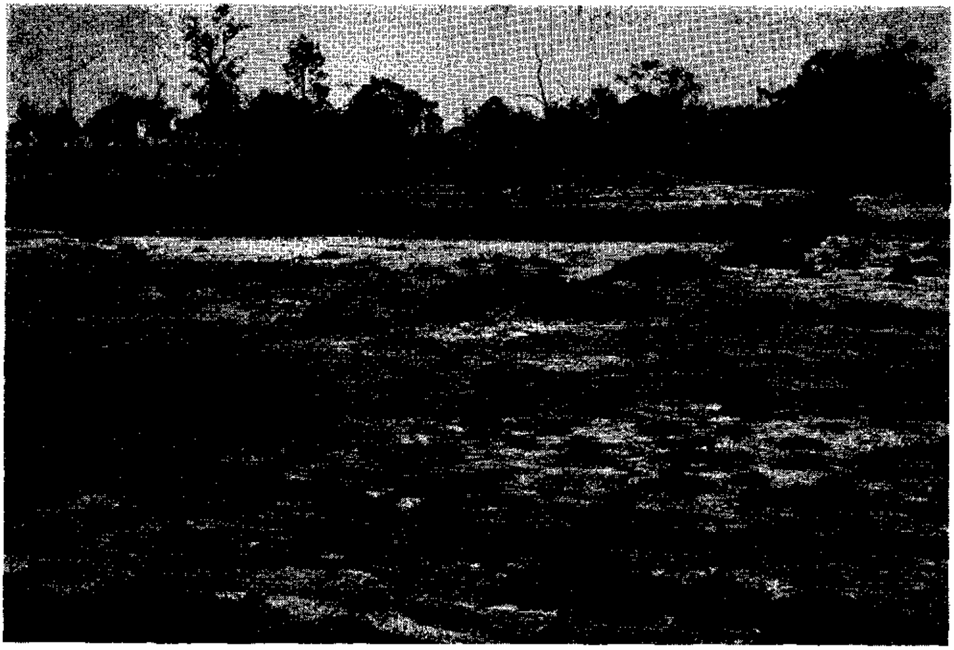

Fig. 2. Virtually barren, abandoned fields with saline-acid surface along the margin of a slight rise (background) in the low terrace.

Fig. 3. Saline-acid surface of virtually barren field. Pencil 14 cm long.

waterlogging hampered cultivation and lowered productivity. These problems were investigated during a short field study near Kalasin (Muang district). The environment and the main rice-growing soil of the area is described, and its genesis discussed, in companion papers (Brinkman et al., 1977; Brinkman, 1977). The present paper reports on the saline and saline-acid conditions encountered, discusses mechanisms of accumulation of sodium, calcium and toxic soluble aluminium salts, describes the range of problem soils caused by and encountered during the development of dry-season irrigation, and discusses means for their efficient reclamation and use.

Climate
Rainfall is extremely seasonal (Fig. 1A). More than 80 per cent of the annual total of 1400 mm falls in the five months May-September, and about 3 per cent in November-February. The mean annual temperature is about 26 °C, the coldest month is January (22 °C) and the hottest month April (30 °C), just before the start of the monsoon rains (Fig. 1C). Potential evapotranspiration is about 100 mm/month, with a maximum in March or April (Fig. 1B). The excess monsoon rainfall over potential evapotranspiration (May-September) is about 700 mm, the excess potential evapotranspiration over rainfall in the dry season (October-April) is 500 mm.

Land use
The dominant land use on the extensive, fine-loamy low terrace is paddy rice cultivation on the rain-water flooded land in summer, and fallow in winter. There are few scattered high trees, which survive the seasonal flooding with no apparent ill effects. Traditionally uncultivated, virtually barren areas (Fig. 2, 3) typically occur along the higher margins of the low terrace, adjoining outcrops of higher, more sandy, still older terrace remnants; and locally on slight rises in the low terrace. Fig. 4 is a schematic cross-section of these landforms. Non-saline, iron-rich perennial seepage strips with a grass and sedge cover were seen in a low part of the low terrace adjacent to a large area of sandy high terrace. The high terrace remnants

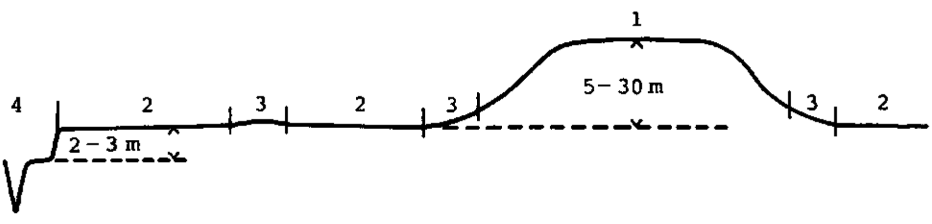

Fig. 4. Schematic cross-section near Kalasin.
1) Sandy, high terrace remnant.
2) Normal, non-saline low terrace including recently waterlogged and salinized parts.
3) Saline-acid, virtually barren higher patches and margins, part with perennially high water-table.
4) Recent river valley.

Table 1. Composition of average rain water, and of river waters in north-east Thailand.

	Ca^{2+} (mmol/litre)	Mg^{2+} (mmol/litre)	Na^+ (mmol/litre)	K^+ (mmol/litre)	Σ^+ (meq/litre)	Σ^- (meq/litre)	HCO_3^- (mmol/litre)	SO_4^{2-} (mmol/litre)	Cl^- (mmol/litre)	SiO_2 (mmol/litre)
'Average' rain[1]	0.002	0.0115	0.086	0.008	0.121	0.121	0.002	0.006	0.107	0.005
River, location[2]										
Chi, Khon Kaen	0.52	0.17	2.48	0.10	3.96	3.91	1.14	0.05	2.67	0.17
Mun, Ubon Ratchathani	0.27	0.09	1.74	0.07	2.53	2.47	0.69	0.02	1.74	0.18

1 From Garrels & Mackenzie (1971, Table 4.7). SiO_2 based on a single estimate.
2 Data after Kawaguchi & Kyuma (1969, Table 2.1).

originally were forested, and many are at present under dryland cultivation of various crops or under bush fallow.

Dry-season irrigation projects have started, which use river water impounded by large and small dams. Pilot experiments were made with several dryland crops, irrigated by basin and furrow methods, on land used for paddy rice in the monsoon season.

Regional salt balance

During and just after the monsoon season, when the soils are wet, the average actual

Table 2. Cation exchange characteristics and composition of soil extracts in non-saline, recently salinized, a

	Soil								
	exchangeable cations (meq/100 g)								pH
	Ca	Mg	Na	K	Al	H	sum	CEC[2]	H_2O
A. Non-saline area.									
Main observation pit (Brinkman et al., 1977)									
16–26 cm	0.5	0.0	0.1	1.0	0.6	0.3	1.6	2.1	4.7
96–140 cm	0.3	0.0	0.1	0.1	4.3	0.3	5.1	6.1	4.5
Groundwater									
Location 761-241, table IV-9 (summarized from USBR, 1971)									
0–18 cm	0.5	0.5	0.0		0.4	0.2	1.6		5.2
120–190 cm	2.2	0.6	2.7		0.1	0.3	5.9		5.6
Location 855–744, table IV-10 (summarized from USBR, 1971)									
14–23 cm	1.2	1.4	0.0		0.4	0.2	3.2		6.1
120–150 cm	2.8	1.9	0.0		0.7	0.1	4.5		5.9
B. Area salinized due to recent high water-table.									
Ridge with failing mung-beans;									
crest of ridge, upper few millimetres (field measurement)									<3
Upper 3 cm of ridge								0.5	5.5
Base of ridge, 5–15 cm depth								1.1	5.6
'White substance'									5.6
'Black substance'									6.5
C. Traditionally uncultivated, saline area.									
White crust with some soil material	0.7	0.1	nd[4]	0.3	0.3	0.3	1.7	1.6	3.7
1 cm soil below white crust								0.3	3.6
Black surface with rusty efflorescence, with 3 mm soil material	0.5	0.1	nd[4]	0.1	1.2	0.4	2.3	2.9	3.8

[1] Saturation extract in samples from USBR (1971); 1:2 soil:water extract in other samples.
[2] CEC: cation exchange capacity.
[3] Approximate values from conductivity data.
[4] Not determined dependably because of great excess of soluble sodium.

evapotranspiration from rice fields, forests and upland crop areas is probably about equal to the potential evapotranspiration. After the end of November, however, from the second month of the dry season onwards, the actual evapotranspiration is probably limited to the amount of rainfall. We therefore may add the potential evapotranspiration May-November and rainfall December-April to estimate the actual annual evapotranspiration: about 800 mm. Total annual rainfall is about 1400 mm; net excess rainfall would therefore be about 600 mm. The concentration of cyclic salts in rivers draining the area would then amount to about 2.3 (1400/600) times the concentration in rain water. We have assumed an average composition

traditionally saline, barren areas of the low terrace near Kalasin, north-east Thailand.

		Soil extract[1]											
		soluble salts (meq/litre)										pH	total salts (g/l)[3]
CaCl₂ (0.01 *M*)	KCl (1 *M*)	Ca	Mg	Na	K	Fe	Al	sum⁺	HCO_3	Cl	SO_4		
3.9		0.0	0.0	0.5	0.0	0.0	0.0	0.5	0.0	0.6	0.01—	5.0	0.03
3.7		0.0	0.0	0.5	0.0	0,0	0.0	0.5	0.0	0.6	0.00+	4.8	0.03
		0.0	0.0	1.1	0,0	0.0	0.0	1.1	0.0	1.1	0.0	6.3	0.06
4.9	3.9	2.0	0.2	4.2	0.2			6.6					0.4
5.4	4.2	0.5	0.5	8.7	0.0			9.7					0.6
5.0	4.4	1.0	0.0	0.4	0.1			1.5					0.08
4.6	3.9	0.5	0.0	0.4	0.0			0.9					0.05
4.9		32	9	8	13	0	0	62	0	36	33	5.5	4
5.0		1	1	1	2.5	0	0	5.5	0	2.5	1	5.6	0.3
5.1		46	9	40	10	0	0	105	2	41	77	5.5	7
5.2		12	1	14	13	0	0	40	1	48	3	7.1	3
3.6	3.6	14	3	3575	2	0	8	3602	0	3600	6	3.5	200
3.6	3.6	15	8	335	1	1	15	375	0	340	1	3.6	20
3.8	3.8	14	7	230	1	14	5	271	0	270	2	3.0	15

of rain-water, because data on salt concentrations in rain-water for north-east Thailand were not available to us. Even though calculations based on these assumptions are necessarily crude, it is clear from Table 1 that most of the salts in the Chi and Mun rivers are derived from other sources than rain. The dominant salts, NaCl and $CaCO_3$, probably originate from salt beds in the substratum of the plains (near Chaiyaphum from 60-70 m below surface, Takaya, 1974) and from limestone in the hill ranges on their western border, respectively. Mg, K and silica were probably contributed by the weathering of silicate minerals.

The sulphate concentrations, however, are in the range expected from rainfall alone. This last point indicates that the acidity and aluminium toxicity in the area, discussed below, do not originate from oxidation of pyrite, as in the acid sulphate soils of the central plain in Thailand or of the Mekong delta.

Local salt balance

The low terrace, which comprises very large, nearly level areas, lies above local river levels, and it would seem unlikely that salts from the rivers or from the deep groundwater would reach the shallow groundwater of the terrace soils. In the central part of the plain, however, near the Chi and between the Chi and Mun rivers, Takaya (1974) found that of the 27 wells to 15-20 m depth reported in or near the area underlain by the Salt Formation, about half are fresh, half are brackish or saline. Also, in half of the 18 boreholes he examined there are beds within 3 m of the surface that contain (little) chloride, for example near Khon Kaen and downstream (south) of Kalasin.

One hypothesis would be that the salts in the shallow groundwater would have been derived from former local salt beds. This would imply that there would have been virtually no through leaching, and that almost all of the net excess rainfall would have been removed over the soil surface. An alternative hypothesis would be that salts in the shallow groundwater may have been derived from remnants of salt in near-surface beds of the Salt Formation somewhere upstream (Sinanuwong & Takaya, 1974a, b). This would require lateral subsurface movement of salt-containing water over distances of at least several kilometres through a nearly level, seasonally flooded area without appreciable additions of monsoon rainfall on top of the groundwater. Neither of these hypotheses would explain the locally high sulphate contents found with the chloride in recently salinized patches (Table 2B).

A third hypothesis is that cyclic salts brought in by rain-water have accumulated in the shallow groundwater. This would explain the presence of sulphates in the salts at the surface. The groundwater at 1.6 m depth at the main site studied by us contains about 1.1 mmol NaCl/litre, whereas the soil solution would contain about 0.3 mmol/litre if all of the 600 mm net excess rainfall would leach through the soil. A concentration of 1.1 mmol salt/litre in the shallow groundwater could be explained by cyclic salts if only about 100 mm would leach through the soil annually. (This would imply lateral removal over the soil surface of about 500 mm of the monsoon rainfall.) With 800 mm total evapotranspiration, as estimated above, the concentration in the groundwater would then be 9 times that in average rain-water. However, an exclusively cyclic origin of the salts would not explain why the chloride/sulphate ratio in the groundwater seems to be higher than in average rainwater.

Both rain and salt beds may therefore have contributed to the salts in the shallow groundwater. Irrespective of the origin of the salts, the data indicate that even in the non-saline low terrace areas, much of the monsoon rainfall is removed laterally over the surface and that net downward leaching through the soil is small, about 100 mm or less per year. Data on saturation extracts in two other profiles of Roi Et series, summarized from USBR (1971) in Table 2A, also show salinity levels in excess of 0.3 meq/litre throughout the profiles and up to about 4 meq/litre in some horizons. The highest of these salinity levels appear to be correlated with the presence of very slowly permeable horizons.

Saline-acid (aluminous) conditions

The normal, non-saline soils have considerable exchangeable aluminium and a low pH (H_2O), but no soluble aluminium (Table 2A), as long as they are not fertilized. With large fertilizer applications, the total salt concentration rises and the soil pH drops (compare the pH in water, in $CaCl_2$ 0.01 M and in KCl 1 M, Table 1A). Where exchangeable aluminium exceeds about 40 % of the effective cation exchange capacity, sufficient soluble aluminium may then be displaced from the exchange complex by the fertilizer cations to cause toxic conditions for the crop.

Areas salinized due to a recent high water-table

In an experimental area recently provided with dry-sason irrigation water, the dry-season water-table had risen to less than half a metre below surface in some parts. Small areas were still waterlogged, with shallowly inundated patches (Fig. 5), when observed in the late dry season (March 1972). The rise in water-table appeared to be due mainly to losses in the distribution system (distributaries and field ditches) aggravated by the absence of an effective drainage system. (Seepage from the nearby reservoir, and from elsewhere, may also have had some effect.) The scattered high trees in the area with the recent perennially high water-table did poorly or were dying, possibly due to lack of oxygen in the root zone.

In this area, considerable problems were encountered in dry-season cultivation of irrigated dryland crops, especially with germination. Soil salinity within the crests of planting ridges was moderate, as illustrated in Table 2B. Thin salt crusts locally on the ridge crests, the absence even of weeds on the crests and their presence on the ridge flanks indicated that surface salinity may have been high, however. The soil extracts from samples taken at 0-3 cm and 5-15 cm depths in a ridge planted with mung beans show no soluble aluminium, but the field measurement of a pH less than 3 in the strongly saline upper few millimetres suggests that local aluminium toxicity may be present, aggravating the effects of the salinity.

Not only dryland crops, but also the early stages of paddy rice may be affected by aluminium toxicity. Urieli (pers. comm.) encountered failure of rice seedlings planted in a recently inundated field. In contrast, he found good growth of replacement seedlings planted a few weeks later in the same field that had been kept under

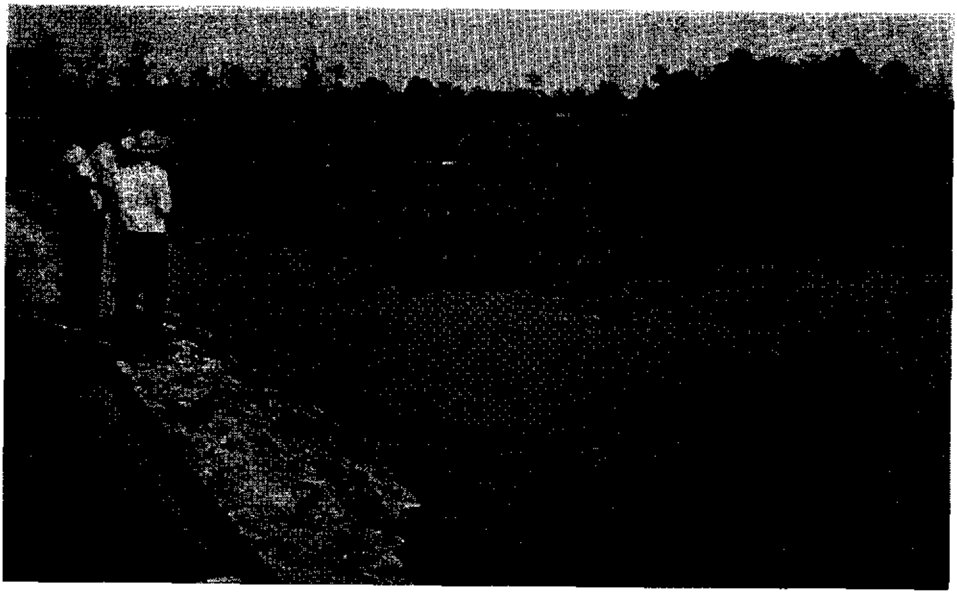

Fig. 5. Waterlogged and partly inundated field in irrigation area, with salt accumulation on field bunds especially along concrete-lined irrigation ditch.

water, presumably after progressive reduction had eliminated the toxic aluminium.

Not all white material seen at the surface in recently salinized areas is necessarily acid or harmfully saline. The analysis of the soil extract from the upper part of the ridge shows mainly gypsum, and the same applies for the white substance taken from the surface in another waterlogged area (Table 2B). The extract of a black substance scraped from the surface in a similar area shows that calcium chloride may also be present locally.

Traditionally uncultivated, saline areas

In the virtually barren parts of the slightly higher margins and rises of the low terrace, surface salinity is very high and NaCl is the dominant salt (Table 2C). In the extracts, contents of soluble Ca, Mg, K and SO_4 are similar to those in the recently salinized areas. In addition, however, toxic concentrations of soluble aluminium, and in some cases iron, are present in the salt crust as well as in the soil immediately below.

These virtually barren sites are not flooded in the rainy season and rain-water disappears mainly by surface runoff. At the same time, the adjacent main expanse of the low terrace is flooded, and the water-table in the margins and rises is very high. During the dry season, the water-table slowly drops in some of these sites. In others, it is perennially high due to lateral seepage from the adjacent higher, more sandy terrace remnants.

Interpretation

The mechanisms causing the different saline, acid and toxic conditions may be summarized as follows.

In the extensive level, non-saline low terrace, the soil solution leaching through during the rainy season is very dilute, so that cation exchange strongly favours ions of higher valence. The cations in the non-saline groundwater are dominantly Na, therefore, most of the Ca, Mg (and probably K as well) from the rain-water being retained in exchangeable form.

Where the water-table remains high during the dry season, capillary rise and evaporation of groundwater causes an increase in concentration and upward movement of NaCl through the soil profile. At high concentrations in solution, sodium is a relatively effective displacing agent for exchangeable potassium and divalent ions and, at very high concentrations, for trivalent aluminium as well.

In the recently salinized area, cation exchange during the passage of the salt causes the appearance of some calcium, magnesium and potassium in solution. As long as the salinity is not extreme, aluminium remains exchangeable and does not appear in solution. The salts appearing at the surface are mixed, therefore, Ca, Mg

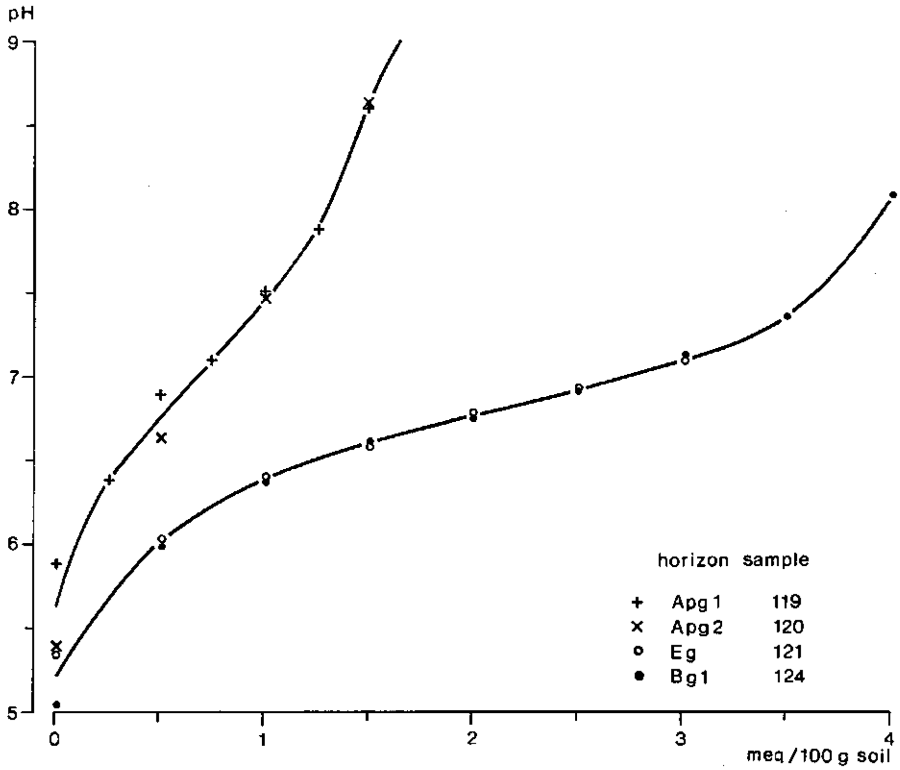

Fig. 6. Slow titration curve of Apg, Eg and Bg1 horizons. 48 h equilibration of 1 g soil in 10 ml solution, between 0 and 4 mmol NaOH/litre.

and K originating mainly from the exchange complex and Na from the groundwater. Only locally at the surface, where salt concentrations are very high, the extreme acidity suggests the presence of soluble aluminium in addition.

The presence of sulphate besides chloride is probably due to its occurrence in the groundwater in concentrations less than 0.1 meq/litre. The non-saline soil contains less than 0.01 meq sulphate/litre.

In the traditionally uncultivated, saline area, some exchangeable aluminium and hydrogen are brought into solution by the very high concentrations of soluble sodium. With further evaporation these, too, are concentrated and brought to the surface. The resulting extreme acidity causes the appearance of soluble ferric iron by dissolution of free iron oxides.

The calcium, magnesium and potassium concentrations in the extracts remain of the same order of magnitude with about a thousandfold increase in sodium chloride concentration, suggesting that their exchange from the soil horizons by sodium may be largely complete even after a few years of salinization. Precipitation of gypsum on high spots in the area may have kept the sulphate concentration from rising further with the rise in chloride concentration. No crystalline iron or aluminium sulphates were observed in X-ray diffraction photographs of even the most saline acid samples, and extracts are undersaturated with respect to Fe and Al sulphates. The extract of the black surface with rusty efflorescence is in equilibrium with amorphous ferric hydroxide. (Activity corrections for these estimates were made by the mean salt method, with the use of coefficients from tables in Robinson & Stokes, 1968; solubility and dissociation constants used were from van Breemen, 1973, and Vlek et al., 1974.)

Reclamation, improvement and management

Chemical aspects

Liming can eliminate the hazard of aluminium toxicity in non-saline surface soils. Applications of the order of 1 tonne $CaCO_3$ per hectare ploughed layer (2×10^6 kg) would neutralize a large part of the exchange acidity, which ranges from 0.6 to 1.6 meq/100 g soil in the surface soils measured. A slow titration experiment was done on the ploughed horizon, ploughpan and two lower horizons of the soil at the main observation site, an example of Roi Et series (Fig. 6). This shows that the surface horizons are neutralized with 1 meq base/100 g soil, and the deeper horizons with 3 meq/100 g. Buffering is very poor: with 1.5 meq base/100 g, the surface soil has a pH value above 8.5. There is a danger of over-liming, therefore, with probably ill effects on the availability of trace elements, such as zinc, and on the physical stability of the soils. Under-liming is safer than over-liming: once the exchangeable aluminium is less than about 40 % of the effective cation exchange capacity, no toxic concentrations of soluble aluminium need be expected even with relatively large fertilizer applications.

Liming as a possible remedy for extreme acidity and toxic concentrations of soluble aluminium (and iron) in saline surface soils should be considered with caution. Liming alone would not eliminate the strong surface salinity which is another cause of poor germination and growth of the irrigated crops in the dry season.

The surface salts in the recently salinized area could be removed by leaching, e.g. under rice cultivation, if the water-table in (open) drains would be kept low for as long a period as possible each year.

During leaching under inundation, either naturally in the rainy season or by surface irrigation, sodium salt concentrations decrease by probably several orders of magnitude. At these lower concentrations, sodium has a very low displacing efficiency for calcium and aluminium, so that especially the soluble aluminium will be adsorbed in the upper horizons during leaching of the salt. This may result in exchange acidities about twice those in the nonsaline soils, even after leaching.

For dryland crops, liming would be necessary to eliminate the aluminium toxicity caused by the very high exchange acidity in leached, formerly strongly saline soils even at low fertilizer concentrations. An initial application of 1 tonne lime/ha can be given in any case; further amounts of lime needed could be estimated by slow titration to pH 7, either by pH meter or by indicator solution. As in the case of non-saline soils, excess lime is expected to be harmful.

If dry-season dryland crops are to be grown in an area still containing acid salts, the crops should be sown as early as possible in the dry season, on the side instead of on top of ridges. Fertilizers should also be applied at the side of the ridges, and irrigation water levels during the first weeks after sowing should be carefully controlled to reach above the level of sowing but not above the tops of the ridges. This would tend to concentrate the salt and soluble acid in the surface of the ridge crests, away from the plants. Although this may be a new procedure for saline-acid conditions, it is a normal recommended method in saline or saline-sodic areas (Kovda et al., 1973, p. 327; Ayers & Westcot, 1976, p. 43-46).

For paddy rice, grown under natural inundation by monsoon rainfall or irrigated in the dry season, liming does not appear essential if seedlings are planted more than about two weeks after the start of inundation. After that time, microbial decomposition of organic matter left by the previous crop or vegetation will normally have reduced sufficient ferric oxides to ferrous compounds to eliminate the aluminium toxicity hazard. During iron reduction, hydrogen ions are consumed and part of the aluminium is hydrolysed and immobilized for the duration of the reducing conditions.

Physical aspects

Crops are at present being grown under rather unfavourable water-table conditions. Normally, the water-table should remain below the plant root zone and, to effect such a condition, a permanent system of deep drains would be necessary. Such a system, however, would require a considerable investment which may not be justified at the present time, when dryland cropping, as an alternative, may still be concentrated on the better drained soils of the higher terrace. Irrigation projects on the low terrace may then be assigned to double cropping of paddy rice.

If, however, it is considered necessary to develop the different soils of the low terrace for irrigated dryland cropping besides monsoon-season rice, the following set of recommendations may be helpful.

The water-table fluctuations may be partially controlled and the normal water-tables maintained at 50-60 cm below surface if the surface drains would be deepened to about 70 cm. The specific technical conditions that favour such a provisional solution are the high quality irrigation and groundwater which minimise the danger of salinity; the relatively low evaporation rates; the seeding on ridges; and the occurrence of a more or less compact soil layer at shallow depth that helps reduce deep percolation losses. The deepened surface drains could be given steep side slopes (2 to 3:1) to avoid land losses, but this entails that the drains will need to be partially re-dug each year at the beginning of the dry season.

The land should be cultivated in dry condition whenever possible, and while the water-table is at least about 0.5 m below the surface. One application of 500 to 1000 kg $CaCO_3$ per hectare should be given before ploughing. This could be repeated once after 2 or 3 years; no further lime should be applied generally except after estimation of lime requirement of specific areas. Instead of the traditional burning, chopped crop residues may be disked or ploughed in to shallow depth after broadcasting about 1 kg N per 40 kg of estimated dry weight of the crop residues. This is expected to raise the stability of the surface soil material. No subsoil material should be brought to the surface, because this contains a generally larger proportion of potentially toxic aluminium than the ploughed layer, and because the subsoil below the ploughpan appears to be generally porous and stable when undisturbed.

For specific kinds of problem soils identified below, the following individual recommendations apply in addition to the above.

On all non-saline land with groundwater at or near the surface at any time during the dry season or at a depth less than 0.5 m at the time of land preparation, either one or two successive rice crops per year may be grown until the groundwater table has gone down by control of irrigation water losses or the establishment of a drainage system or both. Land that is perennially wet due to seepage from adjacent higher areas is best left in its present state.

On other non-saline land with a dense, unstable, very slowly permeable ploughed horizon with a slaked surface, two successive rice crops could be grown with dry cultivation without puddling, and with ploughing in of chopped crop residues and added nitrogen, until the stability of the surface has been improved.

On other non-saline land with a dense, very slowly permeable subsoil horizon extending deeper than the usual thin ploughpan, the depth of this horizon should be estimated in a pit when the soil is moist or dry, or by penetrometer when the soil is wet. The upper part can then be chiselled when the soil is dry; a part should be left intact to minimize water losses under rice. Mixing in about 1 tonne $CaCO_3$ per hectare for every 20 cm chiselled below the normal ploughing depth would probably increase the effect.

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