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- RWANDA -

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PREFACE

Since 1975 the Soil Conservation Service of the U. S. Department of Agriculture has established five international committees for the purpose of critically evaluating and refining the taxa and definitions of the U. S. system of soil classification, Soil Taxonomy, for the soils of the lower latitudes.

In order to provide a forum for discussion of the issues under study by the various committees and to allow the examination of key examples of the soils under scrutiny in the field, the University of Puerto Rico initiated a series of international soil classification workshops. The first such workshop was held in Brazil in 1977 in cooperation with the Servico de Levantamento e Conservacao de Solos of EMBRAPA and concerned the classification of Alfisols and Ultisols with low activity clays. This was followed, in 1978 by a workshop in Malaysia and Thailand which was co-sponsored by the National Soil Survey of the Department of Agriculture of Malaysia and by the Land Development Department of Thailand and focused on the classification of Oxisols and low-activity-clay Ultisols. The third workshop was held in Syria and Lebanon in 1980. It was organized and conducted by the Arab Center for the Studies of Arid Zones and Dry Lands (ACSAD) and dealt mainly with the classification of Aridisols and with soil moisture regimes. Future workshops are planned for the Democratic Republic of the Sudan in 1982, and Chile and Ecuador in 1984. They will focus on the taxonomy and management of Vertisols and Andisols, respectively.

The first three workshops were largely funded by the U. S. Agency for International Development (AID) through grants to the University of Puerto Rico. Beginning with the Rwanda workshop, a new AID-sponsored program of the USDA Soil Conservation Service, the Soil Management Support Services (SMSS), provided most of the funds, in part through a grant to the University of Puerto Rico.

The Fourth International Soil Classification Workshop held in Rwanda in 1981 thus formed part of a comprehensive transnational effort to better adapt Soil Taxonomy to the edaphic conditions of the tropics and subtropics.

It addressed the classification of high-altitude Oxisols and Andisols in the tropics in general, and the mandates of the international committees on the classification of Oxisols (ICOMOX) and Andisols (ICOMAND) in particular.

The Rwanda workshop was a joint endeavor of the Institut des Sciences Agronomiques du Rwanda (ISAR), the Algemeen Bestuur voor Ontwikkelings Samenwerking (ABOS) of Belgium, the Soil Management Support Services of the USDA Soil Conservation Service, the University of Puerto Rico, and the Rijksuniversiteit Gent, Belgium. Major funding for the workshop was provided by AID through a PASA agreement (# AG/DSB 1129-5-79) with the USDA Soil Conservation Service and by ABOS.

The local organizing committee, composed of Rwandese soil scientists under the able leadership of Mr. Henri Neel of ABOS/Kigali, must be highly commended for the excellent logistic and technical preparation of the workshop. Appreciation is expressed to Mr. F. Iyamuremye, Director-General of ISAR, for his early support of the workshop and the willingness of ISAR to assume the responsibilities of the host institution.

The compilation of the proceedings was a joint effort of the University of Puerto Rico and SMSS. ABOS kindly agreed to print the proceedings on the part of ISAR as the publisher. The editors wish to thank the managing editor, Mrs. Sheila A. Oltz, who performed the complex task of editing the technical papers with diligence and competence.

The proceedings contain the papers presented at the workshop and complete descriptive and analytical data for the soils studied in the field. They constitute an up-to-date reference publication on the classification and characteristics of some important Oxisols and Andisols of tropical highlands.

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THE CONTEXT OF THE FOURTH INTERNATIONAL SOIL CLASSIFICATION WORKSHOP REPUBLIC OF RWANDA, JUNE 1981

A. Van Wambeke

This workshop deals with soil classification. Its objective is to review the effectiveness of the American soil classification system known as Soil Taxonomy. This workshop has an international dimension, although it concentrates on soils of the tropics.

There must be compelling reasons for having this gathering of soil scientists convened in the middle of Africa for two weeks, with expertise from all parts of the world to study soil profiles and discuss their classification.

The purpose of this presentation is to define our objectives. They are threefold: the first describes the context in which soils are placed in considering land use; the second deals with the objectives that classifications may pursue, especially in agronomic research and agricultural development; the third places the classification system, more particularly Soil Taxonomy, in a framework of international dimensions.

SOILS

Soils are studied primarily because of their importance as factors of crop production in agricultural development. Governments, as well as farmers, are mainly interested in the economic potential of land to produce outputs which in turn may contribute to their independence as nations or as individuals. The potentials of land to satisfy these needs differ widely from one soil to another. Soil survey and soil classification are serving the objective of measuring this potential and indicating the sites where the greatest potential can be found.

In developing countries the inherent site-specific properties of soils may be more important than in industrial nations. Developing countries often can rely only on the qualities of their natural resources to help them compete with their products in international markets. Detailed knowledge of the soil resources is a major key in planning rural development and strengthening the economies of less developed countries (LDCs). This is the final objective we have to serve.

Besides their action as land-use factors, soils function as protectors of the environment, serving as filters for water percolating through the profiles which replenish the hydrologic resources on which people are dependent. Destruction of soils through erosion may have disastrous effects on the quality of the environment in rural or urban areas.

Therefore, the most effective soil classification system in a planning perspective will be the one which describes soils in terms of qualities that are important for land use. Development planners are anxious to know where environmental constraints will be a barrier to development. Soil survey has to keep these questions in mind if the economic concept of land is the one which justifies its activities.

I am afraid, however, that in this workshop few discussions will be related to the economic importance of the criteria that are used in Soil Taxonomy. There are no soil classification systems as such which directly serve economic purposes. It is accepted that to accomplish this goal, several steps are necessary, some of which seem to deviate from the final economic objective. It is necessary to examine and explain to this audience the pathways that soil scientists are forced to follow.

The concept of soil that classification people deal with considers soils as a product of pedogenetic factors. It describes them as natural bodies making up the landscape. These can only be delineated on maps when their genesis is understood. For this reason mappable pedogenetic properties are of primary interest to soil survey. Without spatial expression, soil classification has little value, since it would only deal with point data. Soil Taxonomy places emphasis on genesis.

It is obvious that the information which soil classification has to provide to planners and decision makers will have to be different from that discussed in the previous paragraph. The soil classification system will have to take into account those properties which are important for conservation of land and the different kinds of uses. After selecting ped-

ogenetic properties, a system has to be incorporated or added to make the necessary interpretations possible.

What are the objectives that Soil Taxonomy has retained as priorities? Its title page states that it is a basic system for making and interpreting soil surveys. Therefore it has accepted the challenge to serve two purposes. The first objective is to recognize soils which can be mapped so that statements made about them have a spatial expression. In this context the names and definitions of taxa given to delineations on maps are such that the names carry the maximum of information related to properties which are important both for understanding the distribution of soils in the landscape and for making predictions on their use.

Soil Taxonomy has other characteristics. It differs from many other systems in that it provides taxa which are mutually exclusive: one soil may only belong to one class in the same category just as one pedon in the field can only be included in one delineation.

Soil Taxonomy serves objectives similar to those that common languages try to achieve: to transfer information by strict definitions from one object to another, from one soil to another. If such a language is not accurate, communications are broken, and the benefits of a great number of activities are wasted. To increase accuracy is one of the major objectives of this workshop.

AGRONOMIC RESEARCH AND AGRICULTURAL DEVELOPMENT OBJECTIVES

There are several approaches to agronomic research. One may analyze plant production as a function of several factors such as solar radiation, water supply, temperature, depth of soil, acidity or other qualities of land which contribute to plant growth. This analytical approach helps to understand the mechanisms and to identify the linkages which connect factors with products. Mathematical models help to predict productivity from such analyses. They contribute considerably to a better understanding of processes.

Another approach is to consider soils as "black boxes" which are taken as a whole and studied as such in relation to crop production. This

shortcut is an effective tool as an information base for development action where factor analyses models are not immediately operational. Soil Taxonomy is a system which should provide units that are uniform enough to expect similar performances or behavior. One of the objectives of this workshop is to refine Soil Taxonomy to serve this purpose more effectively. Less-developed countries cannot afford to duplicate experiments which have already been conducted on similar soils; they must take advantage of work accomplished in other parts of the world.

Some rules will have to be followed in our discussions.

The structure of the system is the result of many years of testing of soil properties against the characteristics of more than 10,000 soil series in the United States. Limits between taxa have been tailored to the variability of soil properties as they are observed in the United States. However, little experience could be gained on the properties of soils in tropical areas, hence the interest in consulting soil scientists in the tropics in order to amend and complete soil information and incorporate it into Soil Taxonomy. The system, however, was originally developed as a national system built on a rigid framework imposed by class definitions which take into account the experience of soil surveyors working in the U.S.

Soil Taxonomy endeavours to be accurate and precise, and does not allow flexibility in the definition of its taxa. Inaccurate definitions would defeat the purpose of technology transfer. Flexibility can be introduced when naming map units in legends. The rules of how to define these mapping units are explained in a new draft of the Soil Survey Manual. At any rate, mapping operations do not directly delineate taxonomic units; a sharp distinction is made between taxa and map units.

INTERNATIONAL DIMENSIONS

Soil Taxonomy is often placed in an international perspective. It is not intended, however, to replace national soil classifications. It can be used as a reference system linking soils among nations who wish to do so. It is perfectly acceptable that soils are identified by two names:

one which serves local purposes and one which relates them to internationally accepted classification systems.

Soil characteristics which will be discussed at this workshop will mainly deal with properties that do not occur frequently in the U.S. The intent is to draw from experiments done elsewhere. This adds an international dimension to our task. However, only proposals can be made to the Soil Conservation Service for testing. They do not carry any official character until they have been accepted in writing and by publication in the USDA National Soils Handbook for use in Soil Taxonomy. Dr. R. Arnold will give us in his presentation at this workshop more detailed information on the subject. At present, the 1975 publication of Soil Taxonomy with the May 1978 amendment is the only official document which should be referred to in publications.

This workshop is the fourth organized in its series. The first workshop was held in Brazil and concentrated on the characteristics of soils with low activity clays. The second workshop in Thailand and Malaysia considered soils in the humid tropics. The third dealt with problems in the classification of soils of arid regions. This workshop is called to refine definitions of taxa in the orders of Oxisols, Entisols and Ultisols.

In advance we thank all the participants for accepting the invitation to come to Rwanda, thus making a valuable contribution to soil classification as a tool for more effective agricultural development.

UTILIZATION OF SOIL RESOURCE INVENTORIES IN AGRICULTURAL DEVELOPMENT

R. Dudal, G.M. Higgins and A. Pécrot

ABSTRACT

According to FAO projections, agricultural production will have to increase by 60% to support the world's population by the year 2000. It is estimated that about one-third of such increase will come from expansion of arable land. Large tracts of potentially arable lands are still available but they are unevenly distributed between countries and their suitability for specific crops may differ widely. There is therefore an urgent need for inventories of land resources at the country level.

Soil resource inventories usually provide the basis for land suitability assessment, but other factors of the environment, mainly the climate, must also be considered. The FAO/UNESCO Soil Map of the World, overlain by a climatic inventory expressing lengths of growing periods, provides a physical basis for assessment of the potential agricultural use of land resources in the developing world. This assessment has been used to estimate the population-supporting capacities of these land resources.

RÉSUMÉ

Suivant les prévisions de la FAO, la production agricole devra augmenter de 60% d'ici l'an 2000 pour nourrir les populations du globe. On estime qu'environ un tiers de cette augmentation proviendra de la mise en culture de nouvelles terres. De grandes superficies de terres aptes à l'agriculture sont encore disponibles mais elles sont inégalement distribuées entre les pays et leur aptitude pour les différentes cultures est très variable. Il faut donc d'urgence effecteur l'inventaire des ressources en terres au niveau des pays.

Les inventaires des ressources en sols sont souvent utilisés comme base dans l'évaluation de l'aptitude des terres, mais les autres facteurs de l'environment, et particulièrement le climat, doivent également être pris en considération. La Carte mondiale des sols FAO/UNESCO, sur laquelle on a surimposé un inventaire climatique exprimé en longueurs de la période de croissance, a fourni la base physique pour l'évaluation du potentiel agricole des ressources en terres des pays en voie de développement. Cette évaluation a ensuite été utilisée pour estimer les densités de populations que ces terres peuvent supporter.

INTRODUCTION

According to FAO projections (AT 2000; FAO, 1979a), agricultural production will have to increase by 60% in the next 20 years to sustain the world's population. It is estimated that 72% of this increase in production will need to come from intensification of existing agriculture and 28% from a further expansion of the cultivated area. For the developing world, such expansion of arable land will result in an increase of approximately 200 million hectares of cultivated land out of which 48 million will be under irrigation. Expansion of rainfed agriculture will take place mainly in Africa and Latin America, while irrigated agriculture will expand chiefly in the Far East.

Although estimates indicate that large tracts of potentially arable lands are still available to meet these requirements, they are at too small a scale to permit practical conclusions with regard to planning and implementing future land use at the country level. The distribution of available land resources varies greatly between and within countries; the suitability for specific crops and management properties of these lands may differ widely. There is an urgent need for inventories of resources at country level.

LAND EVALUATION

The concept of land evaluation is wider than the appraisal of soil

characteristics to which previous soil suitability classifications were sometimes limited. Land is defined geographically as a specific area, the attributes of which relate to soils, geology, hydrology, plant and animal population, climatic conditions and the results of past and present human activities, to the extent that these attributes exert a significant influuence on present and future uses (FAO, 1976).

The methodology used to assess the agricultural potential of land resources is based on six principles now increasingly used in field projects, which are described in the Framework for Land Evaluation (FAO, 1976). Briefly, these principles emphasize that land suitability is only meaningful in relation to a specified use on a sustained basis, taking into account economic aspects such as simple comparisons of inputs and outputs for more than one kind of suitable use.

Soil is an environmental factor that is stable enough to form a base for land evaluation and at the same time is sufficiently flexible to be influenced by man for improvement or degradation (Vink, 1975). Soil resource inventories are therefore a basic data for the evaluation of land suitability, but are only one of the important aspects considered in land evaluation procedures.

The needs for additional information in the years to come will include inventories of the different components of the land: soil, water, relief, geology, landforms, vegetation, land use, soil degradation and climate-matched to crop performance.

Soil Resources

On a global scale the FAO/UNESCO Soil Map of the World (FAO, 1971-80) provides an overall basis for the inventory of land resources. The legend comprises 106 soil units which have been clustered into 26 major groupings (FAO, 1974).

The map units are associations of soils which occur within the limits of physiographic entities. Each association is composed of a dominant soil and associated soils, the latter covering at least 20% of the area of the mapping unit. Important soils which cover less than 20% of the areas are added as inclusions. The textural class of the dominant soil and the general slope class are given for each association. Important land

characteristics, not reflected by the soil associations themselves, are shown as phases, such as the occurrence of salinity or of hard layers at shallow depths. Areas of dunes, shifting sands, salt flats and rock debris are shown separately.

In comparison to other global soil maps, the FAO/UNESCO inventory is unique in that it is the result of wide international cooperation and is based--to the extent possible--on actual survey information and correlation. The reliability of the map differs from one area to another depending on the accuracy and detail of the material used for its compilation. Table 1 shows the sources of information available and provides a picture of soil survey coverage in different parts of the world. Class I areas are systematic soil surveys in which the boundaries are based on field studies; for Class II, boundaries are derived from physiographic data, while Class III information is derived from the interpretation of general data on land forms, geology, climate and vegetation.

Table 1. Soil survey coverage (1974).

	Class I	Class II	Class III
	%		
Africa	7.5	38.0	54.5
Asia	19.0	49.0	32.0
Australasia	11.0	61.0	28.0
Europe	76.3	23.7	-
North and Central America	28.0	16.0	56.0
South America	14.6	45.9	39.5
World	21.0	40.0	39.0

It appears that only about a fifth of the world's soils have actually been surveyed. The highest percentage of survey coverage is found in Europe; the lowest in Africa.

These figures clearly point to the need for an intensive program of soil resource appraisals, especially in areas where an expansion of arable land is envisaged.

A minimum program is the preparation of soil maps at a scale of 1:1,000,000. These exploratory types of surveys provide an overall view of the soil resources of a country and allow for the delineation of areas with development potential which qualify for investigation at the reconnaissance scale (in the order of 1:250,000). In turn, these reconnaissance scale surveys provide the necessary information to select specific project areas which deserve detailed study. It should be stressed that soil surveys should no longer be confined to classifying soils and drawing soil boundaries, but need to consider all the ancillary studies which assist in the interpretation of soil maps. The task of the soil surveyor is not only to map soils but more and more to interpret the data for interdisciplinary assessments of the agricultural potential of the land, taking into account other attributes, such as climate, land use, farming systems and accessibility.

As the general theme of this meeting is related to a number of soil units of the FAO legend of the Soil Map of the World, it is of interest to give an estimate of the extents of these units in the major regions of the developing world (Table 2).

The actual extents of the low activity clay soils is in fact somewhat larger, as soil units such as Plinthic Luvisols, which usually have a low CEC, and Ferralic Arenosols, are not included in the table. These soils are widespread in the developing world. They have specific limitations, other than a low CEC, related to their particular characteristics, and require appropriate management practices.

Climatic Resources

The climatic inventory used in assessing land suitability takes into account the crop's moisture and temperature requirements. The inventory, therefore, refers to the growing period--that is, the number of days when water is available for crop growth, and the temperature regime during this period (FAO, 1978). The growing period is the continuous period during the year, from the time when rainfall exceeds half potential evapotranspiration (calculated by the Penman method) until the time when rainfall falls below half potential evapotranspiration, plus the number of days re-

Table 2. Extents of Ferralsols, Low Activity Clay soils and Andosols in the developing world.

	Ferralsols	Acrisols	Ferric Luvisols	Ferralic Cambisols	Nitosols	Andosols	Total L.A.C. soils
	1,000 ha						
AFRICA	322,495 (10.71)[a]	92,575 (3.07)	138,535 (4.60)	16,082 (0.53)	98,535 (3.27)	5,424 (0.18)	345,727 (11.47)
S.W. ASIA	-	2,090 (0.31)	-	-	-	59 (0.01)	2,090 (0.31)
S.E. ASIA	15, 896 (1.77)	196,659 (21.91)	19,778 (2.20)	9,444 (1.05)	37,534 (4.18)	7,353 (0.82)	263,415 (29.34)
S. AMERICA	425,747 (24.05)	290,146 (16.39)	48,249 (2.73)	5,435 (0.31)	36,519 (2.06)	30,421 (1.72)	380,349 (21.49)
C. AMERICA	776 (0.29)	14,951 (5.50)	3,232 (1.19)	-	11,590 (4.27)	13,526 (4.98)	29,773 (10.96)
TOTAL	764,914 (11.54)	596,421 (9.00)	209,794 (3.16)	30,961 (0.47)	184,178 (2.78)	56,783 (0.86)	1,021,354 (15.41)

[a]Figures in parentheses indicate percentages of regional total land areas.

quired to evaporate an assumed 100 mm of soil moisture reserve.

Length-of-growing period data are calculated and zones with similar lengths of growing period are delineated by constructing isolines at intervals of 30 days (e.g. 90-119 days, 120-149 days, 150-179 days, etc.). Zones with a humid period are designated as normal. Zones without a humid phase and consequently unable to meet full crop water requirements from rainfall, are designated as intermediate. An additional isoline for the growing period of 75 days is also included to cover possible interpretations for pearl millet in drier areas.

For each zone thus delineated by the length of growing period isolines, average values of major climatic elements (radiation, day and nighttime temperature, etc.) characterizing the growing period, are calculated for subsequent potential biomass and yield calculations.

Suitability Assessment

The suitability assessment is made by matching the soil and climatic inventory with the soil and climatic requirements of eleven alternative crops with various levels of input assumptions. Such proved to be difficult because of the lack of precise information on soil requirements of various crops in specific climatic conditions.

The climatic suitability assessment for each crop was defined in terms of a percentage range of the maximum attainable yield without constraints. Growing period zones, capable of yielding 80% or more of the maximum yield attainable, were classified as very suitable; zones yielding less than 80% to 40% as suitable; zones yielding less than 40% to 20% as marginally suitable and zones yielding less than 20% as not suitable. This activity results in a climatic crop suitability assessment of each main climate and length of growing period. The yields so calculated are for high input/ideal soil conditions. Low input yields are computed as 25% of the climatically potential yield under high inputs.

The actual land suitability is obtained by superimposing the soil assessment on the climatic appraisal. If the soil unit largely meets the crop's soil requirements no change is made in the climatic suitability assessment. If the soil unit only partly meets the crop's soil requirements, i.e. if the soil does not allow the full climatic yield potential

to be attained, the climatic suitability assessment is downgraded by one class. Areas of soils which fail to meet the crop's minimum soil requirements are classified as not suitable since severe soil limitations override the climatic attributes.

THE RESULTS FOR AFRICA

The data for Africa are given here as an example of the results being obtained (FAO, 1978a).

Of the total area (3,011 million hectares) of the African continent, 52.0% (1,566 million hectares) is too dry to reliably support food production under rainfed conditions; 10.4% (313 million hectares) suffers from restricted choice of crops because of excessive humidity or cool temperatures. Hence only 37.6% (1,132 million hectares) is climatically suited to a wide range of rainfed crop production. After application of the soil constraints only 24.4% (735 million hectares) of Africa's land area is variously suited for the production of one or more crops with low input level assumptions. With high input level assumptions, this figure is reduced to 23.4% (705 million hectares) due to slope limitations for mechanization.

The need to qualify the concept of arable land is clearly illustrated by the suitability of Africa's lands for different crops. With high inputs, the humid warm tropical lowlands could provide 415 million hectares for cassava production or 428 million hectares for sweet potatoes (6 million and 0.8 million hectares are used respectively for these crops at present). In the drier areas of the warm tropics, possibilities exist for growing maize on 459 million hectares, or cotton on 334 million hectares, or soybeans on 420 million hectares (21 million, 6 million and 0.3 million hectares are used respectively for these crops at present). Only 29 million hectares are suitable for the production of wheat. The areas suitable for different crops do however overlap considerably in certain cases, e.g. maize and soybeans. The above figures therefore are not additive but show the various alternatives that can be envisaged.

Statistically recorded cultivated lands in Africa amount to 195 mil-

lion hectares, i.e. 26 percent of the potentially arable area. Taking into account fallow periods employed for moisture storage, pest and disease control, weed control or fertility requirements, it is estimated that only 108 million hectares are harvested annually. Present day African yields are between a third and a fourth of those that can be obtained under high inputs. Only 2 percent of the cultivated lands south of the Sahara are irrigated. These data reflect the considerable scope for intensification and expansion of agriculture which exists in Africa.

Using such data, a Food Plan, for ensuring food self-sufficiency in Africa by 1990, has been prepared (FAO, 1978b). The Plan proposes a food production increase derived from a 53% expansion of agricultural area and a 47% increase in yield. This would require an additional 31 million hectares of land suitable for crop production and a substantial increase of agricultural inputs.

Such recommendations are made for the continent as a whole but cannot be applied uniformly at country level where their application is dependent on land resources availability in the respective countries.

Soil Degradation Assessment

Productivity potential of land is limited by physical conditions, mainly soil and climate, and the use and management applied to the land. A type of management which is exceeding the limits of such potential will result in the long run in land degradation and progressively decreased productivity.

In certain areas, more land is being lost than can be gained by the further expansion of new agricultural areas. FAO, in cooperation with UNEP, is conducting a general assessment of land degradation hazards including desertification. It is estimated that Africa will suffer a sizeable loss of its productive capacity through soil loss if conservation measures are not introduced and maintained. In certain countries the situation is critically serious. Existing and future pressures on the land point to an urgent need for an active soil and water conservation policy. If soil degradation were allowed to proceed at the same rate as it is now, the 200 million hectares of new lands which should be put into production

by the year 2000, would only just compensate for the amount of soil lost up to that year. Projections of production potential and land requirements for increased food production would be very deceiving if the effects of degradation were to be ignored.

Population-supporting Capacity

While sufficient arable land may be available at a regional level, its distribution and quality varies greatly between and within countries. Land resources are fixed and cannot be moved. Some areas are better endowed than others and there is an urgent need to interpret and inventorize these resources by area. FAO and UNFPA are presently conducting a study of the land resources of developing countries in terms of potential population-supporting capacities.

The methodology developed and used in this study is based on interpretation of the land resources inventories created by the agro-ecological zones project. From these, areas required for irrigation production, fallow periods and nonagricultural use are deducted to give data on the amount of land annually available for rainfed production. This in turn, is interpreted according to climate, soil, texture and slope conditions, under three levels of input assumptions to predict the food-producing capacity and hence the population-supporting capacity of each agro-ecological zone in each country.

Under low input without conservation measures and retaining the presently grown mixture of crops, the potential population-supporting capacity in Africa is 0.25 persons per hectare. Under the intermediate level of input assumptions, the figure is 0.77 and under high input the figure increases to 1.54 persons per hectare. The intermediate and high input level supporting capacities include reduced land losses from degradation through the assumed introduction of conservation measures. It is of interest to note that the 1976 population density in Africa was 0.14 person per hectare, while for the year 2000 it is projected to be 0.29 person per hectare.

Comparing country population-supporting capacities with country populations projected for the year 2000 provides an indication of the number

of countries which will be critical in the future, i.e. where the land resources will not support the populations projected to be living from them at that time. Under conditions of low input, without conservation measures nor modification of the cropping pattern, the analysis shows that some 28 countries in Africa will be in this critical situation by the year 2000. With conservation measures and optimal cropping pattern, this number of critical countries would be reduced to 4 (FAO, 1980).

CONCLUSIONS

Soil resource inventories and interpretations provide basic information for the evaluation of land suitability but are only one important aspect to be considered. Equally important is the need to take all attributes to land (including climate and socioeconomic conditions) into account in determining land potentials.

In addition to providing a physical base for selecting optimum land use, soil and climate inventories provide a reliable framework for the transfer of technology and the effective use of inputs. They are also required for assessing investment possibilities, establishing population policies and orienting government planners in their food self-sufficiency efforts and their strategy for agricultural development.

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RESEARCH ON THE TRANSFER OF AGROTECHNOLOGY BASED ON SOIL TAXONOMY

An Overview of the Benchmark Soils Project

F.H. Beinroth

The Benchmark Soils Project was established in 1974 to demonstrate the viability of a soil classification based approach to the transfer of agroproduction technology in the tropics. This should increase the efficiency of agronomic research through its wide geographical diffusion and thus accelerate the pace of agricultural development in the developing countries. The project comprises two companion research contracts awarded to the Universities of Hawaii and Puerto Rico in 1974 and 1975, respectively, by the United States Agency for International Development. While the project of the University of Puerto Rico terminated in December 1981, the project of the University of Hawaii will conclude its work in June 1983.

As the first comprehensive study of its kind, the Benchmark Soils Project (BSP) ventured to scientifically establish the transferability of agrotechnology, particularly soil and crop management experience. Central to this effort is the benchmark soils concept and the soil family as defined in the U.S. system of soil classification, Soil Taxonomy. The intent of the soil family is to group together soils that are relatively homogeneous in properties important to plant growth. Consequently, comparable phases of all soils of a family should have a common and predictable response to management practices, correlative input-output characteristics, and similar crop production potential. The transfer hypothesis underlying the BSP is derived from these principles: empirical agroproduction experience gained with a soil of a particular family can be transferred and extrapolated to all other comparable members of that family, irrespective of their geographic occurrence.

The general aim of the project is to experimentally and statistically validate this hypothesis. The primary research objectives are:

1. To demonstrate that soil management and crop production knowledge can be transferred among tropical countries on the basis of soil fami-

lies as defined in Soil Taxonomy, and

2. To establish that the behavior of tropical soils and their potential for food production under various levels of management inputs can be predicted from soil taxonomic units.

A secondary objective is to expand the knowledge base for the management of three families of tropical soils of particular concern in the economic decision environment of small farmers in less-developed countries.

The basic research strategy of the project is to conduct a series of identical experiments in a network of soils belonging to the same family, monitor crop performance and weather conditions, and statistically compare response to management and yields. These so-called transfer experiments are complemented by pragmatic soil and crop management experiments and variety trials.

Three contrastingly different soil families representing three distinct agroclimatic zones of the tropics were chosen for experimentation: the clayey, kaolinitic, isohyperthermic Tropeptic Eutrustox; the thixotropic, isothermic Hydric Dystrandepts; and the clayey, kaolinitic isohyperthermic Typic Paleudults.

The project has established a research network that comprises 23 experiment sites in Brazil, Cameroon, Hawaii, Indonesia, the Philippines, and Puerto Rico. Collaborating with the project are the Empresa de Pesquisa Agropecuaria de Minas Gerais (EPAMIG) in Brazil, the General Delegation of Scientific and Technical Research (DGRST) in the Philippines, and the Soil Research Institute (SRI) in Indonesia.

The successful completion of the University of Puerto Rico project provided the first concrete results of the test of the transfer hypothesis. Eighty-one transfer experiments were conducted in Tropeptic Eutrustox at six locations in Puerto Rico and Minas Gerais, Brazil. As at the other sites of the network, these experiments were highly controlled, drip-irrigated fertility trials with phosphorus and nitrogen as variables and maize as the test crop. They were specifically designed to generate the data base for the statistical analyses.

The field data of the transfer experiments were statistically evaluated with three different techniques developed under the auspices of the BSP: the P-statistic, the confidence interval procedure, and a graphical

method. The results with the confidence interval procedure and the graphical method provided strong positive evidence for transferability. The results with the P-statistic were less conclusive but not negative. The graphical method was particularly illustrative as it allowed an instant visual appraisal of the transferability of management practices. The comparison of predicted and observed response surfaces showed that, if certain site variables are considered, fertilizer response at a new site can be predicted on the basis of experiments conducted at other sites with the same soil family essentially as well as by an experiment conducted at the new site.

On balance, the statistical studies yielded a qualified validation of the postulated transfer hypothesis and, by implication, of the concepts of benchmark soils and the soil family. In view of the complexity of the conjecture under study and considering the difficulties encountered in its experimental and mathematical corroboration, these results are very reassuring.

Moreover, the agronomic results of the project demonstrate that soil families as defined in Soil Taxonomy do indeed provide groupings of soils that have relative homogeneity in properties important to plant growth, common and predictable responses to management practices, and similar crop production potential and thus stratify the agroenvironment into distinct niches of agroproduction. This is evidenced, for example, by the very similar maximum yields obtained in Puerto Rico and Brazil with comparable inputs, the absence of response to potassium at both locations, and the fact that one specific variety of maize performed best in the two countries.

The combined analysis of larger sets of experiment data still being accumulated by the University of Hawaii project for three distinctly different families of Eutrustox, Hydrandepts and Paleudults will be particularly useful in further validating the soil family concept. Even a casual interfamily comparison of data obtained so far shows that the three soil families are characterized by distinctly different patterns of soil behavior. The P-isotherms, for example, which are in large measure conditioned by soil family characteristics, are markedly different for the three soil families but very similar for all soils of the same family.

The highest mean maize yields were about 9,000 kg/ha for the Eutrustox

in Puerto Rico and Brazil, 7,000 kg/ha for the Hydrandepts and 6,700 kg/ha for the Paleudults. Although these yields are not vastly different, the fertilizer inputs necessary to achieve them definitely are. Whereas the Eutrustox required only about 40 kg P/ha to obtain these yields, the Dystrandepts needed 150 kg/ha and the Paleudults 100 kg/ha. Furthermore, the Dystrandepts and Paleudults required substantial applications of potassium and lime which were not needed for the Eutrustox. The soil management technology developed for Eutrustox is therefore clearly not applicable to either Dystrandepts or Paleudults, reflecting the soil-specificity of agrotechnology transfer as implied in the transfer hypothesis.

The scientific feasibility of applying the benchmark soils and the soil family concepts to the process of agrotechnology transfer in the tropics has far-reaching implications of consequence to agricultural development in LDCs. As the project results indicate, the stratification of the agroenvironment into distinct niches of agroproduction as provided by Soil Taxonomy, in conjunction with the transferability of soil-specific experience with fertilization, cropping systems, erosion control measures, water management, etc., can be utilized to effectively reduce the cost and magnitude of agricultural research in LDCs. This constitutes a viable mechanism and framework for expediting the wide diffusion of agroproduction technology which will help to minimize duplicity of effort and result in economy of thought and economy of action.

The rational utilization of the benchmark soils concept in the process of agrotechnology transfer, in combination with a minimum of site-specific research for local adaptation, can make a significant contribution to ameliorating the depressing prospects of food deficits in the LDCs by accelerating the pace of their agricultural development. In realization of this fact, the U.S. Agency for International Development recently approved a follow-up program to the Benchmark Soils Project which has been named the International Benchmark Soils Network for Agrotechnology Transfer, IBSNAT, and will be initiated by the University of Hawaii in collaboration with the University of Puerto Rico in mid-1982. This endeavor is designed to demonstrate, in an operational network, the steady flow of agricultural technology from research sites to farmer fields in the tropics and subtropics.

For a more detailed account of the Benchmark Soils Project and its rationales and results, the reader is referred to the publications cited below which also contain extensive bibliographies.

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THE OXISOLS OF KENYA

F.N. Muchena and W.G. Sombroek

ABSTRACT

Oxisols cover only a minor part of Kenyan land surface. They occur on a variety of physiographic positions and are developed on a variety of parent materials. They are also found in varying present-day climates. Most of them are found on plateaus, gently dissected older peneplains ("uplands") and non-dissected erosional plains. Parent materials may be Precambian Basement System rocks, Tertiary volcanics or Cenozoic unconsolidated sediments.

Oxisols in Kenya are found in udic, ustic and aridic soil moisture regimes and in isothermic and isohyperthermic soil temperature regimes. Contrary to what might be expected, their occurrence in udic and ustic conditions is restricted. Most of them do occur in present-day torric climates. They are found on old, stable land surfaces, that apparently have been subjected to humid climates in the past (Pliocene and/or Pleistocene).

Physical and chemical characteristics of these soils largely depend on the nature of the parent material from which they are developed. They have subangular blocky to porous massive structures and a high structure stability. The CEC-clay values (NH_4OAC at pH 7, organic matter corrected) are mainly between 6 and 16 me/100 g clay and the silicate clay minerals are predominantly of the Kaolinitic type.

For all Oxisols mapping units of a number of recent reconnaissance soil surveys carried out by the Kenya Soil Survey, those characteristics thought to be significant for soil classification purposes (averaged over several profiles) are presented in tabular form, to facilitate comparison.

INTRODUCTION

Kenya stands almost exactly astride the Equator. It lies between 4 degrees 20' S and 4 degrees 45' N latitude and 34 degrees and 41 degrees 45' E longitude. It stretches from the western shores of the Indian Ocean to Lake Victoria in the West. Its total area is 583,000 square kilometres of which 569,000 square kilometres is land area.

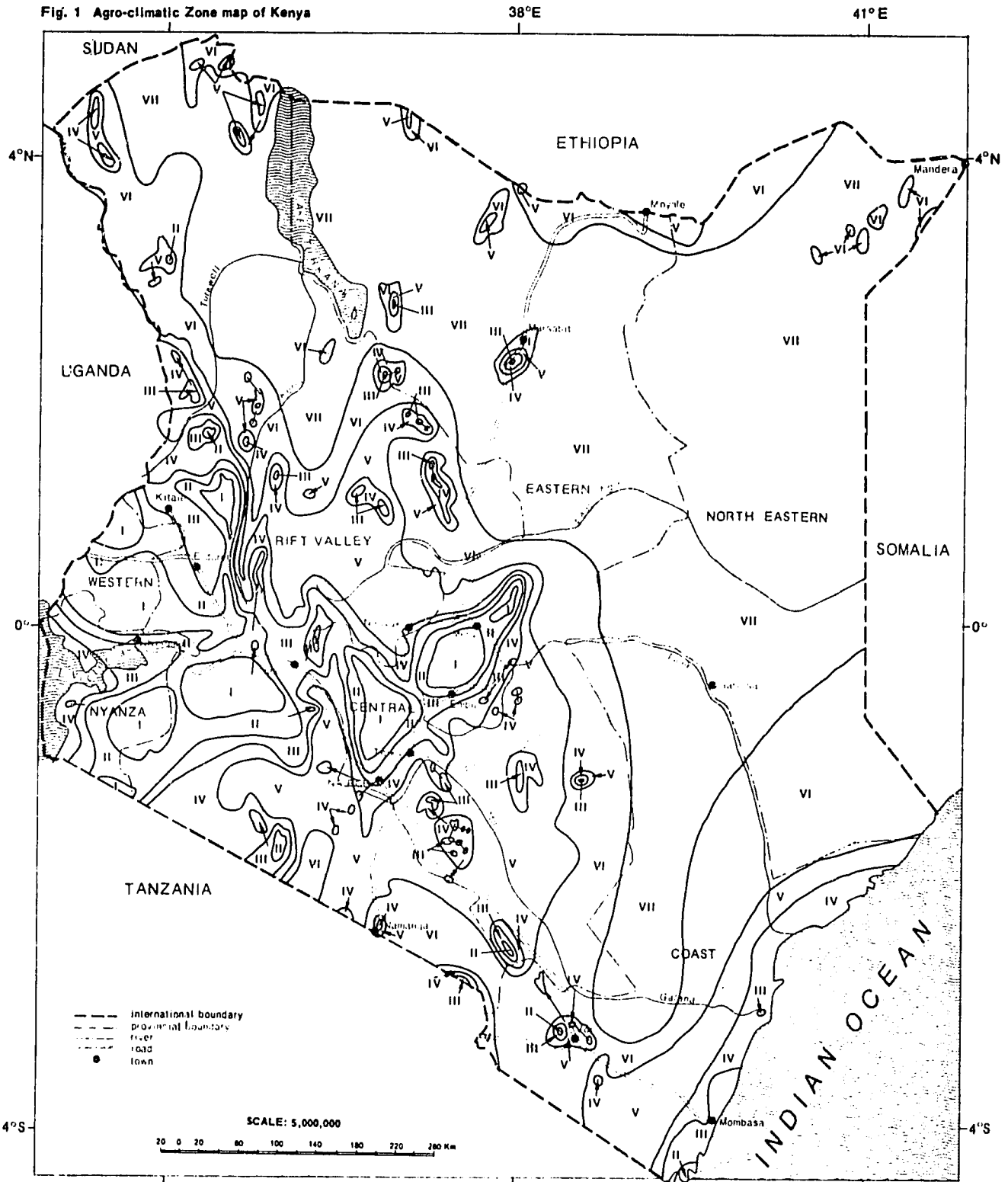
Kenya's landscape is an environment of great topographic diversity. It rises from sea level at the coast to 5,200 metres at the summit of Mount Kenya. As a result of this varied terrain, various parts of the country experience an extremely varied climate both in precipitation and temperature. Fig. 1 gives the agro-climatic zones of Kenya.

OCCURRENCE AND DISTRIBUTION

Oxisols in Kenya occur from the sea level to a maximum altitude of about 2130 metres where the maximum average annual temperature is 30 degrees C and the minimum average annual temperature is 16 degrees C. Fig. 2 shows the distribution of the main Oxisols in Kenya. These soils cover only a minor part of the Kenyan land surface. They occur on a variety of physiographic positions. Most of them are found on plateaus, gently dissected older peneplains ("uplands") and non-dissected erosional plains. They are found on a variety of parent materials which may be Tertiary volcanics (basalts, phonolites, andesites etc.), Precambrian Basement System rocks (granitoid gneisses, biotite gneisses, hornblende gneisses, etc.) or Cenozoic unconsolidated sediments.

The soils occur in udic, ustic and aridic soil moisture regimes and isothermic and isohyperthermic soil temperature regimes (cf Fig. 1). Contrary to what might be expected, their occurrence in udic and ustic conditions is restricted. One of the reasons for this is an apparently relatively recent dissection of many landscapes in the areas concerned. Also, in several parts there is a predominant influence of recent volcanic ash deposition (cf Fig. 2 and Wielemaker, 1979). The Oxisols (Ferralsols) in present-day torric climates cover in fact the most acreage. They are

Fig. 1 Agro-climatic Zone map of Kenya



Agro-climatic Zones

Prepared and drawn by Kenya Soil Survey Apr. 1981

A. Water availability Zones (with rough indications of vegetation, rainfall and evaporation.)

r/Eo	Zones	SMR–STR* (approximate)	Description	vegetation	rainfall	evaporation
>80%	I	udic + isomesic/ isothermic	very humid	moist forest	>1200 mm	1200–2000 mm
65–80	II		humid	moist and dry forest	900–1600	1300–2100
50–65	III	ustic + isothermic/ isohyperthermic	sub–humid	dry forest and moist woodland	700–1400	1400–2200
40–50	IV		sub–humid to semi–arid	dry woodland and bushland	600–1100	1500–2300
25–40	V		semi–arid	bushland	400–800	1600–2400
15–25	VI	aridic/torric + isohyperthermic	arid	bushland and scrubland	250–500	1700–2500
< 15	VII		very arid	desert scrub	< 250	> 2400

Source: Braun H.M.H. (1980)

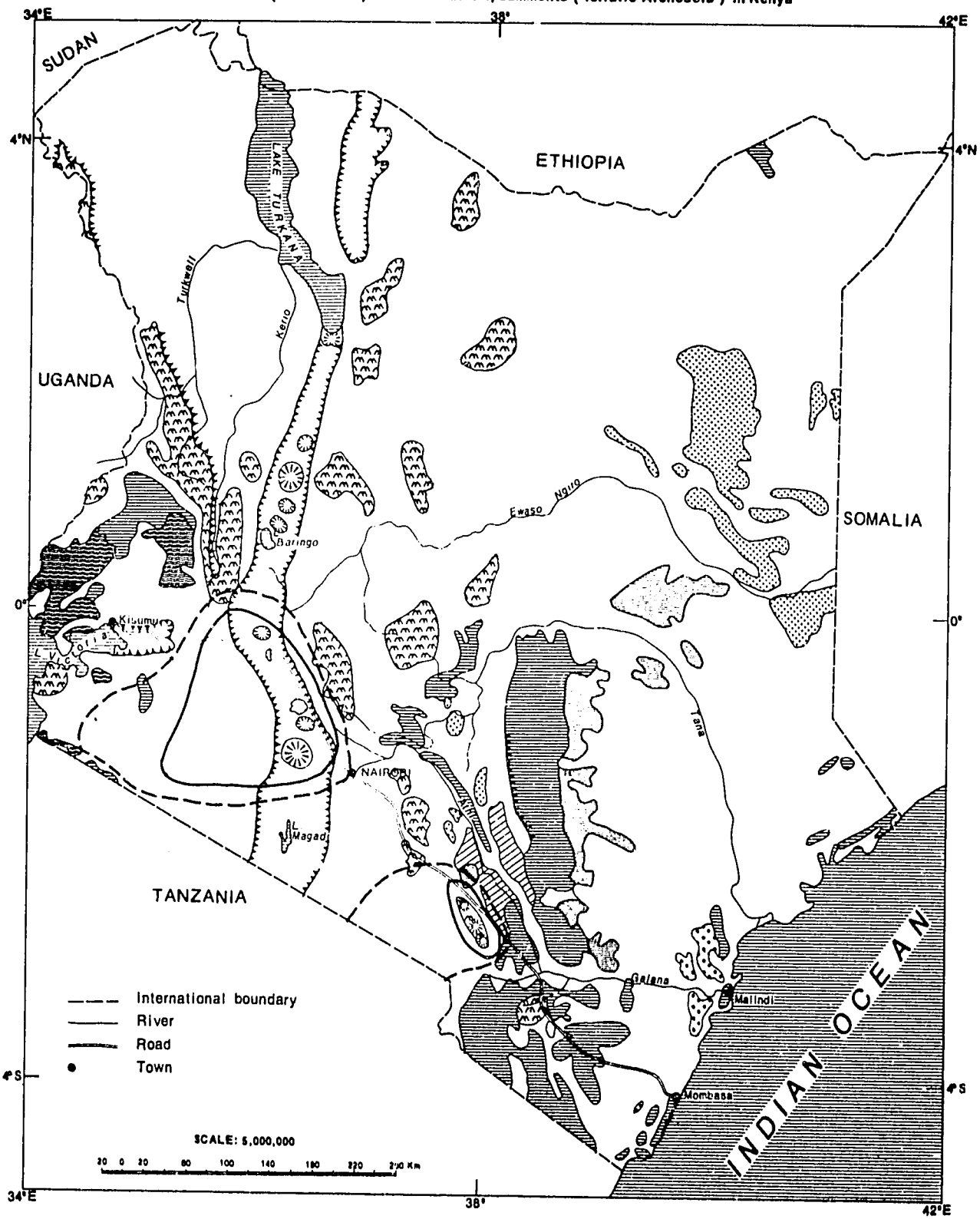
** Van Wambeke (1981) estimated from P, T, PE*

SMR soil moisture regime

STR soil temperature regime

Drawing No. 81018

Fig. 2 Occurrence of Oxisols (Ferralsols) and oxic Quartzipsamments (ferralic Arenosols) in Kenya



LEGEND (FAO terminology)

- rhodic and orthic Ferralsols
- rhodic and orthic Ferralsols with petroplinthite
- orthic to xanthic Ferralsols, and chromic luvisols
- rhodic Ferralsols to ferric Luvisols/Acrisols
- rhodic Ferralsols and ferralic or albic Arenosols
- ferralic Arenosols

KEY

- mountains
- major scarps
- recent volcanos
- limit of major recent ash deposition
- limit of minor ash deposition

found on old, stable landsurfaces that apparently have been subjected to humid climates in the past (Pliocene and/or Pleistocene), flat plateau remnants, flat erosional plains, stable older footslopes and old beach ridges.

PHYSICAL AND CHEMICAL CHARACTERISTICS

In all cases of the Oxisols mapped in Kenya there are no signs of clay illuviation (argillans) in the soil profiles. The textural change is usually small and gradual. The silt/clay ratios are low (most of them are less than 0.20). The weatherable primary minerals are few (less than 8%, including muscovites). The structure is subangular blocky to porous massive and the aggregate stability is high (flocculation index greater than 60, often greater than 80). The bulk density ranges from 1.0 to 1.5 g/cm^3. The moist consistence is very friable to friable.

The clay mineralogy is predominantly kaolinitic. No high percentages of gibbsite have been found. The CEC-clay values (NH_4OAC at pH 7; organic matter corrected) are mainly between 6 and 16 me/100 g clay. A few Oxisols have lower CEC-clay values, though none of these reach values below 1.5 me/100 g clay and/or have a positive delta -pH.

The Oxisols in present-day torric climatic conditions tend to have higher base saturation, more textural differentiation, and higher bulk densities than the ones in ustic and udic climates. The transition to the parent rock of these soils at 2 m or so depth is clear to abrupt, locally via a thin petrocalcic horizon. A part of them have in fact CEC-clay values somewhat above 16 me/100 g clay. In a number of cases the textures are sandy. Textures and CEC's of the soils concerned are often difficult to determine reliably, because of an apparent incomplete dispersion during laboratory analysis.

Very few Oxisols in the areas with udic soil moisture regime and isothermic soil temperature regime have umbric epipedons or high organic matter throughout and no sombric horizons have been observed.

No significant acreage of Oxisols with features of wetness and/or soft plinthite do occur. A number of them do, however, contain hard plinthite (ironstone, which is either massive or loose gravelly) from some depth on-

Table 1: KENYAN OXISOL SOIL PROFILE CHARACTERISTICS SIGNIFICANT FOR SOIL CLASSIFICATION

Survey area	Mapping unit	Soil Classification: FAO/UNESCO (1974)	Soil Classification: Soil Taxonomy (Soil Survey Staff, 1975)	No. of profiles analysed	A-horizon: Organic C%	A-horizon: clay %	A-horizon: base saturation at pH 7.0	A-horizon: base saturation at pH 8.2	transition A/B horizons	clay ratio B/A horizons	B-horizon: clay %	B-horizon: silt/clay ratio	B-horizon: flocculation index	B-horizon: structure	B-horizon: consistence, moist	B-horizon: base saturation at pH 7.0	B-horizon: base saturation at pH 8.2	B-horizon: CEC at pH 7.0	B-horizon: CEC at pH 8.2	B-horizon: clay fraction: clay minerals	B-horizon: clay fraction: molar ratios and % SiO_2/Al_2O_3	B-horizon: clay fraction: molar ratios and % $SiO_2/Al_2O_3+Fe_2O_3$	B-horizon: clay fraction: molar ratios and % $\%Fe_2O_3$	B-horizon: colour: dry	B-horizon: colour: moist descriptive	bulk density (g/cm^3)	porosity (%)	weatherable primary minerals (%)
Kwale	USmr	rhodacric Ferralsols	Typic Acrustox	10	0.7	17	75	–	gradual	1.8	30	0.3	70	pm–sb	friable	55	–	5–12	–	well crystallized kaolinite, traces of illite	1.9	1.6	14.4	2.5YR 4/6	2.5YR 3/6 dark red	1.45	45	very few
	PL2,PL2p	rhodic Ferralsols	Typic Eutrustox	5	0.8	12	82	–	gradual	2.0	24	0.2	65	pm–sb	friable	80	–	14	–	well crystallized kaolinite, traces of illite	2.0	1.3	25.2	2.5YR 5/8	2.5YR 5/8 red	1.51	43	very few
	Flm	rhodic Ferralsols	Typic Eutrustox	2	1.7	46	95	–	gradual	1.2	54	0.3	80	pm–ab	friable	80	–	15	–	poorly crystallized kaolinite, traces of illite	2.3	1.6	19.3	2.5YR 4/4	2.5YR 3/4 dark reddish brown	–	–	very few
	USmb,PA2	orthic Ferralsols	Typic and Arenic Eutrustox	8	0.5	14	90	–	gradual	2.0	28	0.3	60	pm–sb	friable	60	–	10	–	well crystallized kaolinite, traces of illite	1.7	1.4	14.4	5YR 5/8	5YR 4/8 yellowish red	1.49	44	very few
Kindaruma	BUr	rhodic Ferralsols	Typic Haplustox	5	0.7	55	–	50	gradual	1.16	60	0.1	86	pm–sb	very friable	26	30	15	20	kaolinite	1.5	1.4	9.0	2.5YR 3/6–4/8	2.5YR 3/6 dark red	1.1	57	very few
	VKr	rhodic Ferralsols	Typic Haplustox	4	1.8	65	–	50	gradual	1.13	75	0.06	93	pm–sb	very friable	13	20	15	14	kaolinite, traces of illite	1.7	1.5	8.7	2.5YR 3/6	2.5YR 3/4 – 3/6 dusky red to dark red	1.0	64	very few
Kapenguria	U4Ur	rhodic Ferralsols	Typic Haplustox	10	2.05	51	55	–	gradual to diffuse	1.3	63	0.19	70	pm–sb	friable	54	–	13.9	–	well crystallized kaolinite, traces of illite	1.7	–	15.4	–	2.5YR 3/6 dark red	1.1	57	few
	U4Ub	orthic Ferralsols	Typic Eutrustox	3	1.54	38	48	–	gradual	1.3	55	0.20	58	sb	friable	52	–	11.3	–	poorly crystallized kaolinite, illite	2.4	–	11.1	–	5YR 3/4 dark reddish brown	1.2	53	few
Makueni	LIC	rhodic Ferralsols	Typic Haplustox	1	1.41	44	–	51	clear	1.2	54	0.2	96	pm–sb	friable	–	38	–	12	–	–	–	–	2.5YR 4/6–4/8	2.5YR 3/6 dark red	1.16		very few
		orthic Ferralsols	Typic Haplustox	1	0.90	26	–	58	gradual	1.7	44	0.2		pm–sb	friable	–	38	–	13	–	–	–	–	7.5YR 5/8–6/8	5YR 4/6–5/8 yellowish red	1.31		very few
	UIFr1	rhodic Ferralsols	Typic Haplustox	3	0.73	42	–	41	gradual to diffuse	1.3	54	0.2	95	pm–sb	very friable to friable	–	38	–	5–11	well crystallized kaolinite	–	–	–	2.5YR 4/8–10R 4/8	2.5YR 3/6–10R 3/6 dusky red to dark red	1.27		very few
	U2Nb2p	xanthic Ferralsols	Typic Haplustox	2	0.94	45	–	60	gradual to diffuse	1.4	64	0.05	67	pm–sb	friable	–	47	–	13	well crystallized kaolinite, traces of illite	–	–	–	7.5YR 6/6–7/6 to 10YR 5/6	7.5YR 5/6–6/6–10YR 5/6 strong brown to yellowish brown	1.22		few
	UINb1	orthic Ferralsols	Typic Haplustox	3	0.90	27	75	61	gradual	1.8	51	0.2	60	pm–ab	friable	45	54	9	13	kaolinite (80%) illite (20%)	–	–	–	7.5YR 5/8	5YR 4/6 yellowish red	1.3		few

Survey area	Mapping unit	Soil Classification: FAO/UNESCO (1974)	Soil Classification: Soil Taxonomy (Soil Survey Staff, 1975)	No. of profiles analysed	A-horizon: Organic C %	A-horizon: clay %	A-horizon: base saturation at pH 7.0	A-horizon: base saturation at pH 8.2	transition A/B horizons	clay ratio B/A horizons	B-horizon: clay %	B-horizon: silt/clay ratio	B-horizon: flocculation index	B-horizon: structure	B-horizon: consistence, moist	B-horizon: base saturation at pH 7.0	B-horizon: base saturation at pH 8.2	B-horizon: clay fraction CEC at pH 7.0	B-horizon: clay fraction CEC at pH 8.2	B-horizon: clay fraction clay minerals	B-horizon: clay fraction molar ratios and % SiO_2/Al_2O_3	B-horizon: clay fraction molar ratios and % $SiO_2/Al_2O_3 \cdot Fe_2O_3$	B-horizon: clay fraction molar ratios and % $\%Fe_2O_3$	B-horizon: colour dry	B-horizon: colour moist descriptive	B-horizon: bulk density (g/cm^3)	B-horizon: porosity (%)	B-horizon: weatherable primary minerals (%)
Exploratory survey	Lc2	acric to rhodic Ferralsols (acro-rhodic Ferralsols)	Haplustox	2	0.40	30	42?	58	gradual	1.4	42	0.02	95	pm-sb	very friable	47?	70	5	4	kaolinite	2.0	1.6	3.3	10R 3/2	10R 2.5/2 very dusky red	–	–	nil
	Pc3	rhodic Ferralsols to Ferralic-chromic Acrisols	Torrox or (Oxic) Haplargid	4	0.45	30	77	58	gradual to diffuse	1.3	40	0.14	60?	pm-sb	friable	83?	58	13	22	kaolinite, traces of illite	–	–	–	2.5YR4-5/6-8	10R3-4/6 red to dark red	–	–	nil
	Z1	rhodic Ferralsols	Torrox	1	0.30	20	44	–	gradual	1.5	32	0.15	85	pm	friable	43	–	14	–	–	–	–	–	2.5YR 5/8	10R 4/6 red	–	–	nil
	Ps1	terralic Aleonosols	Torripsamment	4	0.15	10	60	64	diffuse	1.3?	13?	0.70	75	pm-sb	very friable	49	56	(20)	(40)	kaolinite, illite (10-20%)	–	–	–	2.5YR 4/8	10YR 3/6 dark red	–	–	nil
Voi and Mitto Andei	Pn2Fr Pn2Frp	rhodic Ferralsols	Eutrustox-Torrox	2	0.71	17	71	–	gradual to diffuse	1.7	29	0.27	57	pm	friable	68	–	16	–	–	–	–	–	2.5YR 4/8	10R 3/6 red	–	–	nil
	LIC	rhodic Ferralsols	Haplustox-Torrox	1	0.70	60	39	–	gradual	1.1	65	0.26	88	pm-sb	friable	31	–	14	–	–	–	–	–	2.5YR 4/8	2.5 YR 3/6 red	–	–	nil
	Pn2Ub	orthic Ferralsols	Haplustox-Torrox	1	0.90	20	100?	–	clear	2.1	42	0.17	–	pm	friable	27	–	18	–	–	–	–	–	7.5 YR 5/6	7.5YR 4/4 brown	–	–	nil
	Pn1Fb	xanthic Ferralsols	Eutrustox-Torrox	1	0.99	48	62	–	gradual	1.3	60	0.17	97	pm-sb	friable	52	–	16	–	–	–	–	–	7.5YR 6/8 to 10YR 6/8	7.5 YR 5/6 strong brown	–	–	very few

Notes

* *KSS – terminology*

– not determined

explanation of abbreviations

structure

pm porous massive

sb subangular blocky

ab angular blocky

weatherable primary minerals (% of the fine sand fraction)

few (4–7%)

very few (1–3%)

Drawing No. 81018

wards. This is notably the case on the lower-level uplands near the Ugandan border.

CLASSIFICATION

The Kenya Soil Survey has adapted the terminology of the FAO/UNESCO legend (1974) as the basis for the national soil classification system. This system has been applied in the exploratory soil map of the country (Sombroek et al., in prep.), reconnaissance soil surveys (van de Weg and Mbuvi, 1975; Gelens et al., 1976; Michieka et al., 1978; Muchena and Njoroge, in prep.; Van Wijngaarden, in prep.; Michieka and Rachilo, in prep.) semi-detailed soil surveys and detailed soil surveys.

For all the reconnaissance soil surveys soil profile characteristics thought to be significant for soil classification purposes (averaged over several profiles) are presented in tabular form, to facilitate comparison. Table 1 gives a summary of those characteristics significant for soil classification for Oxisols identified in recent reconnaissance soil surveys of the Kenya Soil Survey.

The non-humic Oxisols of Kenya and those which do not have plinthite, have been subdivided on their colour, in accordance with the terminology of the FAO/UNESCO legend as follows: rhodic, orthic and xanthic. The impression prevails that this subdivision is less due to the total percentage of iron oxides present than to the form of these oxides. Systematic data on the ratios goethite/haematite, percentages of active form of iron and specific surfaces are not yet available. A tentative subdivision has been made for the rhodic Ferralsols into nitorhodic (ortho-rhodic) and acro-rhodic ("rhodacric"). The former occur on relatively rich and easily weatherable parent materials (basalts, phonolites, hornblende gneisses) and have CEC-clay values near 16 me/100 g. They have a high clay content throughout, have a dusky red rather than red or dark red colour, are magnetic to a degree and often have some shiny ped faces in the lowest part of the profile. They are apparently the better Oxisols (Ferralsols) agriculturally. They have a relatively high inherent fertility and/or show

good response to fertilizing. The acro-rhodic ones have relatively low CEC-clay values (between 1.5 and 7 me/100 g) and are little used agriculturally.

A similar subdivision as for the rhodic Ferralsols may be useful for the orthic and xanthic Ferralsols. However, in such a case the nature of the sesquioxides will have to be determined systematically, in addition to the CEC-clay values.

A number of individual profile descriptions and analytical data, covering the range of Kenyan Oxisols mentioned above, are given in the Kenya Soil Survey Miscellaneous Soil Paper No. 23 (Muchena and Sombroek, 1981). For most of them clay mineralogical data are included. For several of them soil moisture storage and micromorphological data are available, too.

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DISCUSSION

Q. H. Eswaran: Some of the soils appear to have a lighter textured surface horizon and a subsurface horizon meeting the requirements for a FTSH. Is this correct?

A. W.G. Sombroek: We don't think so if the FTSH implies a substantial increase in clay within 15 cm at any depth, after mixing of the upper 18 cm.

Q. A. Herbillon: 1. What is the base saturation percentage in the Torrox? 2. Would the ECEC of these soils be systematically higher than that of similar soils under other moisture regimes?

A. W.G. Sombroek: 1. About 50 to 70%. 2. Perhaps; while the CEC/clay values (NH_4OAc at pH 7) are around 16, the ECEC/clay values would be around 10. ECEC values for the Rhodic Ferralsols under an ustic moisture regime seem to be around 6.

Q. R. Schargel: In view of the fact that some of the soils with oxic characteristics in the torric moisture regime have a somewhat high CEC at pH 7, which would place them into the Camborthids, would you recommend an increase of the CEC limit of 16 meq/100 g clay or correction for organic matter, and how would you make the corrections in the latter case?

A. W.G. Sombroek: Placement into the Camborthids would be very unfortunate in view of the marked differences in land use characteristics as compared to the real Camborthids occurring nearby. We would therefore welcome the raising of the CEC/clay limit for Oxisols to 18 or 20 meq. Incidentally, all of the Oxisols identified in Kenya have (a) no argillans, (b) a low silt:clay ratio, (c) few if any weatherable minerals, and (d) stable structure.

Q. J. Bennema: Your data show that in some Oxisols (Ferralsols) of Kenya there is a strong clay increase from the surface horizon to the underlying horizon, sometimes by more than a factor of 2. In the coastal areas, clay increase is also observed in the second and third horizon and the increase is more than 1.4. Could you comment on this situation?

A. F.N. Muchena: The increase from the first to the second horizon is not due to illuviation but the result of other processes such as erosion. Also, dispersion of surface horizon material may not have been perfect due to extremely strong iron oxide coatings on the structural aggregates resulting from the torric conditions. In the coastal areas, the clay increase is very gradual which, according to your own statements, should be a reason to retain these soils in the Oxisols.

THE OXISOLS OF BURUNDI

L. Opdecamp and G. Sottiaux

ABSTRACT

Oxisols are very extensive in Burundi. Typic Haplustox are the most common Oxisols at medium and low altitudes and in eastern Burundi. Sombrihumox are the representative Oxisols of the highlands. The Oxisols of Burundi have low base saturation and may develop aluminum toxicity for most cultivated plants. Food production, tea and coffee are common land utilization types for Oxisols in Burundi. Other LAC soils such as Oxic Paleustalfs, Oxic Paleustults and Oxic Agrudalfs are proposed to be included in the Oxisol order. It is suggested to correct the unrealistic ammonium acetate CEC values for organic matter-derived charge in carbon-rich Oxisols for calculations of CEC per clay.

RESUMÉ

Les Oxisols sont très bien représentés au Burundi. Les Typic Haplustox sont les sols les plus répandus dans les régions orientales de moyenne et basse altitude. Les Sombrihumox sont représentatifs des régions de haute altitude. Les Oxisols du Burundi sont fortement désaturés en bases et présentent un risque de toxicité aluminique pour la plupart des plantes cultivées. Les cultures vivrières, le thé et le café sont les principaux types d'utilisation des Oxisols du Burundi. D'autres sols tels que les Oxic Paleustalfs, les Oxic Paleustults et les Oxic Agrudalfs sont caracterisés aussi par des argiles de faible CEC; on propose des lors de les ranger égalment dans l'ordre des Oxisols. On suggère enfin de tenir compte de

la CEC de la matière organique pour le calcul de la peu réaliste CEC à l'acétate d'ammonium sur argile dans les Oxisols riches en carbone.

INTRODUCTION

Soil maps made in Burundi are based on the Classification of the Soils of the Republic of Congo (Kinshasa) (Tabernier and Sys, 1965). The ferrallitic horizon of this classification is largely equivalent to the oxic horizon of Soil Taxonomy (Soil Survey Staff, 1975). But the ferrallitic horizon is diagnostic of soils where shining cutan-like films may be present (Ferrisols). This fact can be interpreted as evidence of illuviation, so that an argillic horizon can be identified. Only "Ferralsols" and "Ferrisols intergrading to recent tropical soils" do not have these coatings. In the latter the ferrallitic horizon is generally missing but an oxic horizon may be found with a ratio of fine silt:clay greater than 0.15 on magmatic and eruptive rocks or greater than 0.20 on sedimentary rocks. As a first approximation, ferralsols and some ferrisols intergrading to recent tropical soils may be considered as Oxisols. Their extension is very large in Burundi where altitude rises from 800 m up to more than 2,500 m.

Mean annaul temperature varies from 24 degrees C in low altitudes to 11 degrees C in high altitudes; daily temperature variation is 10 degrees C to 15 degrees C and monthly variation less than 2-3 degrees C. Soil temperature regimes are isothermic in high altitudes and isohyperthermic in lower altitudes.

Annual rainfall ranges from 900 to 1800 mm. A three to four month dry season occurs during June, July, August and September. Soil moisture regimes are mainly ustic, udic in high altitudes, and aquic in swamps and recent fluviatil deposits.

GEOGRAPHICAL DISTRIBUTION

The 1:750,000 scale map (Fig. 1) shows the large units where Oxisols are the most dominant soils. Plinthaquox and Umbraquox may be found all over the country in small depressions where colluvial material is flooded during the rainy season. From west to east five altitudinal areas may be distinguished (Fig. 2): western lowlands, western medium altitude lands, highlands, eastern medium altitude lands and eastern lowlands.

Western Lowlands

This area is formed by the Tanganika coastal and Ruzizi plains, commonly called "Imbo." There one finds mainly alluvial deposits with Fluvents, Usterts, Aquolls, Ustalfs and Tropepts. Oxisols occur only on relict peneplaned Precambrian formations or on cover deposits of the Central-Africa rift. The most representative are Typic Haplustox, associated with Ustults.

Western Medium Altitude Lands

On the western side of the abrupt Zaïre-Nile crest, from 1000 to 1700-1800 m, few Oxisols are found. There are essentially Tropepts and Orthents associated with rejuvenated landscapes with steep slopes on acid micaceous rocks. This area is undergoing considerable erosion.

Highlands

The high altitude Oxisols contain high amounts of organic carbon. Humox are common, especially Sombrihumox, Haplohumox and locally Acrohumox. Orthox are rare. Agrudalfs occur in the northern part under old banana plantations. Lithic Ustorthents are representative on ironstone, sandstone, and quartzite outcrops. Tropepts and Tropeptic Haplohumox may be developed on steep slopes. Schists and acid micaceous rocks are the main parent materials.

Eastern Medium Altitude Lands

Ustox are the most common soils of the medium altitude undulating

Figure 1: Occurence of Oxisols in Burundi

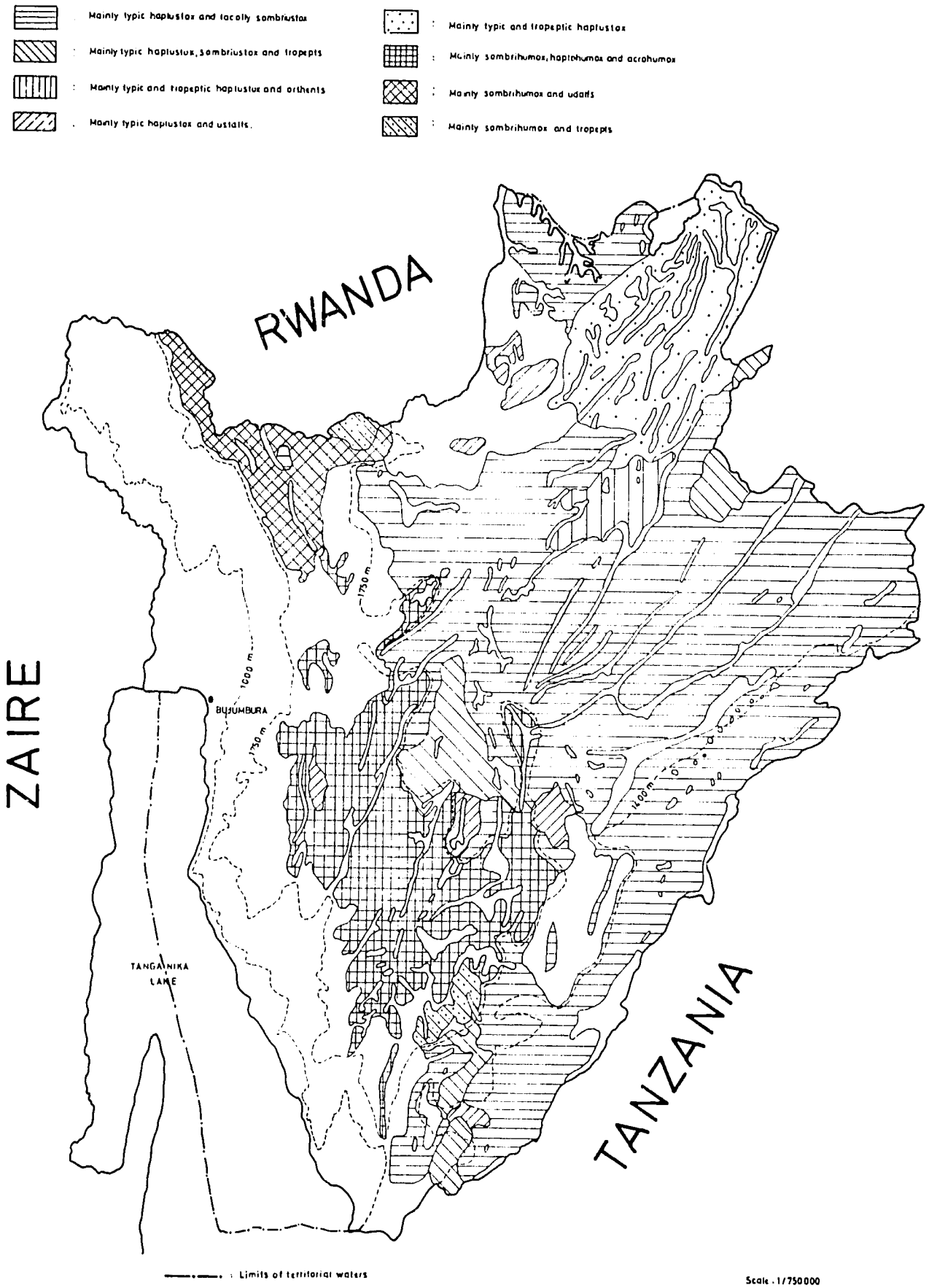
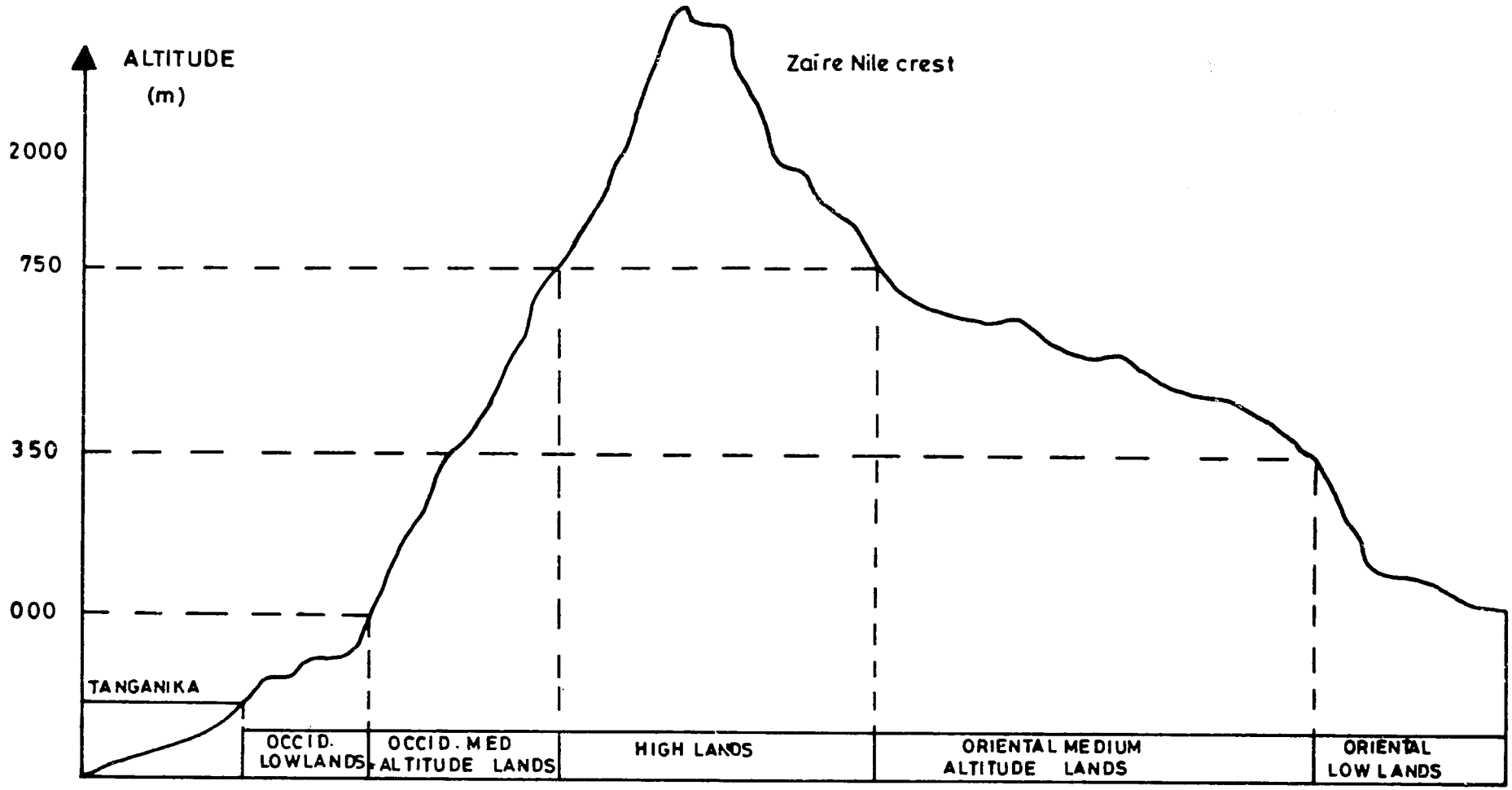


FIGURE 2 : THE FIVE ALTITUDINAL AREAS OF BURUNDI
CROSS SECTION WEST - EAST



landscapes (1700-1800 to 1350 m). Mainly Typic Haplustox and Sombriustox are developed on schists and acid micaceous rocks. On basic rocks Typic Eutrustox occur locally. Clayey Ustalfs are found under banana and coffee plantations in the north of Ngozi. Ustorthents and Tropepts on sandstone, ironstone, and schists outcrops are associated with Tropeptic Haplustox on slopes and Typic Haplustox on colluvium in the northeastern zone of Kirundo.

Eastern Lowlands

This area called "Mosso" extends to Tanzania with altitudes varying from 900 to 1300-1400 meters. Typic Haplustox and locally Sombriustox are developed on schists and basic rocks. On the alluvial deposits of Malagarazi river occur Saprists, Aquents, Tropepts and Ustalfs.

FIELD AND ANALYTICAL PROPERTIES

Field Morphology

The oxic horizon of the Ustox has a clay or sandy-clay texture with massive or weak blocky structure. In the Humox the color is more brownish with lower chroma due to organic matter content. Muscovite flakes are common in materials derived from acid micaceous rocks. An ochric, umbric or more rarely mollic (Eutrustox) epipedon overlies the oxic horizon. In tropeptic subgroups a clayey-skeletal or fragmental C horizon appears within 1.25 m. Texture changes slightly and progressively with depth but generally not significantly enough for identifying ultic subgroups. Nevertheless some Ultic Haplustox occur in lowlands on flat surfaces. A remarkable horizon develops regularly under grassland and sometimes under forest in high and medium altitudes. It has a massive structure, low bulk density, dark color and underlies directly the surface horizon. It is named "socle" (Frankhart and Sottiaux, 1972). A sombric horizon is identified in Sombrihumox and Sombriustox.

Physical Properties

According to several results obtained in the Imbo and Mosso areas

(Normand, 1974-1979), the permeability of Oxisols of Burundi is assumed to be moderate and available water retention low, about 5-10%. Bulk density is about 1.5 g/cm^3. Soil textural classes are strongly correlated to parent materials. On basic rocks very highly clayey Oxisols are developed.

Clay is the typical soil textural class identified on schists. Quartzitic influence on schists gives sandy-clayey materials and basic rocks influence gives clayey materials. On acid micaceous rocks sandy clay and clay are common. Table 1 distinctly shows these connections.

Table 1. Particle-size distribution of some oxic horizons of Oxisols developed in different parent materials.

Profile Number	Parent Material	Particle-size Distribution		
		clay	silt	sand
		----------%----------		
72	Schists	50.8	28.0	21.2
84	Acid micaceous rocks	56.8	11.6	31.6
22 MM	Schists and quartzites	41.2	4.6	54.2
97	Basic rocks	90.2	5.1	4.7
KS 6	Schists and basic rocks	75.3	4.9	19.8

Clay Mineralogy

Frankart et al. (1978) have identified mainly kaolinite and goethite with traces of gibbsite, hematite and illite in some Oxisols of the highlands and eastern lowlands. Aluminum-interlayered chlorite was detected in some samples where gibbsite was systematically present. Traces of illite are expected in all materials derived from acid micaceous rocks.

Chemical Properties

Fifteen representative Oxisols are included in Table 2 and some chemical properties of their oxic horizon are shown in Table 3.

Table 2. Selection of representative Oxisols of Burundi.

Profile Number	Localization	Altitude (m)	Parent Material	Other Diagnostic Horizons	Classification
1 MM	Makamba	1460	Schists and quartzites	Ochric	Typic Haplustox
MS 15	Kigamba	1630	Schists and basic rocks	Umbric	Typic Haplustox
72	Muramvya	2000	Schists and basic rocks	Umbric, Sombric	Sombrihumox
86	Nyakararo	2230	Schists and basic rocks	Umbric, Sombric	Sombrihumox
204	Ngozi	1870	Acid micaceous rocks	Umbric, Sombric	Sombrihumox
200	Ngozi	1380	Basic rocks	Mollic	Typic Eutrustox
KS 2	Karuzi	1630	Acid micaceous rocks	Umbric	Typic Haplustox
KS 6	Karuzi	1710	Schists	Umbric	Typic Haplohumox
OR 10	Rumonge	850	Rift cover deposits	Ochric	Ultic Haplustox
Kaj 3	Bututsi	1760	Schists	Ochric	Typic Acrohumox
97	Mosso	1150	Basic rocks	Umbric	Typic Haplustox
S 5	Mosso	1350	Schists and quartzites	Ochric	Typic Haplustox

Table 2 (continued)

Profile Number	Localization	Altitude (m)	Parent Material	Other Diagnostic Horizons	Classification
MS 35	Mubira	1750	Basic rocks	Ochric	Typic Acrohumox
MS 30	Mukigo	1635	Schists	Umbric	Typic Haplustox
MS 32	Nyabikere	1610	Schists	Ochric	Typic Haplustox

Table 3. Chemical properties of oxic horizons of selected Oxisols of Burundi.

Profile Number	CEC per Clay	ECEC per Clay	KCl-extractable Aluminum	pH(H_2O)[b]	Base Saturation (%)	Aluminum Saturation[c] (%)
	meq/100 g					
1 MM	12.1	2.5	1.1	5.4	3.4	84
MS 15	11.7	1.7	0.7	5.3	5.0	58
72	15.5[a]	less than 10	-	5.0	0.4	-
86	14.4[a]	less than 10	-	4.9	0.3	-
204	12.4[a]	8.3	2.4	5.3	23.2	49
200	8.2	4.6	0.0	5.4	55.8	0
KS 2	12.9[a]	4.5	2.7	5.1	0.5	98
KS 6	13.7[a]	4.1	1.8	5.3	7.1	60

Table 3 (continued)

Profile Number	CEC per Clay	ECEC per Clay	KCl-extractable Aluminum	pH(H_2O)[b]	Base Saturation (%)	Aluminum Saturation[c] (%)
	meq/100 g					
OR 10	14.9	less than 10	-	5.2	7.9	-
Kaj 3	11.8	0.7	0.2	5.1	3.0	34
97	14.7	3.1	0.0	6.0	36.6	0
S 5	15.4	5.5	1.4	5.1	19.5	43
MS 35	14.2	0.8	0.4	5.4	1.2	61
MS 30	16.0	5.7	0.0	6.1	35.9	0
MS 32	10.1[a]	2.3	1.0	4.9	3.3	68

[a]Correction has been made for organic carbon content (1% C = 5 meq.)

[b]Ratio soil:solution is equal to 1:5.

[c]KCl-extractable aluminum x 100 divided by sum of bases (NH_4OAc) plus KCl-extractable aluminum.

Cation exchange capacity per clay. Corrections have been made with regards to organic matter expected charge, especially in Humox, for calculations of ammonium acetate CEC values on clay. Organic matter is expected to have a CEC (NH_4OAc) of 300 meq/100 g which means approximately 5 meq for 1% of organic carbon. According to these corrections ammonium acetate CEC on clay satisfy the oxic horizon criterion.

Effective cation exchange capacity (ECEC) per clay (bases extractable with NH_4OAc plus aluminum extractable with KCl) is always less than 10 meq/100 g. Because lack of some data on KCl-extractable aluminum and NH_4Cl cation exchange capacity, Acrohumox may be more extensive in highlands than previously suggested.

Base saturation. Very low base saturation percentages characterize most Oxisols of Burundi. This is due to negligible amounts of exchangeable bases frequently inducing potassium, magnesium and calcium deficiencies. On basic rocks higher values are obtained but few Eutrustox occur.

Extractable aluminum. Significant amounts of KCl-extractable aluminum are generally observed. The "m value" of Kamprath (1967), cited by Boyer (1976), considering aluminum saturation expressed as a percentage of effective cation exchange capacity (ECEC), is frequently greater than 45. According to Muzilli and Kalckmann (1971), also cited by Boyer (1976), a "m value" of 45 is the upper limit above which serious risks of aluminum toxicity occur for the most cultivated plants.

LAND USE ASPECTS

Pasture is a common form of land use of Oxisols in Burundi, especially in highlands and eastern medium altitude lands. The development of the "socle" horizon is thought to be related to slow biodegradation of Eragrostis[1] roots.

Tea plantation is also an extensive land utilization type for Oxisols in highlands. Coffee is mainly cultivated around Ngozi on clayey Ustalfs and sandy-clayey Haplustox and Sombrihumox. The main food crops produced

[1] Eragrostis olivacea (ex boehmii) is the representative grass of the pastures in these areas.

on Oxisols are cassava, sorghum, maize, potatoes, beans and bananas[2] all over the country. Mixed cropping, hoe cultivation, dry season fallow, low or no fertilizer use are the main practices of the farmers whose holdings are generally small and incomes low. In farmer gardens, more intensive management produces higher yields.

DISCUSSION

Other low activity clay soils occur in Burundi as oxic subgroups of Paleustults, Paleustalfs and Agrudalfs. They are mapped as "ferrisols" in the INEAC classification. Their upper B horizon has cutans which are partially associated with illuviation cutans. Under banana plantations an agric horizon is frequently identified. Sys and Tavernier (1979) suggested including these soils in the Oxisol order. We agree with this idea, giving more importance to low activity clay content than to illuviation processes.

Organic matter charge is highly pH dependent so that ammonium acetate CEC of acid carbon-rich Oxisols is unrealistic. In these soils corrections are desirable to calculate ammonium acetate CEC per clay. A value of 5 meq for each carbon percent is suggested.

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[2]Bananas do not grow well above 2000 meters.

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DISCUSSION

Q. J.A. Comerma: Could you propose a value for organic carbon or organic matter above which we should make corrections for CEC in oxic horizons?

A. L. Opdecamp: We do not have sufficient data to support a definite value. But I should think that corrections are desirable even for low organic carbon contents.

THE SOILS WITH SOMBRIC HORIZONS IN RWANDA AND BURUNDI

R. Frankart

ABSTRACT

In Rwanda and Burundi, we have identified, in addition to the central concept of the sombric horizon, subsurface horizons coloured by organic matter which we call sombric horizons with "spots" and horizons with "dark polyhedra." These facies have been tentatively included in the central concept. Their geographical distribution seems to be related to the present climates, vegetation, and landforms.

The presence of the sombric horizon and possibly its "spotted" facies is frequent at altitudes above 1900 m, on often hilly landforms, under Cw or Aw3 climate according to Köppen and under forest or savanna vegetation. It is more sporadic at lower altitudes (1600-1900 m) under savanna. The "dark polyhedra" facies is essentially localized around Central Bugesera (Rwanda), between altitudes of 1400 and 1750 m, on wide plateaus, under an Aw 3-4 climate and under savanna.

Its occurrence, which is independent of the lithological origin, the nature and the texture of parent material, does not necessarily coincide with textural variations in the pedon, and is often not accompanied by chemical modifications other than those linked to organic matter. The sombric horizon (sensu lato) may be slightly discontinuous, with variable thickness and colour. They are roughly parallel to the present soil surface and mainly develop on tops and nonconvex (less than 30%) slopes, with little or no gravel. They are present in well-drained Oxisols, Ultisols, Alfisols and more rarely in Inceptisols. Their genesis is not yet completely understood. Two hypotheses are suggested at least for the central concept: either as an old buried humic horizon or as an illuvial humic horizon. Whatever their origin, their geographical extension should be considered as one of the arguments allowing their recognition among the

diagnostic subsurface horizons.

RÉSUMÉ

Au Rwanda et au Burundi, on a identifié, outre le concept central de l'horizon sombre, des horizons de profondeur, colorés par la matière organique auxquels on a attribué le nom d'horizons sombres en "taches" et d'horizons "à polyèdres foncés." Ces facies ont été provisoirement assimilés au concept central. Leur répartition géographique paraît associée aux climats, végétations et formes de relief actuels.

La présence de l'horizon sombre et accessoirement de son facies "en taches" est généralisée aux altitudes supérieures à 1900 m, dans un paysage souvent accidenté, sous climat Cw et Aw3 de Köppen et sous végétation forestière ou de savane; elle est plus sporadique aux altitudes inférieures (1600-1900 m). Le facies à "polyèdres foncés" est essentiellement localisé en périphérie du Bugesera Central (Rwanda), sur de larges plateaux, entre 1400 et 1750 m d'altitude, sous climat Aw 3-4 et sous savane. Leur existence qui est indifférente à l'origine lithologique, à la nature et à la texture des matériaux parentaux, ne coïncide pas nécessairement avec des variations texturales du profil et n'entraîne pas souvent des variations des propriétés chimiques autres que celles liées à la matière organique. Ils peuvent être (légèrement) discontinus, d'épaisseur et de couleur variables. Ils sont approximativement parallèles à la surface actuelle du sol et généralement développés sur les sommets et sur les versants non convexes peu ou pas graveleux à inclinaison inférieure à 30%. Ils sont présents dans des Oxisols, des Ultisols, des Alfisols et plus rarement dans des Inceptisols bien drainés.

Leur genèse n'est pas encore (complètement) élucidée et des études complémentaires multidisciplinaires s'imposent. Pour le concept central, deux hypothèses sont proposées: ancien horizon humifère enfoui ou horizon illuvial enrichi en matière organique. Quelle que soit leur origine, leur extension géographique devrait constituer un des arguments permet ıt de les ranger parmi les horizons diagnostiques de profondeur.

INTRODUCTION

Some thirty years ago, Kellogg and Davol (1949) mentioned the presence of a B horizon with a darker color and higher content of organic carbon than the adjacent horizons in several "reddish brown latosols" of high altitude regions of Rwanda (more than 1800 m). They considered this B horizon to be a buried postforested humic horizon. This was the first description and characterization of the "sombric horizon" whose occurrence was later reported in several countries of Central Africa (Burundi, Uganda and Tanzania) and in South America as well. In Kivu (Zaïre), Ruhe (1956) described its physico-chemical properties and its geomorphological distribution. He concluded that the sombric horizon ("subsoil dark horizon") is a "subsurface horizon" where organic matter had accumulated. Before 1960, the majority of the soil scientists of the "Institut National pour l'Etude Agronomique du Congo Belge (I.N.E.A.C.)" agreed with the illuvial origin of this horizon; the processes responsible for this illuviation being, however, unknown. Since then, in spite of new pedological, geomorphological and analytical data, uncertainty still remains concerning its genesis. The chronological survey of the various definitions of this diagnostic horizon reflects these uncertainties:

> "Black, dark gray or dark reddish brown illuvial horizon with an accumulation of organic matter below a B2c (consistence B2) or a B2s horizon (structural B2), in the high altitude kaolisols." (Sys et al., 1961).

> "Subsurface horizon of 10 cm or more, at least one unit darker in value and containing more organic matter than the overlying horizon." (Tavernier and Sys, 1965). Note that in this definition, the illuvial origin of the sombric horizon is not mentioned.

> "Subsurface horizon of mineral soils formed under free drainage. It contains illuvial humus that is neither associated with aluminium as in the humus in the spodic horizon, nor dispersed by sodium, as is common in the natric horizon. The sombric horizon does not underlie an albic horizon. Sombric horizons are thought to be restricted to the cool moist soils of the high plateaus and mountains of tropical and subtropical regions. The degree of saturation of these soils is low. The sombric horizon has a lower colour value or chroma or both, than

> the overlying horizon and commonly, but not necessarily, contains more organic matter than the overlying horizon. It may have formed in an argillic, a cambic or, possibly, an oxic horizon. It is easily confused in the field with a buried A1 horizon." (Soil Taxonomy, 1975).

The present paper is a summary of our own personal observations concerning the occurrence of soils with sombric horizons in Rwanda and Burundi. It is also based on information contained in regional reports and on available analytical data. This report is certainly not exhaustive and may need to be clarified on several points. It is of importance to note that in these two countries local soil survey reports allow the identification of subsurface dark horizons whose morphology does not exactly fit into the definition given for the sombric horizon (*sensu stricto*). These dark subsurface horizons, tentatively approximated to the genuine sombric horizon, are called "spots sombric horizons" and "horizons with dark polyhedra."[1] Transition facies also exist.

The sombric horizon will be symbolised by Hsom. Its genesis and taxonomical importance will also be discussed.

NATURAL ENVIRONMENT OF THE SOMBRIC HORIZON IN RWANDA AND BURUNDI

The regions of soils with sombric horizons belong to a complex and very diversified geological, geomorphological, climatic and biological environment. Two diversely metamorphized systems of Precambrian age, the Ruzuzian and the Burundian, principally form the bedrock of the soils (Cahen et Lepersonne, 1967). These layers have been modified by tectonic effects and have been submitted to cycles of peneplanation during the middle and the end of the Tertiary age, and perhaps as well, the end of the Secondary and beginning of the Tertiary (Moeyersons, 1979).

These cycles are responsible for the presence of erosion surfaces, with lateritic material to varying extents, showing different degrees of rejuvenation and residual reliefs ranging in altitude from 1500 to 2300

[1] Structural entities darker than the enclosing soil material.

m or more. Quaternary surfaces related to the actual geographical cycle mark the edge of the older surfaces of peneplanation. The areas located at altitudes higher than 1800-2000 m are mainly characterized by a Köppen climate Cw (Bultot, 1950), with a dry season lasting 2-3 months, a total annual rainfall higher than 1300-1400 mm and a mean temperature of the coldest month below 18 degrees C. They are covered with mountain forest, postforested formations and grassy savannas. The adjacent regions are savannas and have an altitude between 1800 and 1400 m. They belong to the climatic type Aw 3-4, a 3 to 4 months dry season, an annual rainfall of approximately 1200 mm or less (lower than 1000 mm), and a mean temperature of the coldest month higher than 18 degrees C.

CENTRAL CONCEPT OF THE SOMBRIC HORIZON

The sombric horizon (Hsom) is a subsurface horizon, usually with homogeneous colour that may differ from the over- and underlying horizons by having darker chromas and/or values of at least one unit, and a higher organic matter content. If peds are present the darker colours are most pronounced on ped surface. Some peds seem to be not completely invaded by organic matter.

Morphological and Analytical Data[1]

Chemical properties. Under natural cover (forest, grassland), soils with an umbric epipedon at altitudes greater than 1800 m often contain more than 450 tons organic matter per ha/m under forest and more than 300-350 tons/ha/m under savanna, grassland or postforested formations (Neel, 1971)[2]. The organic matter content decreases generally in a progressive way with depth; the C/N ratio, greater than 10 (11-15) in the epipedons, drops below 10 with depth. This evolution is interrupted by the presence of the sombric horizon which has always a higher C content, C.E.C. and C/N

[1] See analytical data in annex.

[2] Data obtained by neglecting the litter and by assuming a bulk density of 0.7 for the forest, 0.8 for the Eragrostis savanna humic layers and 1.1 or 1.3 for the mineral horizons of the same vegetation, respectively.

ratio than the adjacent horizons. The increase of C percentage in the Hsom is variable, 0.2 to 2%, and is always more pronounced towards the underlying than towards the overlying horizons. The increase of C/N ratio which is often greater than 10-12, is mainly due to the increased C content. Other chemical properties (pH, cation loading, exchange acidity, free ion, etc.) are usually in accordance with the general scheme of vertical chemical evolution in the pedon. Sometimes, however, the Hsom is relatively richer in exchangeable cations. Under natural cover, and at altitudes higher than 1800 m, the profile is strongly unsaturated and rich in exchangeable Al and H.

Thickness, depth of occurrence, continuity, limits. Its thickness is variable but always greater than 20 cm; it may reach 60 cm or more. The presence of two Hsom in the same profile has been very rarely identified. The top of the Hsom is usually located between 60 and 100 cm. It seems continuous, although with variable thickness at the pedon level. The limits are gradual to distinct, sometimes undulating, rarely abrupt, largely parallel to the soil's actual surface. However, examination of road cuts shows noticeable variations of its thickness, colour and local continuity (broad panels, vertical tongues of soil without organic matter). The direct contact of Hsom with the actual epipedon is also well evidenced; this includes cases where, at the pedon scale, the presence of Hsom would not be identified.

Hsom, stone line, saprolite relations. We ourselves have never noticed the intrusion of the Hsom into the saprolite in place or under the stone line, although this horizon often lies on the stone line or engulfs it completely or partly. Locally the occurrence of an upstanding quartz vein, crossing the continuous Hsom, has been observed. However Ruhe (1956) observed in Ituri (Zaïre), under thin surficial sediments, sombric horizons within the saprolite covered by a stone line. Similarly in Burundi Niyongabo (1975) found Hsom horizons breaking through the stone line and impregnating the top of the saprolite. The same observation has been made by Neel (personal communication).

Morphology, parent materials, profile development. The presence of Hsom is not related to texture, lithological origin or nature of the par-

ent materials; it is, however, very scarce in sandy materials (less than 20% clay). The surficial deposit is composed of badly sorted materials, as indicated by the cumulative curves of their sand fractions. The mechanical composition of the subsurface horizons is frequently not affected by the Hsom; the same applies to the mineralogical clay composition. Its occurrence in very gravelly soils, mainly in lateritic materials, is difficult to identify, although it was sometimes observed. It is associated with well-drained Oxisols, Alfisols, Ultisols and Inceptisols.[1] Only materials recently eroded have no traces of Hsom.

The structure of Hsom is variable and seems to be largely correlated with the degree of weathering and kind of soils: a) subangular or angular blocky structure, well-developed with coatings (Ultisols, Alfisols); b) poorly developed blocky structure without coatings (Inceptisols); very poorly developed structure, often massive, floury (Oxisols). In the Northern Kivu, Jongen et al. (1970) distinguished three degrees of morphological development of Hsom and showed the relationships between its thickness, morphology and the thickness of the structural Bs horizon (argillic B), the former increasing when the latter is decreasing. These relationships have not been verified in Burundi and Rwanda.

Natural Environment and Distribution

The Hsom horizon occurs especially at altitudes higher than 1900-2000 m, under climate Cw, often on hilly or very undulating landscapes. It is more dispersed or sporadic at lower altitudes (1600-1900 m), under climate Aw 3-4 and on undulating or tabular landforms. Several regional studies, however, report their existence, very localized at altitudes near or lower than 1500 m, without specifying the facies. Ruhe (1956), in Ituri, mentioned its occurrence at 1550 m already. Usually, it is located either on the top of the landscape units or on plane, concave or shallow convex slopes covered with loose, deep soils which are either slightly gravelly or not at all, on slopes ranging from 0 to 30%. Under natural cover, in-

[1] Correlations established by tentatively equating the structural B2s horizon (with coatings) of the I.N.E.A.C. classification (Sys et al., 1961) to an argillic horizon of the Soil Taxonomy.

suring an efficient protection against erosion, it may subsist on slopes higher than 50%.

"SPOTS" SOMBRIC HORIZON

"Spots" sombric horizon is a subsurface horizon characterized by a marked heterogeneous colour, resulting from diffuse, discontinuous and unequal impregnation of humic substances in the surface or within some peds. The spots, of variable sizes and shapes, have a chroma or a value or both darker (at least one unit) than the matrix or the enclosing material. Reports concerning this facies are scarce (Rwanda) and its geographical distribution is yet unknown.

Morphological and Analytical Data

Chemical properties. The relative random distribution of the spots within the Hsom is such that the variation in the colour is the only means of identifying it. If the C content, the C.E.C. and the C/N ratio are rarely diagnostical at the horizon level, their values are, nevertheless, significantly different if spots and enclosing material are compared. The other chemical properties usually do not exhibit any specificity at the level of the pedon.

Thickness, depth of occurrence, limits texture. Its thickness may extend from 100 to 150 cm and it may appear to a depth of 50-60 cm. The transitions are often gradual or diffuse. The parent materials, poorly sorted, are relatively homogeneous and generally do not show any significant textural variations in the level of the Hsom. In certain cases, dark spots form inclusions in a continuous Hsom. Its presence in well-drained Oxisols, Ultisols and Alfisols has been observed.

HORIZON WITH "DARK" POLYHEDRA

This horizon is a subsurface horizon of heterogeneous structure, col-

our and thickness, characterized by the presence of variable quantities of dark blocky structural units. These units may appear as angular, subangular, nuciform peds, whose size may reach 3-4 cm. They are often stable, homogeneously coloured or not, with darker chroma and/or value of more than one unit than that of the enclosing material.

Morphological and Analytical Data

Chemical properties. The organic profile of these soils, generally containing an ochric epipedon (content of organic matter generally lower than 200 tons/ha/m), is often little modified by the presence of this horizon. Although the coloured peds can be easily identified in the field, their influence on the C content, the C/N ratio and the C.E.C. is a function of their relative abundance. Relative increases of the C content, i.e. 0.2 to 0.5%, have been locally observed. The ped's colour is thus influenced by the C content: the greater the C content, the darker the colour. The degree of saturation of these soils is often higher than 25%; it may even reach 50% or more.

Thickness, depth of occurrence, continuity, limits. Its thickness is variable (40 to 120 cm and over), likewise the depth of occurrence (50 to 100 cm). It appears as continuous within the same relief unit; its upper boundaries are diffuse or gradual, according to the density of the coloured peds, while its lower limits are often more distinct.

Morphology, parent materials, kinds of profile development. Its morphology is very complex in terms of the dimensions, shapes, colour and density of the dark peds concerned. It is possible to observe in the same horizon, black, dark-brown and brown peds. The invasion of the aggregates by the dark-coloured materials may be either total (homogeneous or not), partial or diffuse (spots or tongues). The percentage of dark aggregates lies between 20 and 90%; in the latter case, it might be morphologically identified as Hsom (central concept). The presence of this kind of Hsom horizon is unaffected by the texture, nature and lithological origin of the parent materials and has been observed in well-drained Oxisols, Ultisols, Alfisols and more rarely in Inceptisols. The parent material with poor sorting is generally homogeneous and rarely presents textural discor-

dances at the level where dark polyhedra occur.

Natural Environment and Distribution

This type of Hsom is characteristic for tableland surfaces (wide plateaus) at altitudes between 1450 and 1700 m, with an Aw 3-4 climate and an annual rainfall less than 1100 m. The typical vegetation is savanna. The lowest altitude where it is possible to observe this facies is about 1400 m. It is mainly located in the neighbourhood of Central Bugesera in loose deep materials virtually free of gravels overlying straight, concave slopes (lower than 25%) and rarely on top of the landscape units.

GENETIC APPROACH

It appears that, in the actual conditions, the presence of the central concept and perhaps of the "spot" facies is generalized on the surfaces which are higher than 1900-2000 m, often on hilly or undulating landscapes and under Cw, Aw3 climates; more dispersed at lower altitudes (1600-1900 m) on slightly undulated hills or plateaus. These facies appear to coexist with the coloured "dark polyhedra" facies at the level of the same surface groups of medium altitude (1700-1800 m), but not necessarily on the same types of landforms. The dark polyhedra facies is chiefly abundant between 1450 and 1700 m, on plateaus, under Aw 3-4 climate and savannas, in areas surrounding the Central Bugesera (Figures 1 and 2). It also appears that without neglecting the possible consequences of the paleoclimates on the environment, the geographical distribution of the described facies seems to be related to the present climatic conditions, vegetation types and kinds of landforms.

The genesis of the central concept of the sombric horizon only will be examined. Two general hypotheses are presently proposed: the first considers the Hsom horizon as a relict buried A horizon (Neel; Riquier, 1966; De Craene and Laruelle, 1955; Escobedo, 1980); the second as the result of a progressive illuviation process coupled with the accumulation of organic matter (Sys et al., 1961; Soil Taxonomy, 1975). The contribution of both processes working either simultaneously or separately cannot be precluded.

The working hypothesis will have to account for the morphological and analytical facts that have been described.

a. Real but local, weak discontinuity and general appearance in the uneroded relief of the regions whose altitude is higher than 1900 m; more discontinuity and apparently more localized presence in the lower zones (1600-1900 m).

b. Heterogeneous thickness and colours on a same slope complex of the same landscape unit.

c. Distinct but often gradual and slightly undulating limits.

d. Relatively uniform burying depth and broad parallelism with the level of the actual surface on the same slope of moderate inclination, protected from intense erosion.

e. Textural characteristic homogeneity of the pedon freqauently unmodified by its presence.

A generalization of the hypothesis which likens the sombric horizon to a buried horizon has difficulty in covering the points mentioned in d and e. Pollen analysis, which has as yet only been performed on a few samples, indicates that the floral composition of the pollen may be either similar or different between the epipedon and the Hsom. However before giving a definite opinion, complementary studies are needed if we wish to exclude the possibility of pollution of the Hsom by migration of pollen from the epipedon (Munaut, personal communication). On the other hand, a micromorphological study of only one sample of Hsom shows some similarities with the characteristics of a humic surface Al (Stoops, personal communication). Finally a ^{14}C dating performed on one Hsom sample only gives an age of about 12,000 years B.P. (Gilot, personal communication).

If this hypothesis is kept in mind, the above objections being neglected, several origins of surficial deposits could be considered: overlying of old soils by colluvial materials showing similar textures (mass movement at short distance in the landscape) or a process of material inversion (Segalen, 1969; De Craene et Laruelle, 1955).

The illuvial origin of Hsom should cover most of the above remarks. Even so, the mechanisms of this differentiation are still unknown. As far as we know the Hsom horizon does not exhibit specific properties which are related to the type of the humic compounds. It should be pointed out, however, that cultivation of these soils by the addition of an abundant sup-

ply of organic matter, over a long period of time, is accompanied by physico-chemical and morphological metamorphosis of the pedon (structure improvement, coloured coating development on the peds, increase of the degree of saturation of the exchange complex, etc.). By progressive and cumulative invasion of the pedon by humic matter, this process can affect soil thickness greater than 100 cm (anthropic soils). De Craene and Laruelle (1955) also suggest that the homogenization of Hsom occurs by a progressive impregnation of the parent material.

Summarizing, numerous questions are still unanswered and it is necessary to complete the present information by a systematic multidisciplinary study carried out both in the field (pedology, geomorphology, etc.) and in the laboratory (physico-chemical, micromorphological, palynological, ^{14}C dating characterization, etc.).

TAXONOMY

Whatever its origin, the geographical extension and the specific properties of the sombric horizon are such that its existence cannot be ignored. It is therefore logical to include it among the diagnostic subsurface horizons, and its presence can be interpreted at any classification level. In this case, its inclusion into the classification scheme of Oxisols, Alfisols, Ultisols and Inceptisols should be considered.

If various facies are included under the definition of the sombric horizon, then its definition should be extended. In this context, Eswaran's (1980) proposals constitute an excellent basis for discussion.

We would also note that the interpretation of charge properties allowing the identification of the presence of an oxic horizon is difficult in the high altitude humic soils of Rwanda and Burundi, if no allowance is made for their organic matter content. The difficulty is further enhanced when a sombric horizon is present.

Moreover, it should be pointed out that there is still controversy concerning the influence of the Hsom on the land capability of the soils.

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DISCUSSION

Q. A. Osman: Did you find any difference between the kind of organic matter in the surface horizon and in the sombric horizon?

A. R. Frankart: Preliminary results concerning this point--fractionation of the organic matter into fulvic and humic acid and humine--are not conclusive.

Q. P. Segalen: Have you determined heavy minerals above and below the sombric horizon?

A. R. Frankart: No, unfortunately not.

Annex 1

SOMBRIHUMOX or SOMBRIORTHOX

Localisation : TEZA (Burundi)
Altitude : 1960 m
Topography : slope 27%

Parent materiel : Schist
Vegetation : Savanna (Eragrostis)
Annual precipitation : 1600 mm

Depths cm	Horizon	Color wet	Particle size distribution (µ,%) 0 20	2 20	20 50	50 100	100 250	250 500	500 1000	1000 2000	C %	N %	C/N
0 - 23	A1	7.5YR3/4	51.3	5.7	6.3	6.2	23.4	6.4	0.6	0.1	2.60	0.22	11.8
23 - 40	AB	5YR4/4	58.4	6.1	6.2	5.9	17.9	3.8	1.1	0.6	1.26	0.12	10.5
40 - 94	B2ox	5YR4/4-4/6	57.8	6.5	6.5	5.7	16.4	4.5	1.6	1.0	0.75	0.10	7.5
94 - 110	Hsom 1	5YR3/2	57.6	6.3	6.8	6.4	17.3	4.0	1.0	0.6	1.02	0.10	10.2
110 - 140	Hsom 2	5YR3/3-3/4	56.7	6.2	7.2	6.3	17.5	4.1	1.0	1.0	1.19	0.10	11.9
140 - 180	C1	5YR4/6	57.7	6.0	5.7	5.9	17.1	4.6	1.5	1.5	0.51	0.06	8.5
> 180	C2	5YR4/6	56.0	6.0	6.0	6.8	18.2	4.4	1.4	1.2	0.20	0.03	6.7

Horizon	pH 1/5		NH_4Ac meq/100 g soil Extractable bases							Ex. acidity meq/100 g soil		Fe_2O_3
	H_2O	KCl	Ca	Mg	K	Na	Sum	C.E.C.	V%	Al	H	%
A1	4.6	4.2	0.2	0.2	0.2	-	0.6	17.2	3.5	3.9	0.5	5.7
AB	4.3	3.9	0.1	0.1	0.2	-	0.4	12.6	3.2	4.1	0.6	6.7
B2ox	4.4	4.0	0.2	-	0.1	0.1	0.4	8.7	4.6	4.1	0.7	6.9
Hsom 1	4.6	4.0	0.2	-	0.1	-	0.3	11.2	2.7	4.6	0.4	6.7
Hsom 2	4.3	4.0	0.2	0.1	0.3	-	0.6	12.9	4.7	6.2	0.7	6.9
C1	4.5	4.1	0.1	-	0.2	0.1	0.4	7.9	5.1	3.9	0.4	7.0
C2	4.8	4.0	0.2	-	-	-	0.2	6.5	3.1	2.7	0.5	6.9

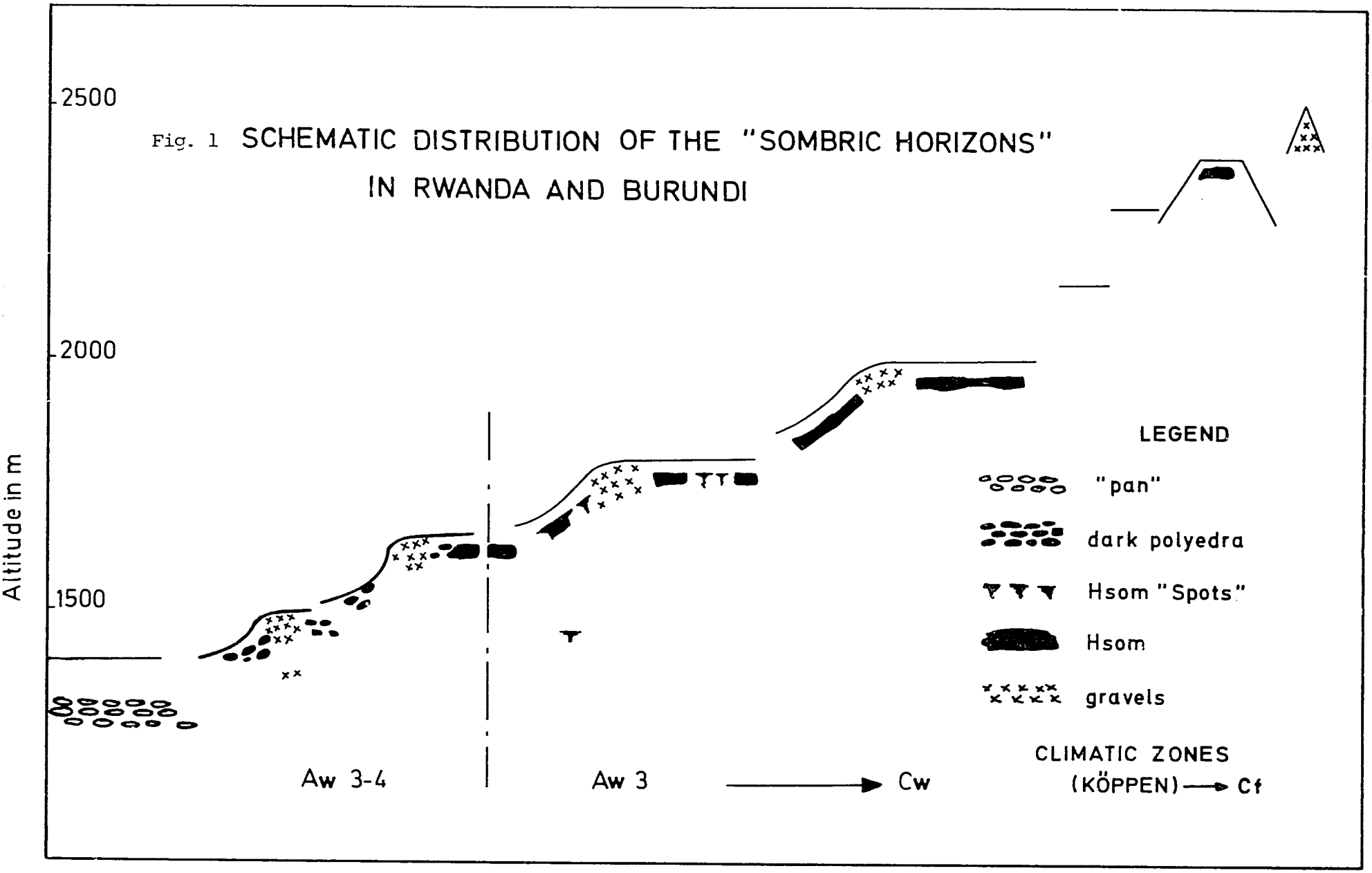
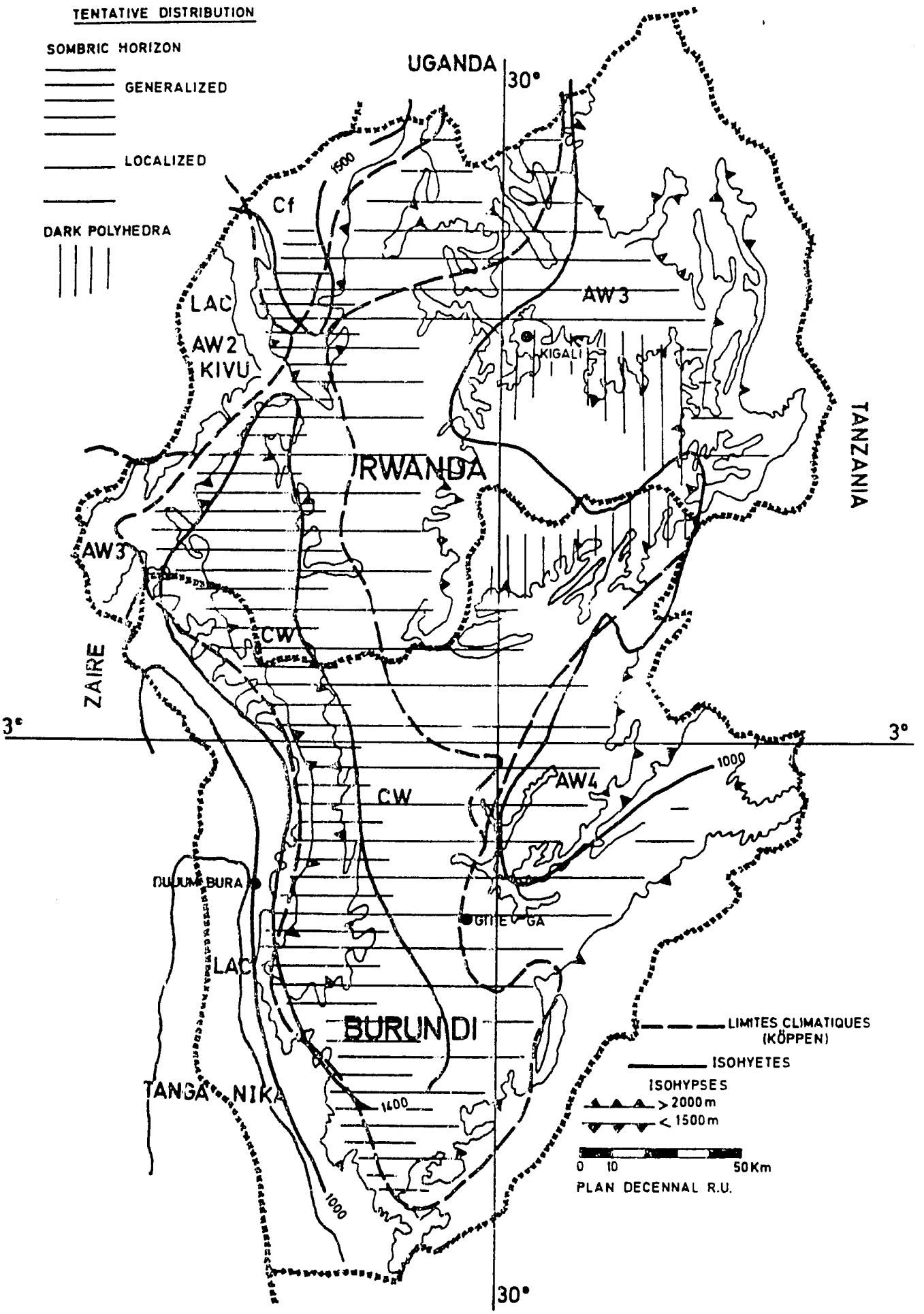


Fig. 1 SCHEMATIC DISTRIBUTION OF THE "SOMBRIC HORIZONS" IN RWANDA AND BURUNDI

Fig. 2


TENTATIVE DISTRIBUTION
SOMBRIC HORIZON
GENERALIZED
LOCALIZED
DARK POLYHEDRA
UGANDA
30°
1500
Cf
LAC
AW2
KIVU
AW3
KIGALI
RWANDA
TANZANIA
AW3
CW
ZAIRE
3°
3°
1000
AW4
CW
BUJUMBURA
GITEGA
LAC
BURUNDI
TANGANIKA
1400
1000
30°
LIMITES CLIMATIQUES (KÖPPEN)
ISOHYETES
ISOHYPSES
> 2000 m
< 1500 m
0 10 50 Km
PLAN DECENNAL R.U.

THE OXISOLS OF MALAGASY

P. Segalen

INTRODUCTION

Soil studies in Malagasy started a long time ago, as early as the beginning of the century. Pioneer work was done by A. Lacroix (1926) and H. Erhart (1933). Before World War II, a great number of mineralogical data were already available on the main soils of the island and a few characteristic profiles had been described that were later considered as references by various soil scholars and geographers.

After the war, systematic soil surveys began with ORSTOM pedologists (Bourgeat, Claisse, Hervieu, Moureaux, Ratsimbazafy, Riquier, Segalen, Sourdat, Soubies, Tercinier, Vallerie, Vieillefon, Zebrowski), and many maps at various scales were issued.

In neighbouring fields, many important works were done by Besairie and his colleagues (geology); Humbert, Bosser, Perrier de la Bâthie (botony and vegetation patterns); Dixey, Bourgeat, Petit, Tricart (geomorphology); Battistini, Bied-Charreton et al. (geography and quaternary).

A number of agronomists have also contributed to a better knowledge of Malagasy soils, among them Dufournet, Didier de St. Amand, Roche, Velly.

What soils have been encountered on this island? Most of the field and laboratory work was done before 1970, even if some of the publications were issued later on. The interpretation of the soils was done by French pedologists using a French soil classification system. To my knowledge, no correlation with Soil Taxonomy has been attempted. So it is not easy to give general information on Oxisols to begin with. The nearest class is undoubtedly "Sols Ferrallitiques." So we shall start with these, see what their characteristics are and then try to correlate them with Oxisols.

FACTORS OF SOIL FORMATION

Madagascar is an island off the southeast coast of Africa, located in the Indian Ocean between 12 degrees and 26 degrees S. Lat. The whole area represents 585,000 km^2 and is 1,600 km from the northern to the southern end. A few outstanding features are:

- Abundance of granites and gneisses in the east and center; a set of monoclinal sediments on the west.
- The elevation of the central highlands is generally between 1,200 and 1,600 meters with very steep scarps on both sides.
- The predominant red color of the soils which gave the island the name of "Ile Rouge" (red island).

Parent Rocks

The nature of the parent rocks offers an apparent simplicity. Madagascar is a piece torn from Gondwanaland during the mesozoic. Various entities of metamorphic rocks have been recognized by geologists, but we cannot go into further details here. Marine sedimentary rocks, mostly limestones and marls, appear along the western coast. They all present a slight dip towards the Mozambique Canal and the stratigraphic column is quite complete from the Carboniferous up to the Pleistocene. During the Pliocene and Quaternary, sandy or clayey sands were deposited over these sediments and their reddish colors make them known as "sables roux" (reddish-brown sands). In various places appear volcanic rocks, mostly basaltic. A fast fluid outflow spread over cretacic sediments and is gradually exposed now by erosion. Elsewhere, other volcanic masses are known in the southern Androy, in the central Ankaratra and in the northern Tsaratanana and Montagne d'Ambre. Smaller ones like the island of Nosy Be and others have also been studied. Most are end tertiary or quaternary rocks; some are very recent with barely weathered lava flows or volcanic ashes.

Geomorphology

It is not very easy to give a simple view of the area. The main feature is the central highlands, the elevation of which is 1200 to 1600 m.

The eastern and western rims are very steep, with a difference in level of more than 1000 meters. Locally, faults lower or raise parts of the topography, as in the Alaotra basin. Volcanic accumulations raise the land in some instances up to 2800 meters.

Generally speaking, the mean elevation is quite constant. However, one can notice various levels which have been smoothed by erosion. The highest one is known as Tampoketsa (1600 m high) and is thought to be Cretaceous. The intermediate one (1350 to 1450 m) is attributed to the medium Cenozoic. The lower one is always less than 1300 m high, and is End Tertiary.

As a whole, the topography is ever changing and very seldom flat, except in some valley bottoms. Hills are the dominant element of the landscape and some valleys are very deep. Presently, very severe erosion prevails almost everywhere, and a particular form named "lavaka" is widespread. Everywhere except in very flat valleys where hydromorphy may be important, drainage is pretty good and usually profiles seldom show mottles.

Climate

Located in the southwestern part of the Indian Ocean, with a sort of upright position, Madagascar is run against by the trade winds blowing from the east. The oriental rim is like a 1600 m wall which they have some difficulty overcoming. So most of the precipitation falls on this narrow strip of land: more than four meters in the central part, decreasing gradually towards both ends, especially in the north where precipitation goes down below 1 m. The monsoon blowing from the northeast crosses the equator and swings round to the southeast so that the northwest coast of the island receives additional rainfall. These two winds combine their effects on the east, central and northwest part of the country, while the southwest is out of their reach. Ferrallitic soils will match quite well with this more rainy area.

There are some exceptions to this general rainfall distribution pattern. Like the extreme south, the northern end of the island is pretty dry (less than 1 m). But very close to it, rainfall climbs up to 2.5 m to decrease steadily towards the south. On some mountain tops, where re-

cords are available, especially in the Ankaratra massif, rainfall above 2 m is common.

Temperatures are much more influenced by altitude than by latitude. Mean annual temperatures vary from 23 to 26 degrees C along the eastern coast as well as on the western one. But on the central highlands, means drop to 18 to 20 degrees C. At high elevations temperatures are near 12 degrees C. Snow is unknown all over the country but morning frosts are frequent and severe during winters on the highlands.

The weather regime is equatorial along the east coast with high rainfall (2-4 m) and temperatures with no dry season. In the other parts of the country, the regime is tropical with various lengths of rainy and dry seasons.

Vegetation

Ferrallitic soils have all initially developed under forest vegetation. Primary evergreen rainforest is limited to the eastern slopes and is being steadily cut down by rice growers. On the central highlands or western coast the primary deciduous forest has almost completely disappeared, eaten away by bush fires, and replaced by expanses of savannah and mostly grasslands. In the south and southwest a very peculiar xerophytic vegetation rich in endemic genera and families offers better resistance to all sorts of degradation but is also slowly receding.

The Quaternary Record

Quaternary deposits in various valleys have been used as benchmarks in the central highlands. Alluvial deposition is correlated with decrease of rainfall; likewise high rainfall and dense vegetation periods favour deep weathering and soil development. Three displuvials are known to correspond to alluvial terraces. Datation based on stratigraphic correlations and radio carbon ages have been proposed. The upper terrace is more than 120,000 years old; the second is 40,000 years old and the younger one is 20-25,000 years old. The flandrian transgression is considered as the last pluvial, whereas the present is considered as somewhat drier.

Whatever the exact age may turn out to be in the future, one thing is certain: Here, as elsewhere in the tropics, climate has changed several

times, from humid to dry, and soils, vegetation and geomorphology have been affected. These changes are certainly responsible for some of the features to be studied presently. But altogether ferrallitisation has been for a very long time the main soil-forming process. The soils we see now originated a very long time ago. Even if they were disturbed by dry spells, however lengthy, they all bear the marks of weathering under long rainy periods and good drainage.

DISTRIBUTION OF MALAGASY SOILS

Now that the main soil-forming factors have been reviewed, let us see how soils are distributed (Fig. 1).

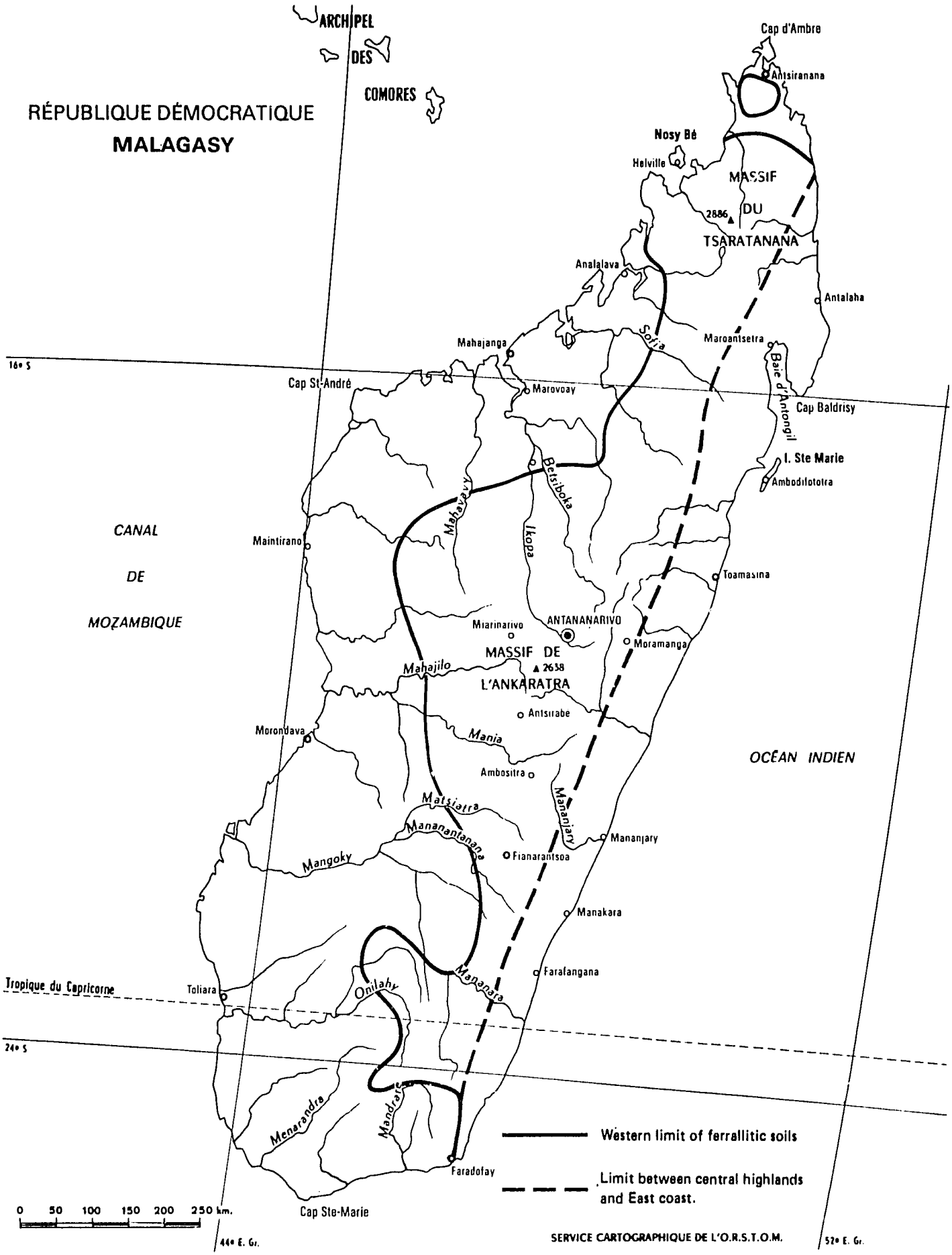
Ferrallitic soils cover half the land--almost all the eastern coast and a great part of the central highlands. However, some important areas are occupied by bare rock or lithosols. High volcanic mountains correspond to Andosols and some valleys or basins are occupied by hydromorphic soils. But we can consider that the general trend is given by ferrallitic soils, facing the east and northwest.

Along the western and the southern coasts fersiallitic soils are predominant, along with halomorphic, hydromorphic and again bare rocks and lithosols. In this area, patches of ferrallitic soils are known, but too small to appear on a small scale map. Vertisols are present; Mollisols are virtually unknown.

MAIN CHARACTERISTICS OF FERRALLITIC SOILS

As mentioned previously, these soils were studied as early as the first half of the century by Lacroix (1926) and Erhart (1933). The former made quite a large number of analyses which contributed to the notion that all Malagasy ferrallitic soils contained high amounts of gibbsite. This was considered a decisive characteristic, besides various amounts of iron oxides, hydroxides and kaolinite.

This constant presence of gibbsite must be emphasized. Many French


ARCHIPEL
DES
COMORES
RÉPUBLIQUE DÉMOCRATIQUE
MALAGASY
Cap d'Ambre
Antsiranana
Nosy Bé
Helville
MASSIF
DU
TSARATANANA
2886
Analalava
Antalaha
Mahajanga
Sofia
Maroantsetra
Baie d'Antongil
16° S
Cap St-André
Marovoay
Cap Baldrisy
I. Ste Marie
Ambodilototra
Betsiboka
Mahavavy
Ikopa
CANAL
DE
MOZAMBIQUE
Maintirano
Toamasina
Miarinarivo
ANTANANARIVO
Moramanga
MASSIF DE
L'ANKARATRA
2658
Mahajilo
Antsirabe
Morondava
Mania
OCÉAN INDIEN
Ambositra
Matsiatra
Mananjary
Mananantanana
Mananjary
Fianarantsoa
Mangoky
Manakara
Faralangana
Tropique du Capricorne
Toliara
Onilahy
Mananara
24° S
Menarandra
Mandrare
Faradofay
Western limit of ferrallitic soils
Limit between central highlands
and East coast.
0 50 100 150 200 250 km.
Cap Ste-Marie
44° E. Gr.
SERVICE CARTOGRAPHIQUE DE L'O.R.S.T.O.M.
52° E. Gr.

soil scientists concluded that ferrallitic soils must contain amounts of gibbsite. Indeed a sharp break exists as far as this mineral is concerned between the central highlands and the western low-lying soils where it is seldom to be found. In addition, differences in morphology were important. Of course this position was changed later on.

Erhart was the first to study the morphology of the soils and to give descriptions of a few profiles, especially on the eastern rim and central highlands. He insisted on the thickness of the weathering zone, which had already been pointed out by Lacroix, and on the various red, yellow and humic horizons. He also studied some laterites on the Tampoketsa and proposed explanations for the formation of the main soil types.

So, when the first ORSTOM pedologists arrived in 1946, they were provided with a general frame of reference giving some data on the mineral contents and the morphology of ferrallitic soils. Of course, things were not that simple. Little by little, a number of differences appeared, that I shall now try to account for.

As far as constituents are concerned, the presence of gibbsite was confirmed by all those who analysed the soil material. In many instances, high free alumina content was considered at group level, when the SiO_2/Al_2O_3 ratio fell below 0.8. Typical ferrallitic soils were those where the ratio was higher than this value (Bourgeat, 1972; Zebrowski, 1979). This low ratio was observed in soils derived from any kind of parent rock.

The soil organic matter content very often appears high. In the central highlands, the content is often near or above 5%. At high elevations, 8 or 10% is not uncommon. These high percentages call for a humic group. Usually the organic matter decrease in the profile is gradual and at 1 m depth, the content is still near 1 or 2%, and the colour of the soil is more brown than red.

If we consider now some important chemical properties, the CEC of the mineral fraction of the soil is pretty low as compared to normal for oxides and kaolinite rich soils. The degree of saturation is low on the eastern warm and rainy coast. On the central highlands at medium elevations (1200 to 1400 m) S/CEC is around 30-50%, but decreases rapidly at higher elevations. But on the western coast, ferrallitic soils have a higher degree of saturation. The exchangeable bases are often low to very low, calcium being as usual the dominant base.

A careful scrutiny of the profiles enables several observations. The B horizons are red almost everywhere in the central highlands. But along the eastern rim the upper part of the soil turns to yellow, while the lower part remains red, with no textural differentiation. This can be compared with some Amazonian soils. Entirely yellow soils appear now and again, but are not so common.

The thickness of the profile is generally great but appears to be due to two factors: time and the basic composition of the rocks (granites and other metamorphic rocks). As a result, the weathering zone is several tens of meters thick, and is visible everywhere, since erosion is severe and tears open most of the hills in the central highlands. But soils derived from other parent rocks, such as basalt or limestone, are never so and are only 2-3 m thick.

Most of the soils of the central highlands show a stone-line, as a result of local or general erosion affecting the upper part of the profile, mostly during the Quaternary drier periods referred to previously. This is a rather constant feature, and such soils are called "remaniés," reworked. This stone-line is also common in central and western tropical Africa.

Many profiles are considered truncated. Probably several meters of soil have been lost by erosion and the highly weathered horizons have gone. Now, near the surface some weatherable minerals can be found, the silt content is pretty high, and the fertility status is much better. These soils are always considered as ferrallitic as the evolution trend is the same as that of the neighbouring ones. They are called "pénévolué" or "rajeuni."

In some areas, plinthites can be found, but not so often as one could imagine after reading the first papers describing them in the Tampoketsa and Horombe. They occupy rather small plateaux with steep slopes. Some contain very high amounts of alumina.

And now, let us consider the variations of clay content in the profiles. Many soils do not show any significant clay variation. In some profiles, the upper horizons show less clay than in the underlying horizons. But this is not accounted for as eluviation. True textural B horizons have seldom been described and no information about clayskins or mi-

cromorphology are available. These soils are considered impoverished. An impoverishment index is calculated by dividing the clay content of the richer horizon by that of the poorer one. If the value falls below 1.4 the soil is considered weakly impoverished; above 1.4 the soil is impoverished. Most of these soils are considered reworked.

CORRELATIONS WITH SOIL TAXONOMY, ESPECIALLY WITH OXISOLS

All those who have worked for some time in Madagascar agree that they have not encountered true argillic horizons in any ferrallitic soil. But of course, this opinion may have to be revised when new observations supported by micromorphological determinations are available. So at the present time, Ultisols, and eventually Alfisols, must be considered as unimportant in the ferrallitic zone. Most of the soils can be accounted for as Oxisols.

Most of them, along the eastern rim and many places in the central highlands can be considered as Orthox, many of them being Haplorthox. On the drier parts of the central highlands and in various places of the western coast, soils are Ustox (Haplustox or Eutrustox).

As mentioned before, gibbsite is present in many soils, but few comply with the definition of a gibbsic great group. Acric great groups may exist but it is not possible to locate them now.

Those soils that show a thick organic matter A horizon, have also a low base saturation, dark brownish colors, and are met at high elevations with cool temperatures. They can be accounted for as Humox; the great groups are Sombrihumox or Haplohumox.

The soils that are called "pénévolué" or "rajeuni" probably should not be considered Oxisols, as they contain some weatherable minerals and have a CEC too high for a true oxic horizon. They are likely to fall into Oxic Dystropepts.

USE OF THE SOILS

When the use of the soils is concerned, a sharp distinction must be

made between the eastern rim and the central highlands. Along the eastern coast where temperatures are warm and rainfall high, ferrallitic soils are planted with trees, mostly *Coffea robusta*, and also with various spices like clove or vanilla. In various places, eucalyptus or pines are planted for timber. Natural forests are very often cut down to grow rice.

On the central highlands, ferrallitic soils are seldom cultivated. Most of the land is kept for grazing by abundant cattle. Topography is undulated and erosion is severe. People live off irrigated paddy fields so they very seldom cultivate the hills. But whenever they do, pénévolué ferrallitic soils give better results than the others.

CONCLUSIONS

Ferrallitic soils occupy about half of the surface of Madagascar. They are generally derived from granite and gneiss, are very deep, rich in gibbsite and locally very badly eroded.

Many of them can be correlated with Oxisols (Orthox or Humox). Furthur determinations are needed to know what part of them has to be attributed to other orders like Ultisols.

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THE FERRALSOLS OF ZAIRE

C. Sys

SOIL-FORMING PROCESSES

The Ferralsols represent the ultimate stage of ferrallitic weathering. The main soil-forming process is ferrallitization. This consists of a residual accumulation of iron and aluminum oxides as a result of intensive weathering of primary minerals with a nearly complete elimination of bases and an important elimination of silica. The most important alumino-silicate clay mineral is kaolinite. The term "ferrallitic" therefore represents a type of weathering and not a soil group.

However, this type of weathering can be subdivided according to the progress of the weathering process in successive stages: recent, intermediary and ultimate. These successive stages of weathering can be recognized in a deep residual End Tertiary peneplain soil with free drainage (Fig. 1). The recent stage at the bottom of the profile is not more than 50 cm thick and includes some weatherable minerals and rotten rock fragments.

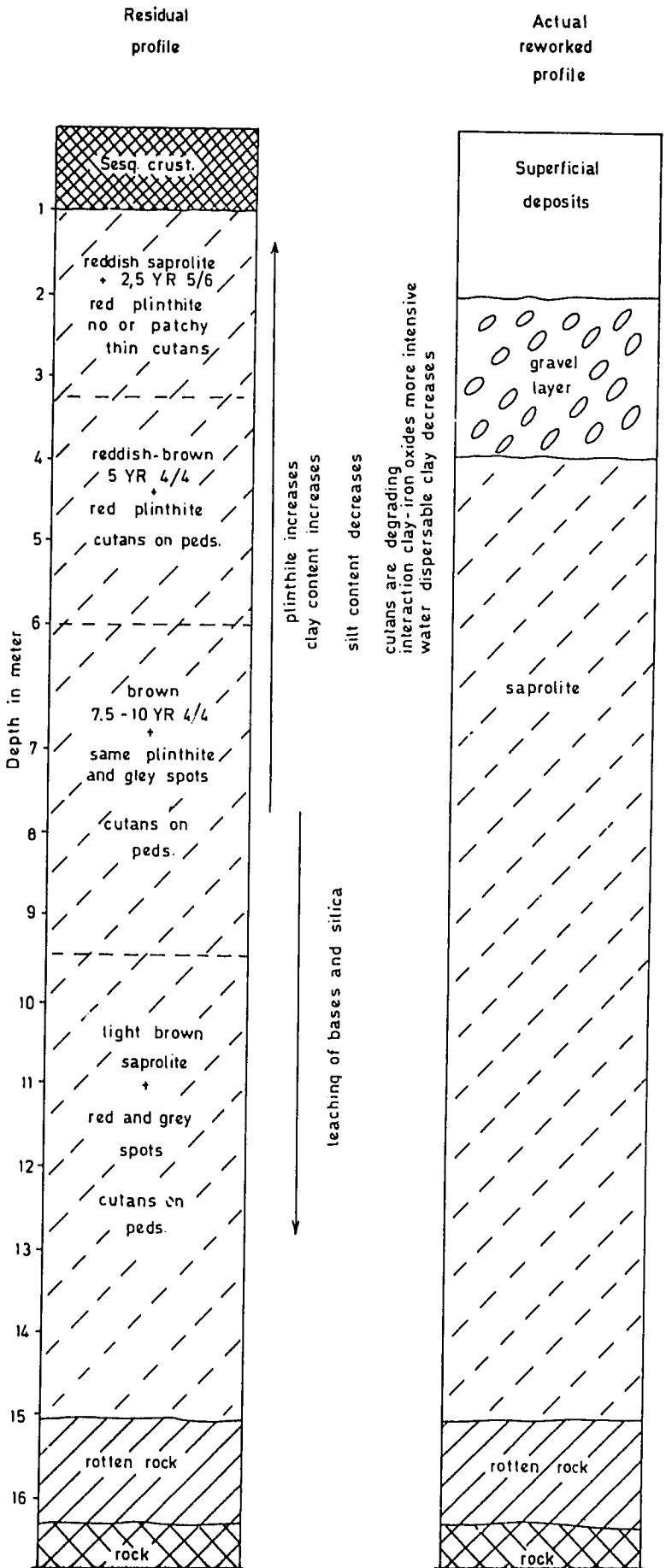
With progressive weathering from bottom to top we see an increase of clay content and individualized iron oxides (plinthite) and a decrease of silt. A degradation and final disappearance of cutans toward the top associated with a progressively more intensive interaction between clay and iron oxides and a decrease of water dispersable clays is also noted.

The intermediary stage of weathering from about 50 cm above the rotten rock up to the depth of 2-3 m has the following characteristics:

- dominance of low activity clays and in addition
- strong to moderate structure with clay skins on ped surfaces
- and/or a medium fine silt/clay ratio
- and/or some few weatherable minerals.

The ultimate stage of weathering characterizes the upper saprolite often capped by an iron crust. The loose soil below the crust containing

Fig.1. THE FERRALLITIC PROFILE



low activity clays is very loose, has a weak structure, no or only thin patchy cutans, a low, fine silt/clay ratio and no or no more than traces of weatherable minerals.

As a result of geological erosion the residual profile has been disturbed and a reworked material laid down over the lower residual saprolites. This reworked material consists of a gravel layer and a layer of superficial deposits (pediments). The weathering stage of the reworked profile will depend on its position and pre-weathering stage in the residual saprolite.

In the INEAC classification soil materials in the intermediary and ultimate stages of weathering, as defined above, are called, respectively, Ferrisols and Ferralsols.

Therefore the Ferralsol, as the ultimate stage of ferrallitic weathering, has all the characteristics of the Oxisols.

In most cases the intermediary stage of weathering (Ferrisol) has the mineralogical characteristics of oxic material; however the structure is too strong, and cutans indicate the mobility of the clay fraction. Therefore the subsurface horizon is considered as argillic.

SITUATION OF THE FERRALSOL IN THE LANDSCAPE

In Zaire the situation of the Ferralsol in the landscaple will depend on the broad geological units.

Zone of Soils Formed on Sedimentary and Metamorphic Rocks of Paleozoic or Pre-Paleozoic Age (Fig. 2)

The geological substratum consists of basement complex migmatites; high grade metamorphic rocks such as gneiss and amphibolite; low grade metamorphic rocks such as shist and mica shist; sedimentary rocks as conglomerates, sandstones, shales, limestones; all affected by tectonic movements. Intrusions of granites, diorites, gabbros and other plutonic materials are also present.

Most of this area has been subjected to peneplanation and different peneplain levels have been described, of which the most important are:

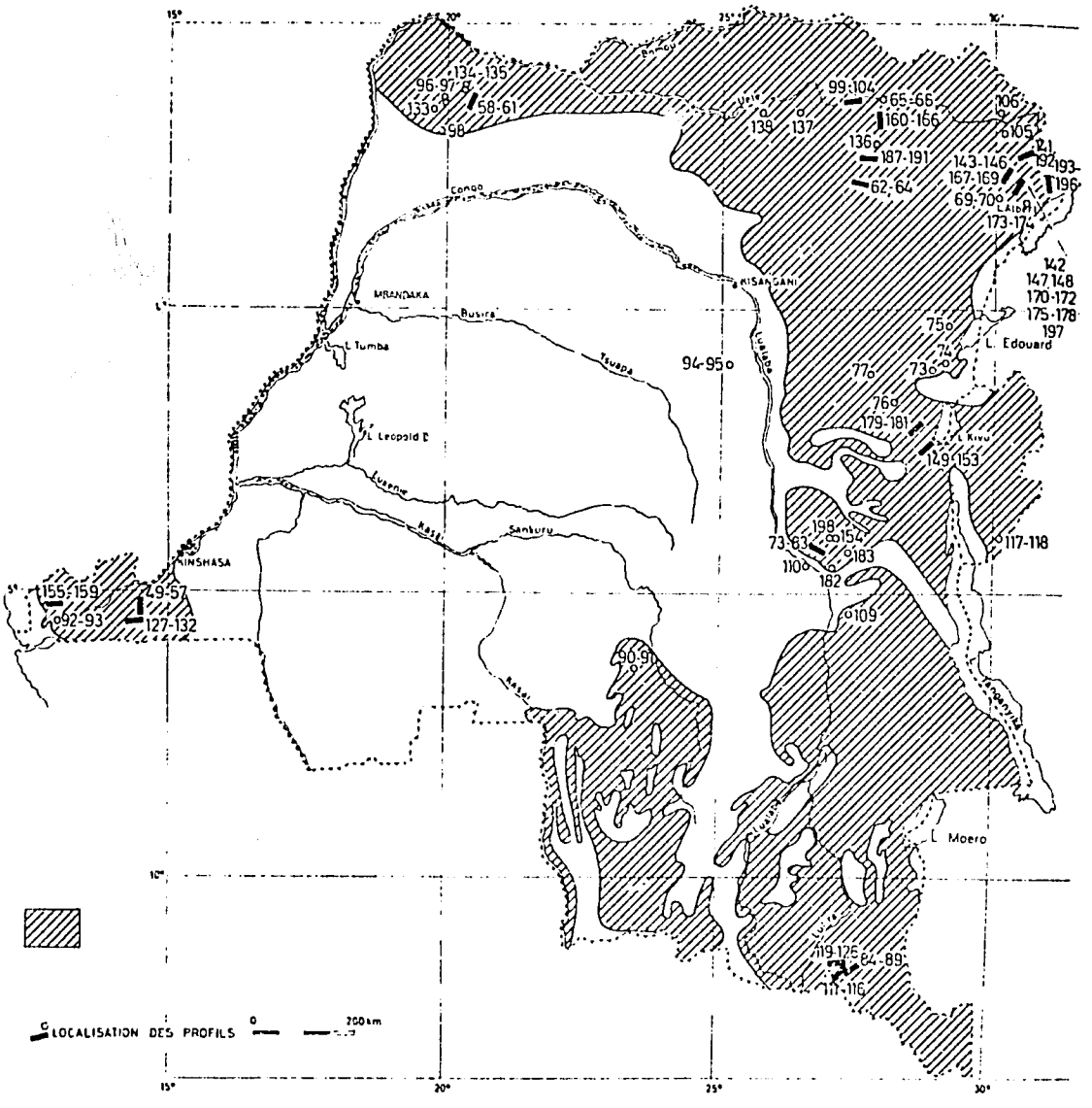


Fig. 2

Soils formed on weathering products of Paleozoic and Pré-Paleozoic rocks

PII: mid-tertiary peneplain

PIII: group of upper tertiary peneplains

These peneplained zones may be interrupted by residual landscapes as a result of the dissection of the peneplains during the Quaternary period (lower residual) or rejuvenation of uplifted areas (upper residual) (Fig. 3).

Zone of Soils on Mesozoic Rocks (Karroo)

This geological substratum consists of horizontal beds of argillites and soft sandstone more or less hardened according to their position in the stratigraphic succession. Fig. 4 indicates the geographical distribution of the soils formed on these rocks. Most of them appear in a lower residual landscape and are at the intermediary stage of weathering.

In some areas, however, (West of Leopold II lake, and N-E sector of the Zaire basin) some remnants of the tertiary peneplain on these rocks are remaining in the landscape. The soils on these peneplain remnants are at the ultimate stage of weathering and are Ferralsols.

Zone of Soils on Cover Sands

The soils developed on the accumulation surfaces of the cover sands occupy an important part of Zaire (Fig. 5). Formerly they were considered eolian deposits; however, more recent studies indicate the rather fluviatile and fluvio-lacustrine character of these deposits. The age is from End Tertiary for the Kalahari sands to more recent Pleistocene for the deposits of the lower Zaire basin.

All these soils have the characteristics of the ultimate stage of weathering and are Ferralsols. Therefore we presume that the deposits originate from highly pre-weathered materials.

As a conclusion one can say that the Ferralsols represent the ultimate stage of ferrallitic weathering and are associated with old peneplain levels of Tertiary or early Pleistocene age. When present on more recent Pleistocene surfaces or as accumulation deposits they are formed on highly pre-weathered materials.

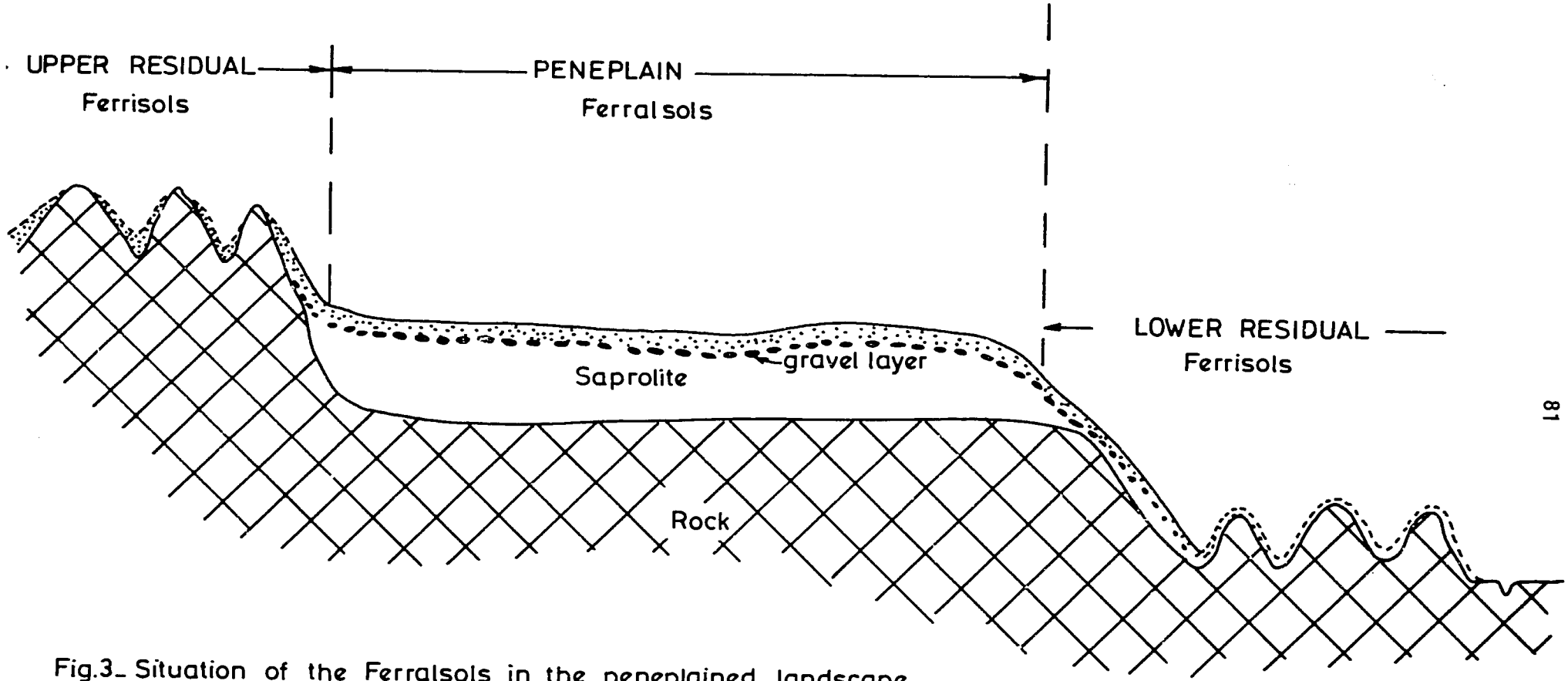


Fig.3_ Situation of the Ferralsols in the peneplained landscape on Paleozoic or pre-paleozoic rocks

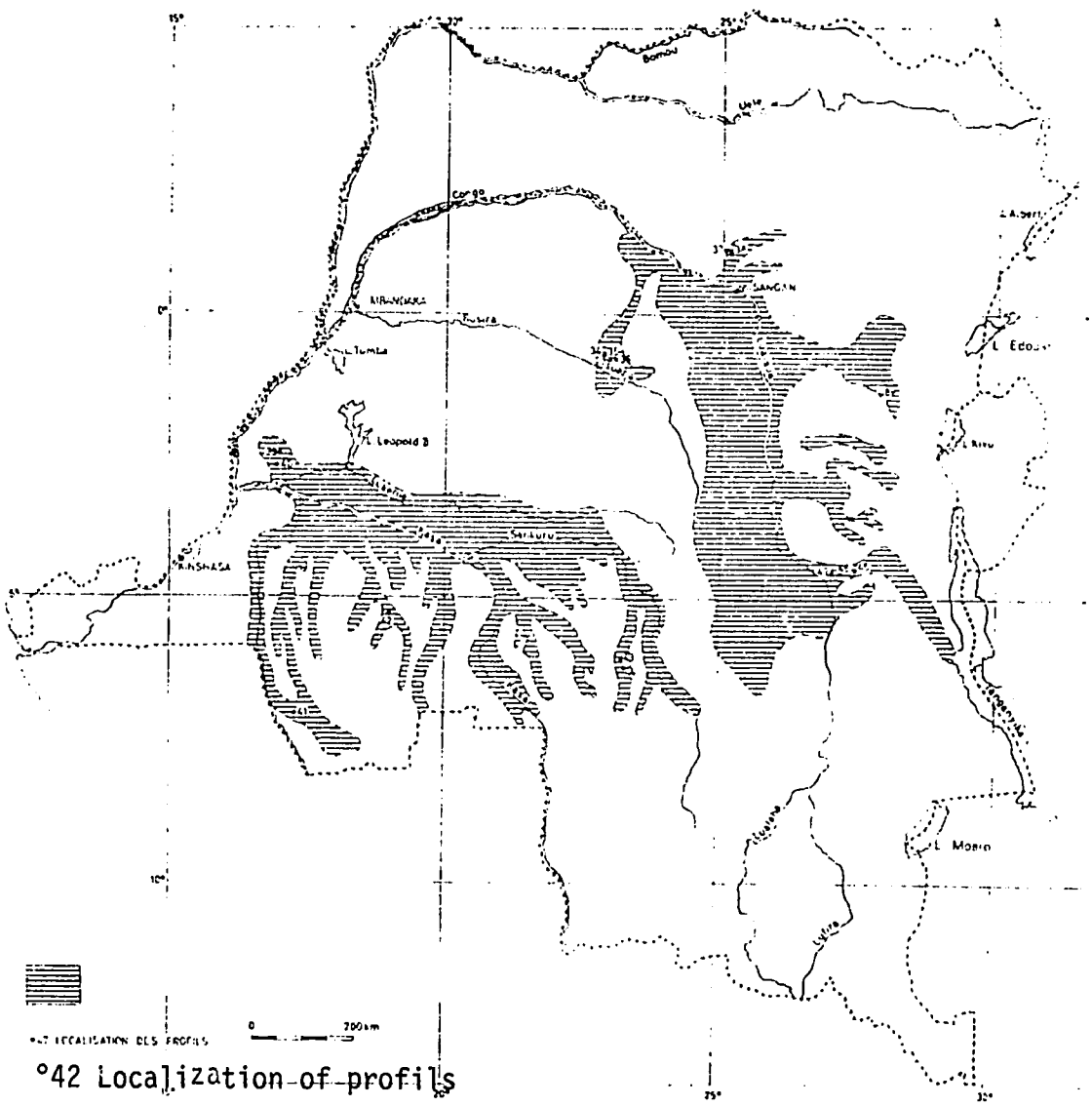


Fig. 4
Soils formed on Karroo rocks.

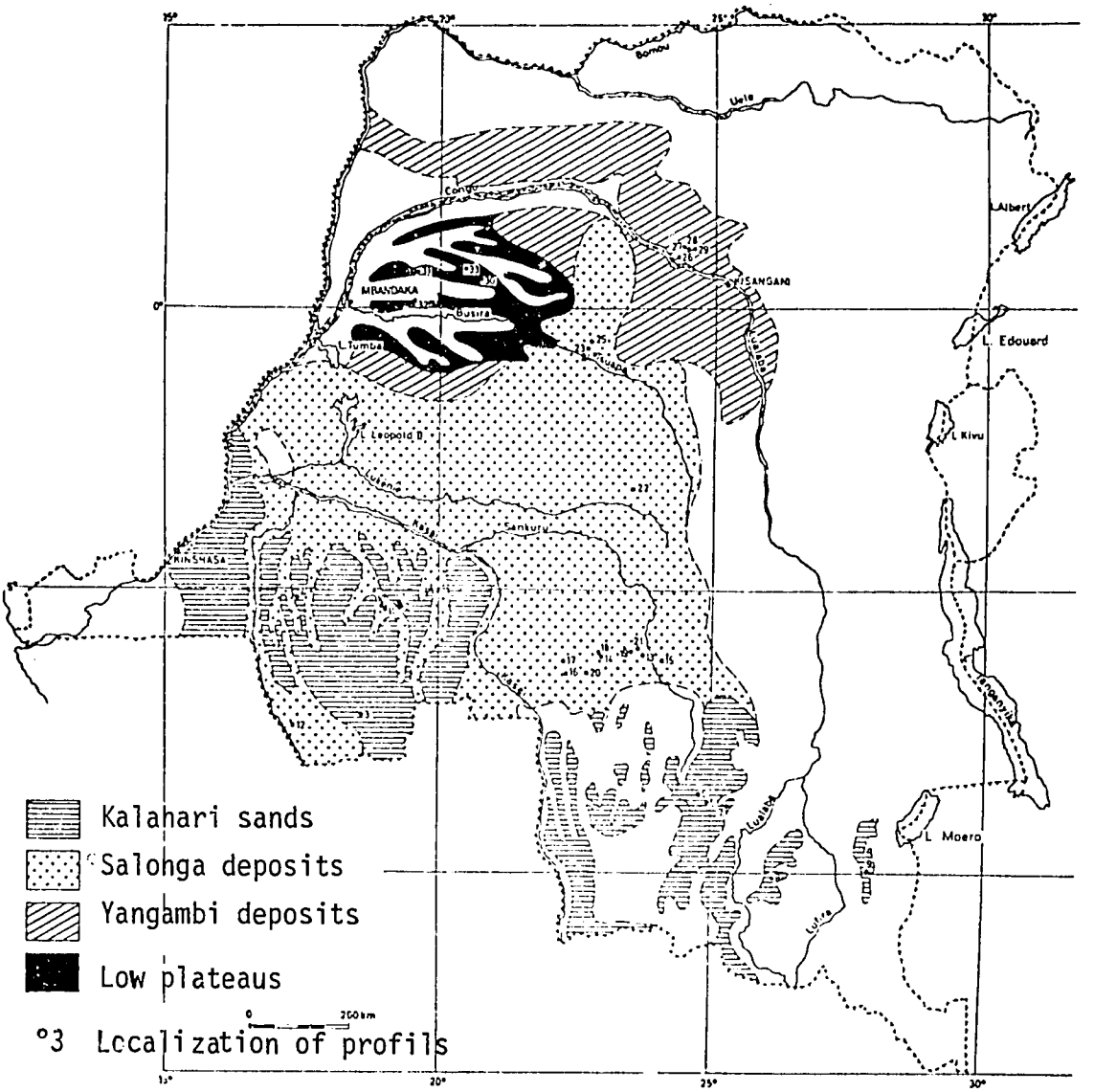


Fig. 5
Soils formed on cover sands

CHARACTERISTICS OF THE FERRALSOLS

Texture

General textural characteristics (Table 1, Fig. 6). The particle size distribution of the Ferralsols is characterized by:

1. a variable clay content (15-85%) related to the nature of the parent rock
2. a low fine silt content
3. presence of great amounts of pseudo-sand and pseudo-silt.

Table 1. Texture of B horizons of Ferralsols.

Geological Substratum	Particle size classes in micron			
	0-2	2-20	20-50	50-2000
Shales	54.0	3.0	6.5	36.5
Sandstone	34.9	2.1	3.2	59.8
Limestone	64.0	4.9	11.0	20.1
Granite	55.4	3.0	1.8	39.8
Amphibolite	86.2	2.1	1.2	10.5
Kalahari sand	20.1	2.0	14.7	43.2
Salonga sand	21.5	0.9	4.0	74.6
Yangambi deposits	37.6	1.4	2.2	58.8
Lower plateau deposits	40.7	2.0	2.3	55.0

The textural profile. The textural profile of typical Ferralsols, sometimes in comparison with Ferrisols, is illustrated in Figs. 8-17 for the most important lithological units occurring in Zaire. In these diagrams a profile number[1] is added to the line representing the textural profile. Two other figures related to the weathering stage are indicated; the upper one refers to the cation exchange capacity of the clay fraction of the B-horizon and the lower one to the ratio fine silt/clay.

Fig. 7 shows a topo-sequence on shales in Shaba of which the textural

[1] Profile number refers to: SYS, C. 1972; Caracterisation morphologique et physico-chimique de profils types de l'Afrique Centrale.

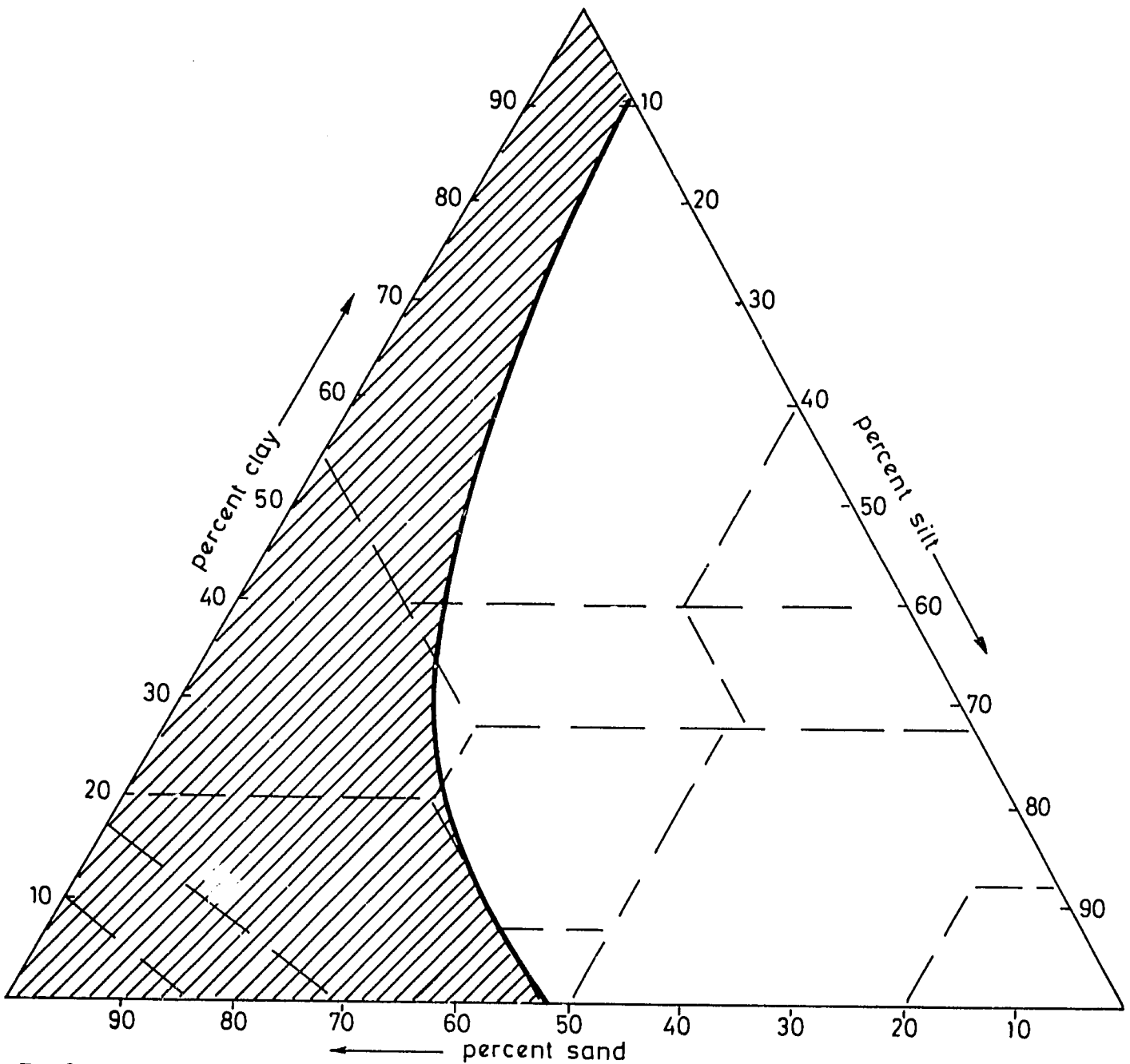


Fig.6_Place of the ferralsols in the textural diagram

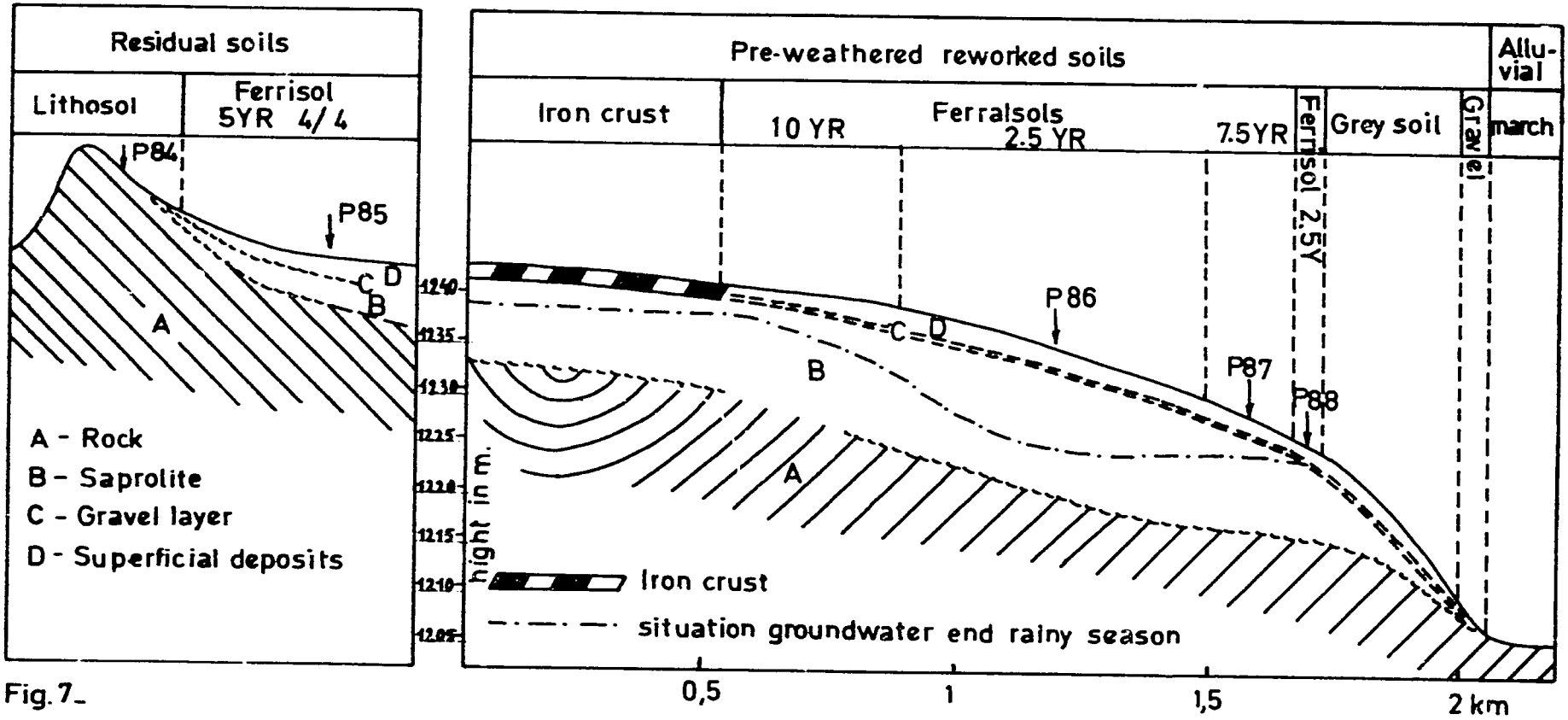


Fig. 7_
TOPOSEQUENCE ON SHALES IN S.ZAIRE

profiles are given in Fig. 8. Profile 84 is a recent Lithosol with more than 55%, by weight, of coarse shale fragments. Profiles 85 and 88 are both at the intermediary stage of weathering, with lower apparent CEC values and medium fine silt/clay ratio; profile 85 has a clearly differentiated textural profile. Profiles 86 and 87 are Ferralsols at the ultimate stage of weathering; the apparent CEC of the clay is as low as 6-7 meq/100 g of clay and the fine silt/clay ratio is extremely low. Both profiles have a textural differentiation; however, it is better pronounced in profile 86.

Other textural profiles of soils on shales are represented in Figs. 9 and 10.

The textural differentiation of soils on sandstone (Fig. 11) does not permit formulation of a general rule with regard to the textural profile. Two profiles belonging to the same mapping unit (92 and 93), and both Ferralsol, have a completely different textural differentiation.

The textural profile of some limestone and dolomite soils is given in Figs. 12 and 13.

The heavy clay soils on basic rock may or may not present a textural differentiation (Fig. 14). In most cases the intermediary and the ultimate stage of weathering present a similar trend. The same can be noted for soils on granite (Fig. 15).

On Karroo rocks (Fig. 16) one may note in some cases a better differentiated textural profile on the intermediary stage of weathering and vice versa in other cases.

In the Ferralsols on cover sands the clay increase is very gradual for Kalahari, Salonga and Yangambi deposits; on the other hand the lower plateaus of the Zaire basin have a well-differentiated textural profile (Fig. 17).

In conclusion we may say that in all the profiles there is an increase of clay content with depth. In most profiles this clay increase satisfies the clay increase criteria of the argillic horizon; only in very rare cases the criteria of the "fine textured subsurface horizon" are satisfied.

One also notes that at an advanced stage of weathering the clay increase may differ from profile to profile even in the same series. This is a normal feature on reworked materials where clay content seems more

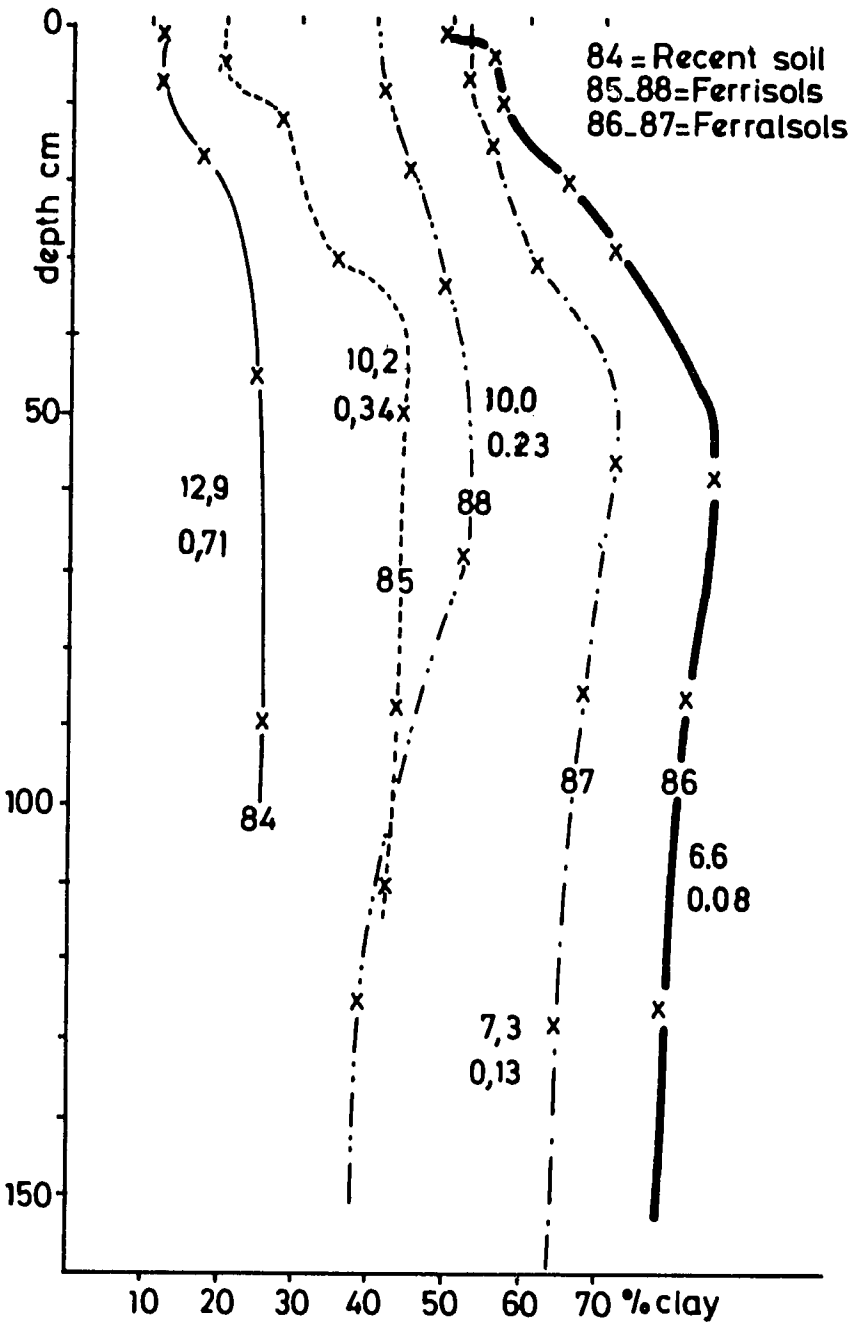


Fig.8 _ Textural differentiation of the profiles of the topo-sequence of shales in S-ZAIRE

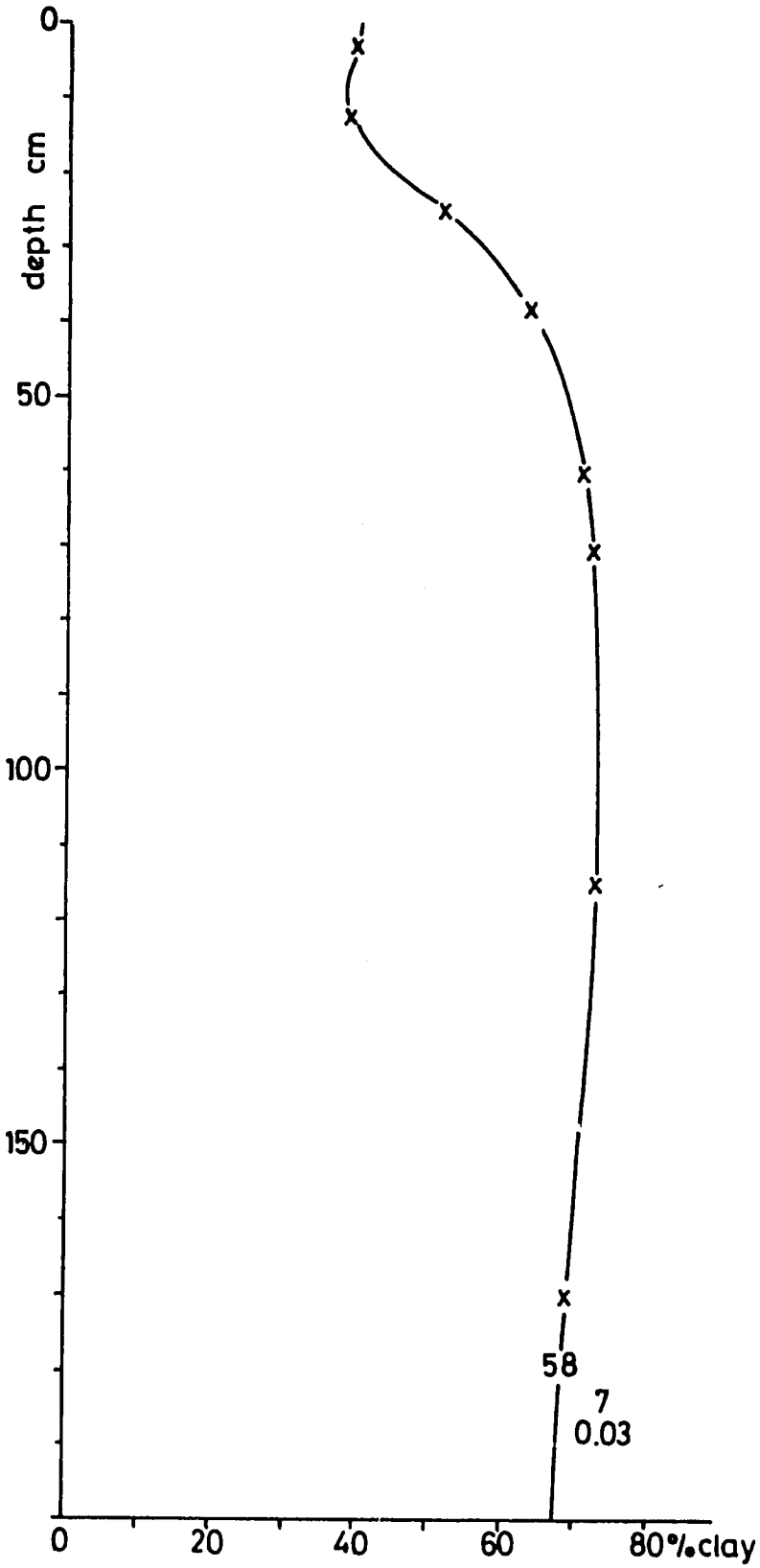


Fig. 9 _ Ferralsol on the End-Tertiary peneplain on shales UBANGI (N-W ZAIRE)

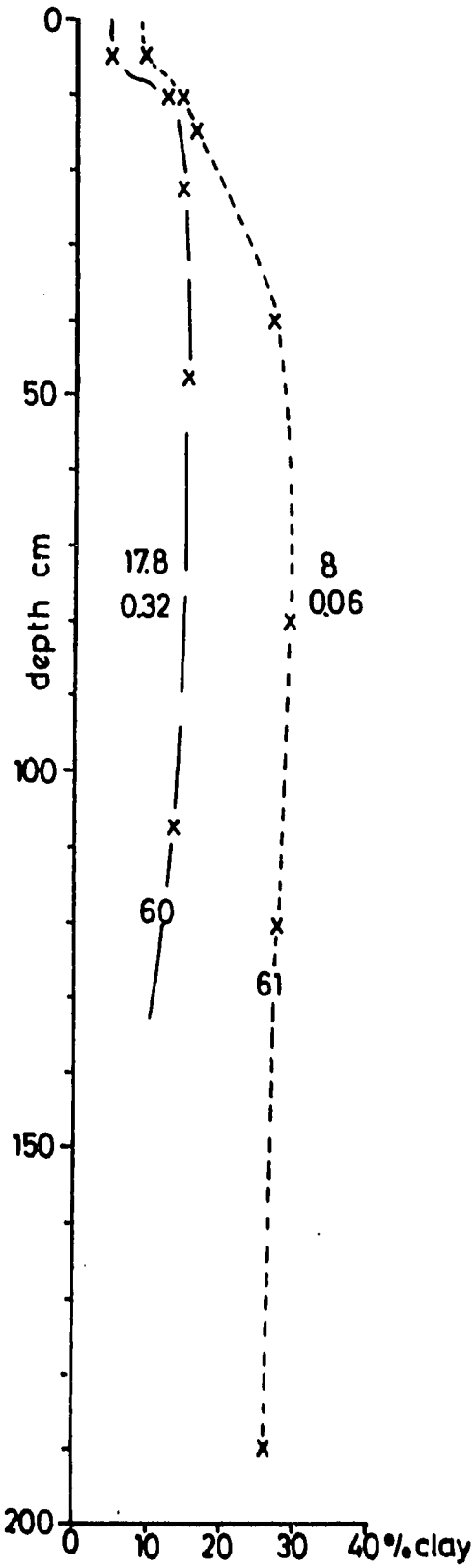


Fig.10_ Ferrisol (60) and Ferralsol (61) on shales in N-E ZAIRE

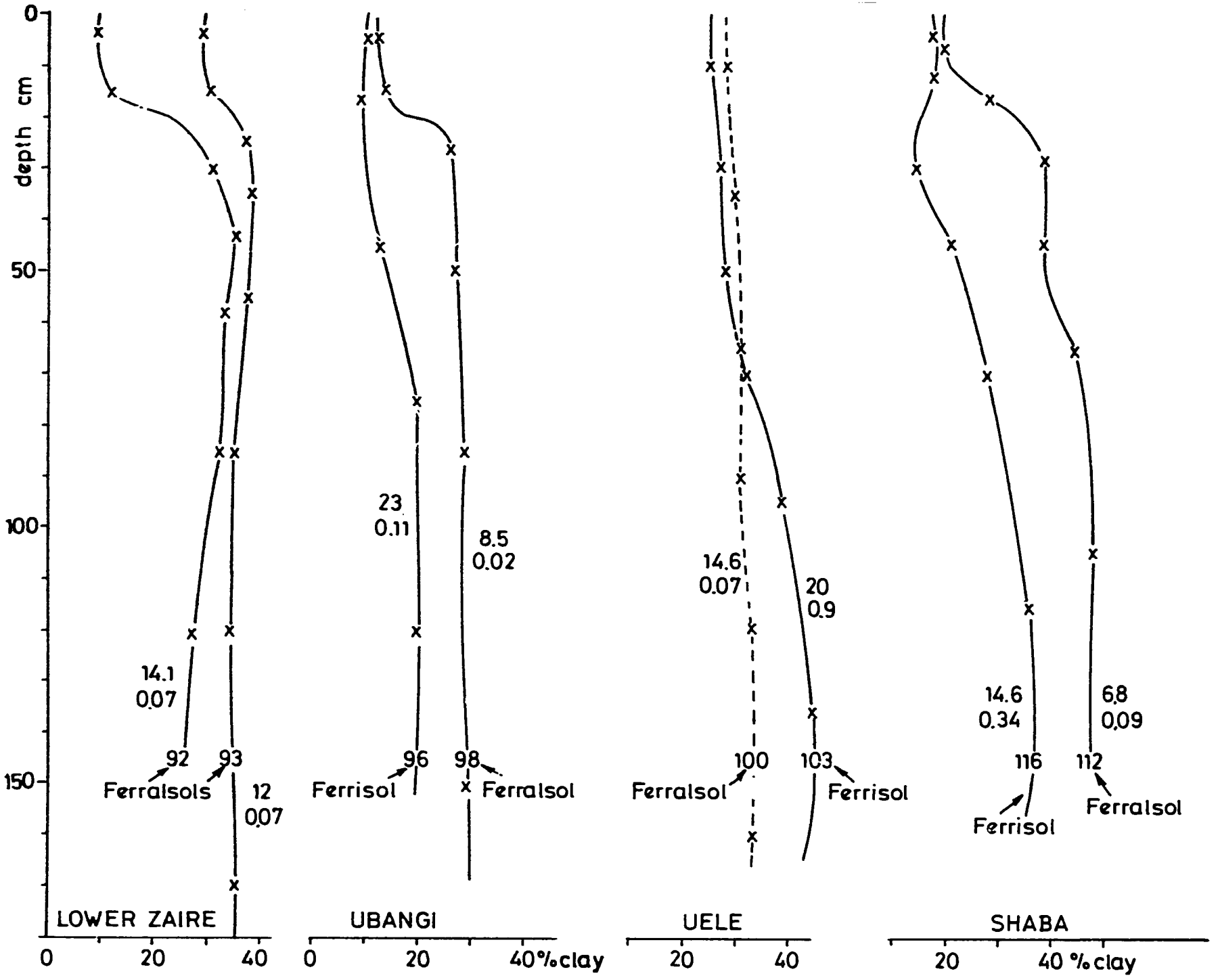


Fig.11 _ Soils on reworked materials from sandstone

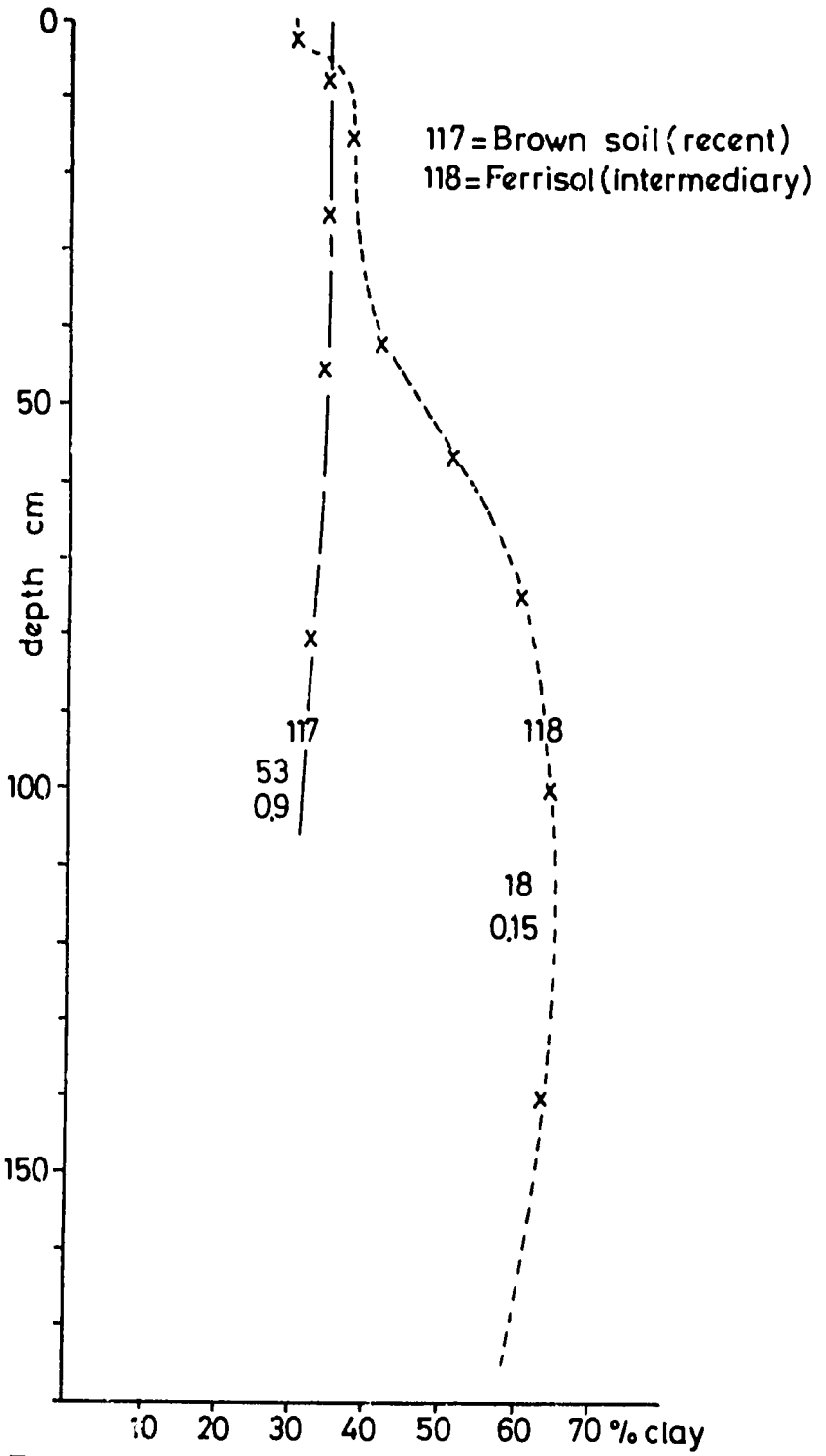


Fig.12 _ Soils on limestone (Mosso)

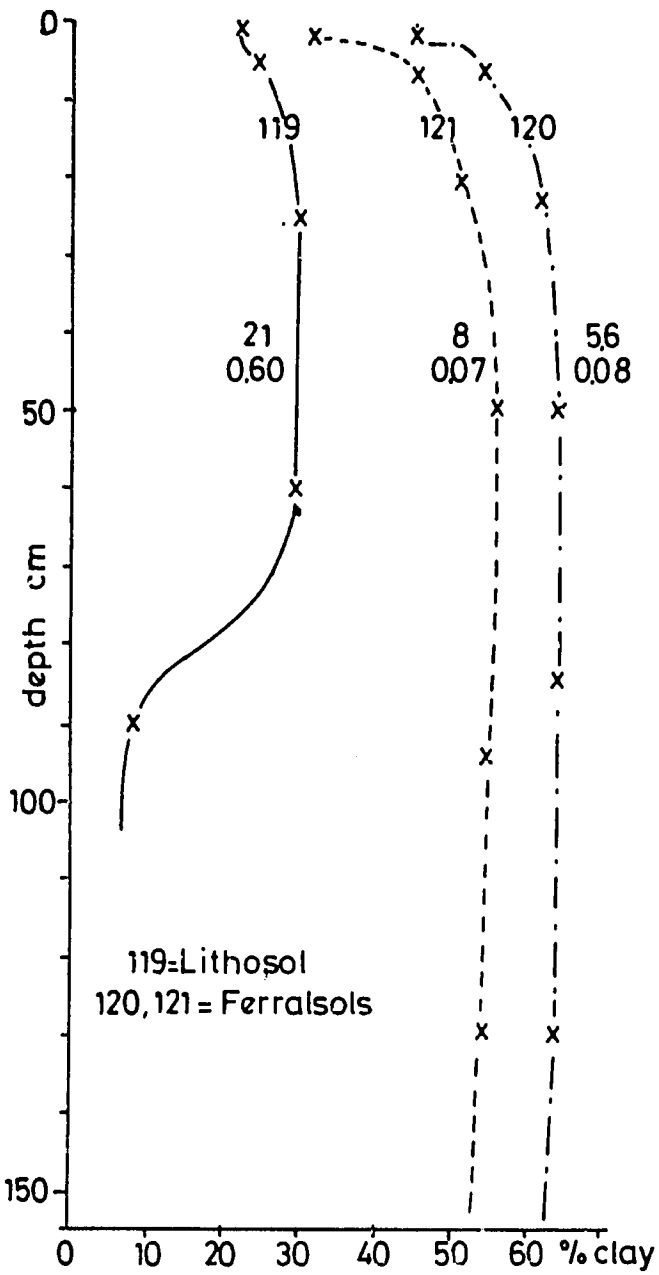


Fig.13 _ Soils on dolomite in Shaba

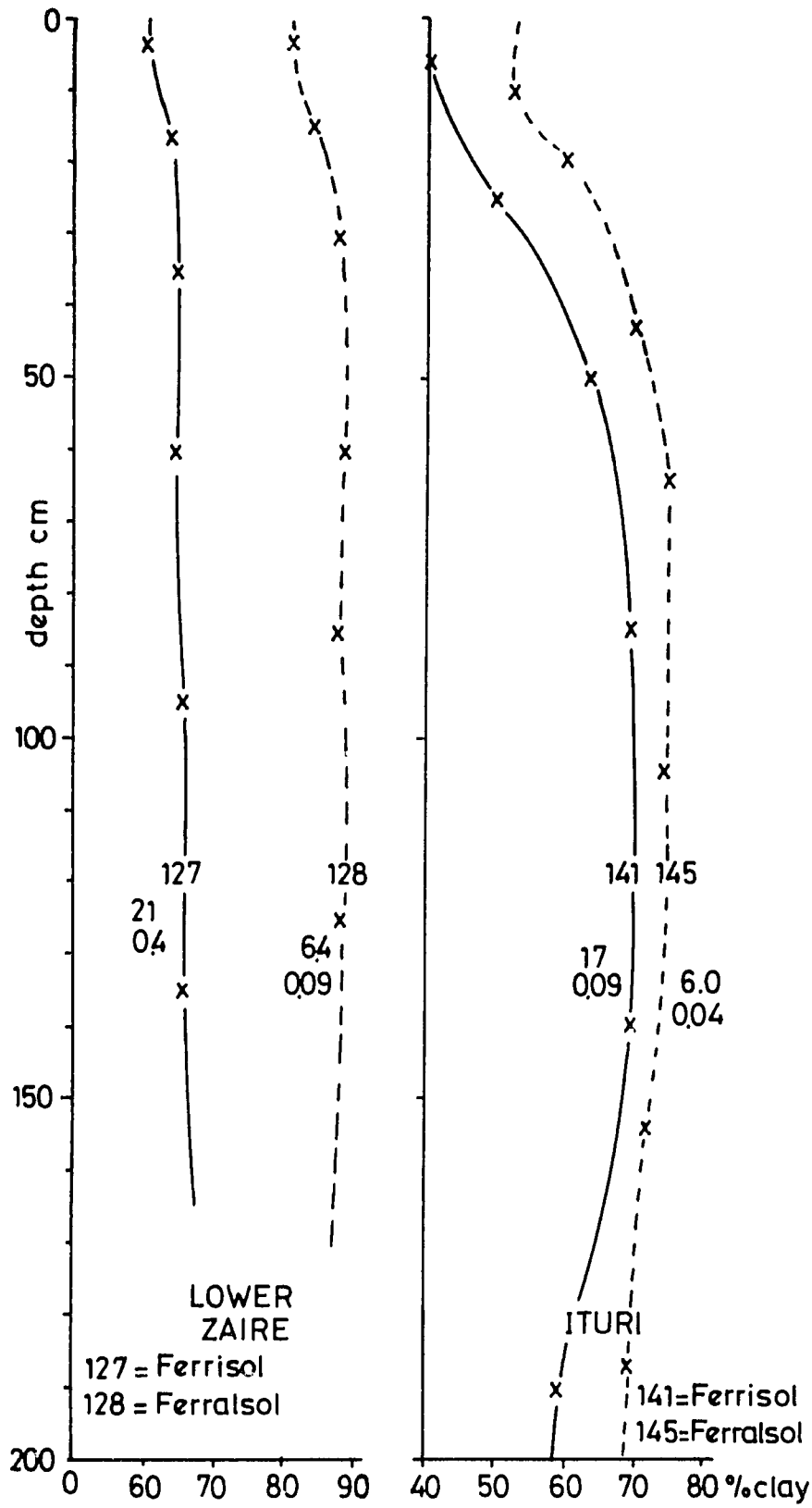


Fig.14 _ Soils on reworked materials from basic rocks

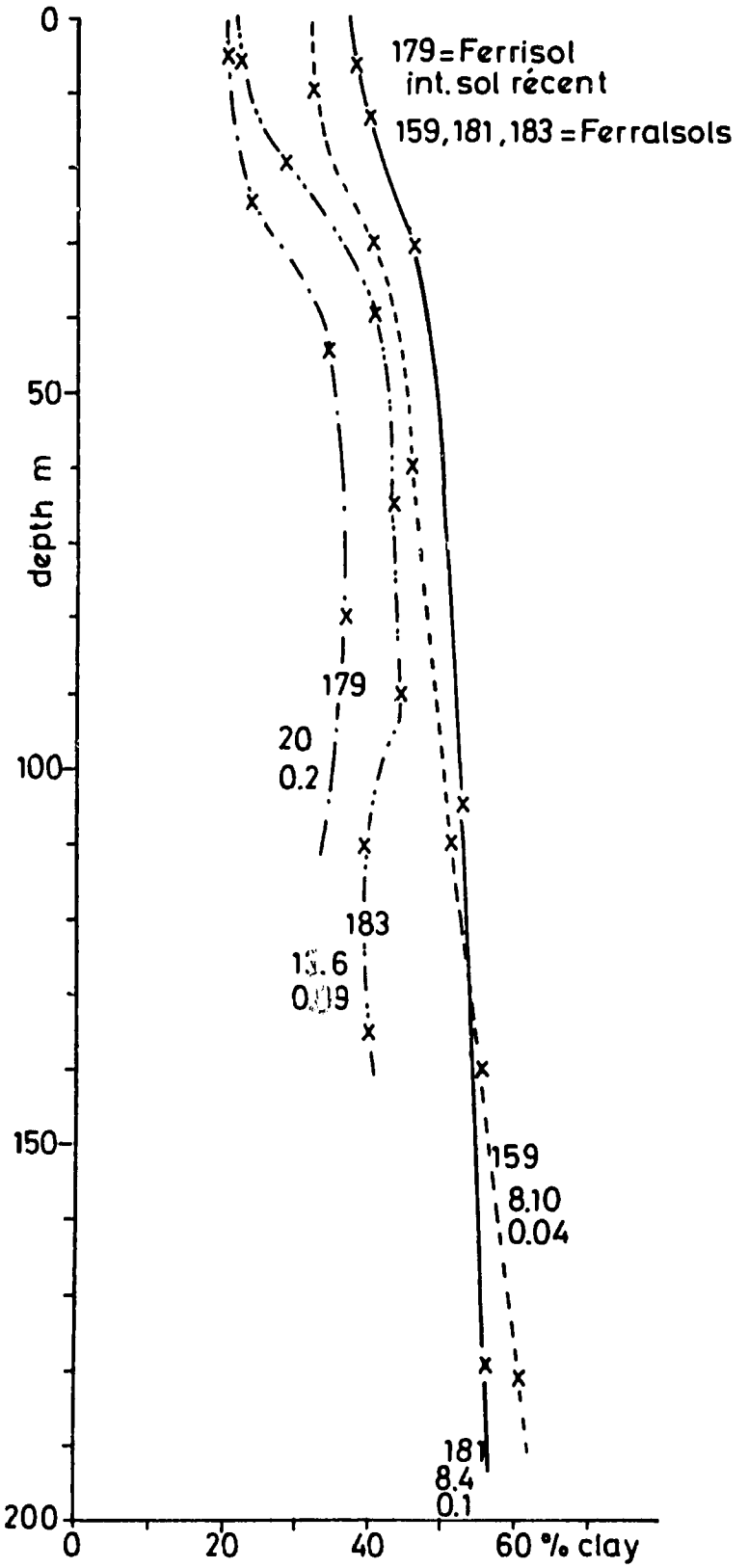


Fig.15 _ Soils on granite

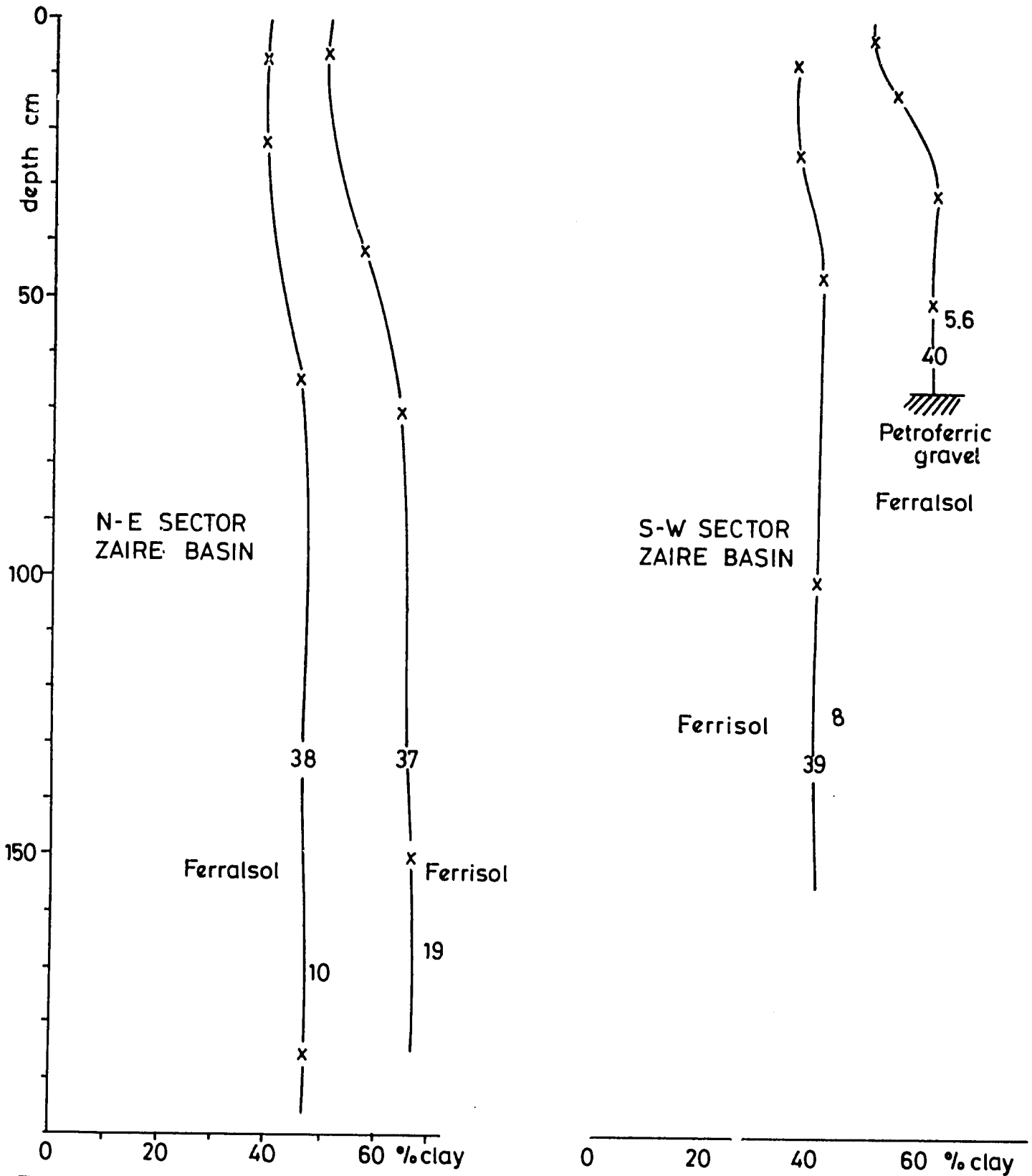


Fig.16 _ Textural differentiation of typical profiles on KARROO

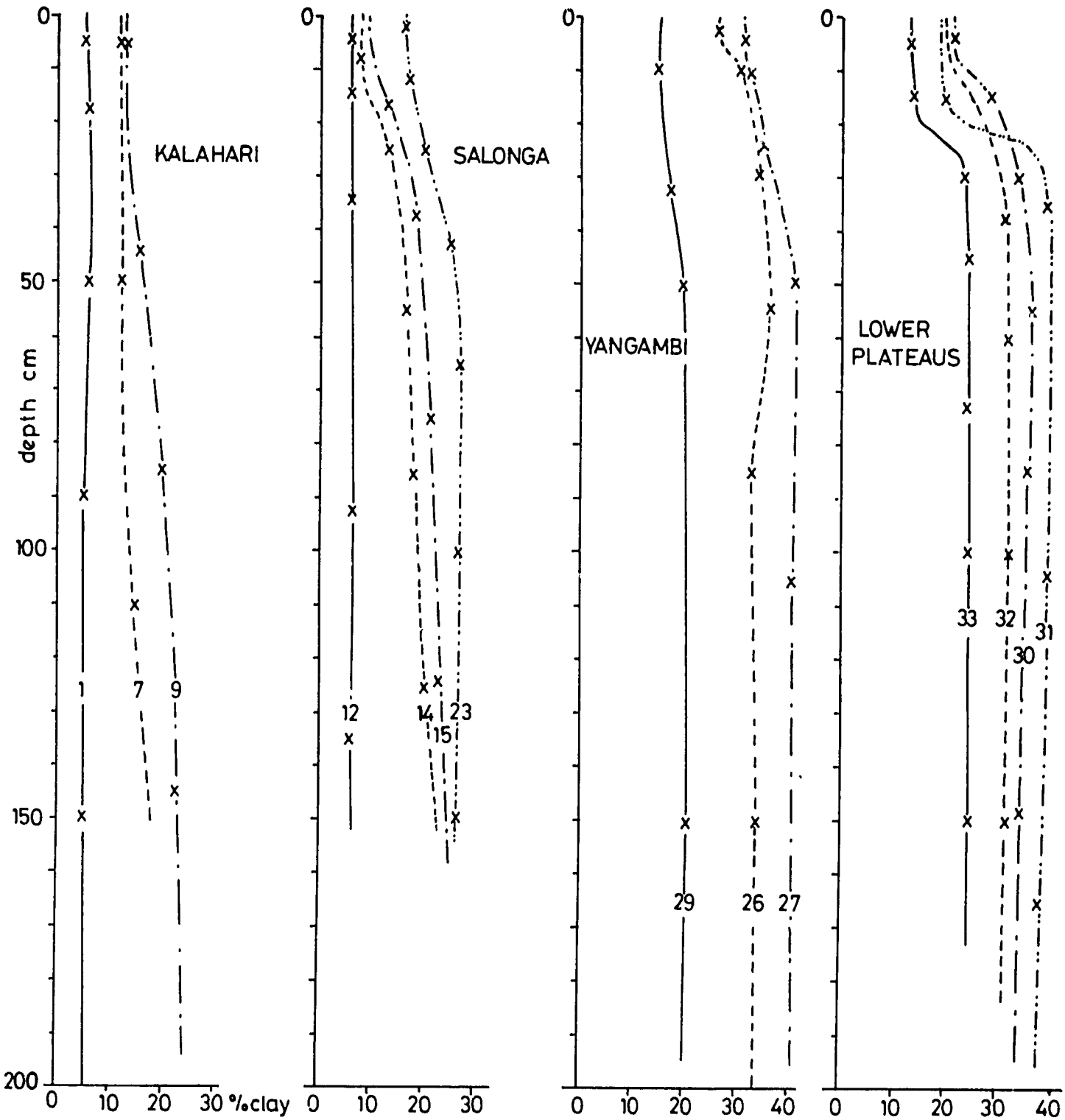


Fig.17 _ Textural differentiation of typical profiles on cover sand

related to local features of surface erosion, reworking and disturbance by termites than with other processes.

Mineralogical Composition

The Ferralsols of Zaire have the following mineralogical composition:

- a sand fraction with quartz, other resistant minerals and concretions. On a muscovite-containing rock this mineral may still be present in the sand fraction.
- a silt fraction with mostly quartz, sometimes mica and very often coarse kaolinite crystals.
- a clay fraction with kaolinite as the dominant mineral associated with oxides of Fe and Al. The oxides are amorphous or crystallized to goethite, haematite and gibbsite. Some illite occurs in association with kaolinite on shales and other mica-containing materials.

Mineralogical differentiation of the clay fractions of the ferralsols on cover sands is illustrated in Fig. 18.

Fig. 19 illustrates the clay mineralogical evolution of the sequence on shales (Fig. 7). The overall evolution of characteristics related to weathering intensity of these profiles is given in Fig. 20.

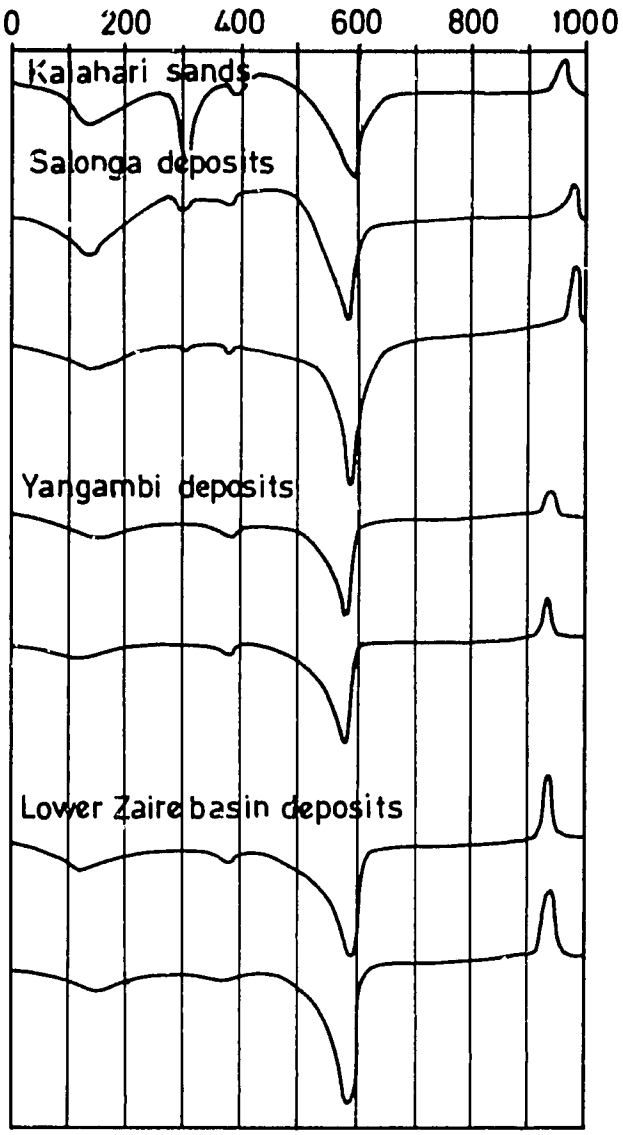
Structural Characteristics

The macrostructure of the Ferralsols is weak to very weak, subangular blocky in the subsoil, and it breaks up to very fine stable granular aggregates. The consistency is very loose. The upper part of the B horizon may present a somewhat more stable macrostructure and a firmer consistency.

From the micromorphological point of view the lower B horizon of Ferralsols has a fine material, mainly of kaolinitic clay stained by iron oxyhydrates. It is reddish or yellowish. Isotic fabric is predominant, with localized ooidsepic features.

Different types of nodules may be found. Generally they have moderate to sharp boundaries and possess striated extinction in the internal fabric. The composition is variable. Some are composed entirely of fine material and others have a mixture of coarse and fine material in various proportions.

Fig. 18_ DTA of cover sands



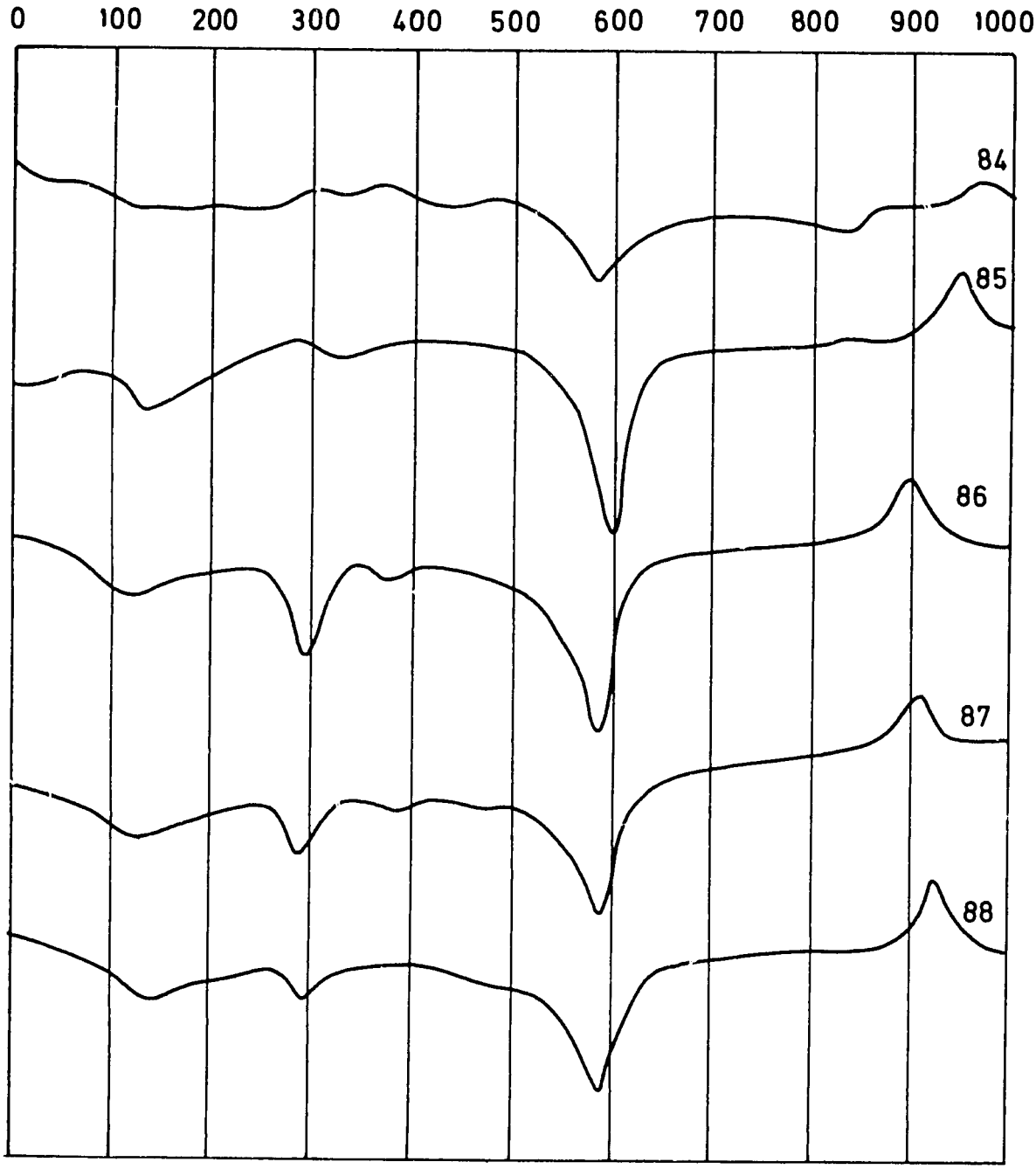
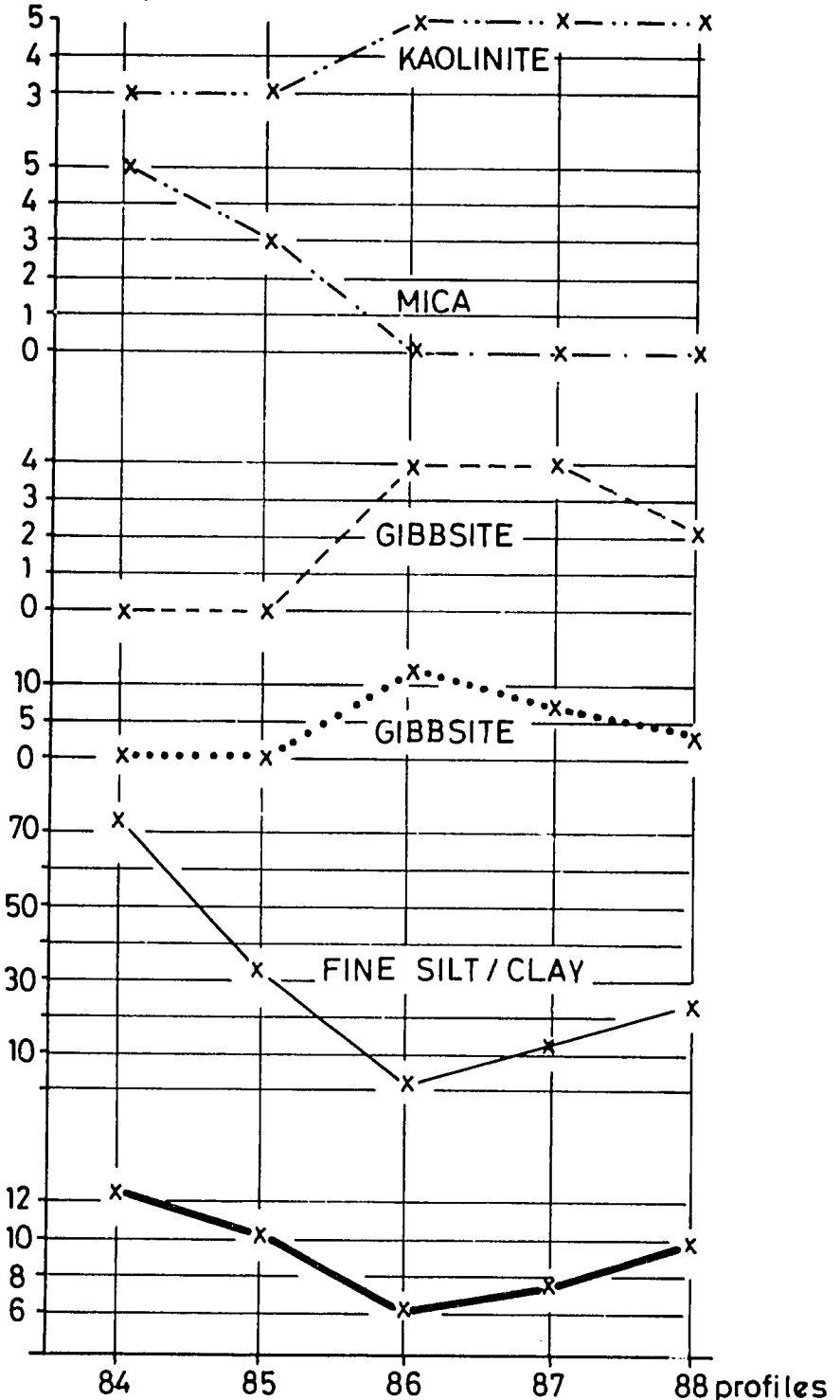


Fig. 19.

DIFFERENTIAL THERMAL ANALYSES OF THE TOPOSEQUENCE IN S. ZAIRE - PROFILES 84 TO 88

Fig.20. Evolution of weathering parameters through topo-sequence on shales in S-ZAIRE



—··— Intensity of d_{hkl} lines of kaolinite in X-ray spectrum

—·-- Intensity of d_{hkl} lines of mica in X-ray spectrum

- - - - Intensity of d_{hkl} lines of gibbsite in X-ray spectrum

•••••• Intensity gibbsite peaks in DTA (mm)

—— Fine silt/clay ratio's

▬▬ CEC clay fraction (meq/100g)

Sometimes clear and hyaline argillans are locally found, particularly in the upper B. They are generally thinly deposited in voids and channels.

Soil-Moisture Relationship

All Ferralsols have a good permeability and a high infiltration rate. The average permeability of a fine-textured B horizon may be as high as 4-5 cm/h. The moisture content at 15 bar (pF 4.2) can range from 5 to 25% (Fig. 21, Table 2).

It is assumed that the clay content of Oxisols equals 15 bar water multiplied by 2.5. For the Zaire Ferralsols we found that the clay content equals 15 bar water multiplied by 2.95 but with variations from 2.14 to 3.35.

Table 2. Moisture content of African Oxisols at different pressures.

Clay	Weight percentage of water at		
(%)	15 bar	1/3 bar	1/10 bar
14	6	11	13
15	7	9	12
21	7	9	13
24	8	11	13
26	10	13	17
29	11	14	18
32	13	18	21
44	14	18	22
46	15	19	22
49	16	19	22
55	20	23	27
58	19	22	27
60	20	23	26
81	24	-	-

The Adsorption Complex

The cation exchange capacity of the Ferralsols is low. The apparent CEC of the clay fraction is always less than 16 meq/100 g.

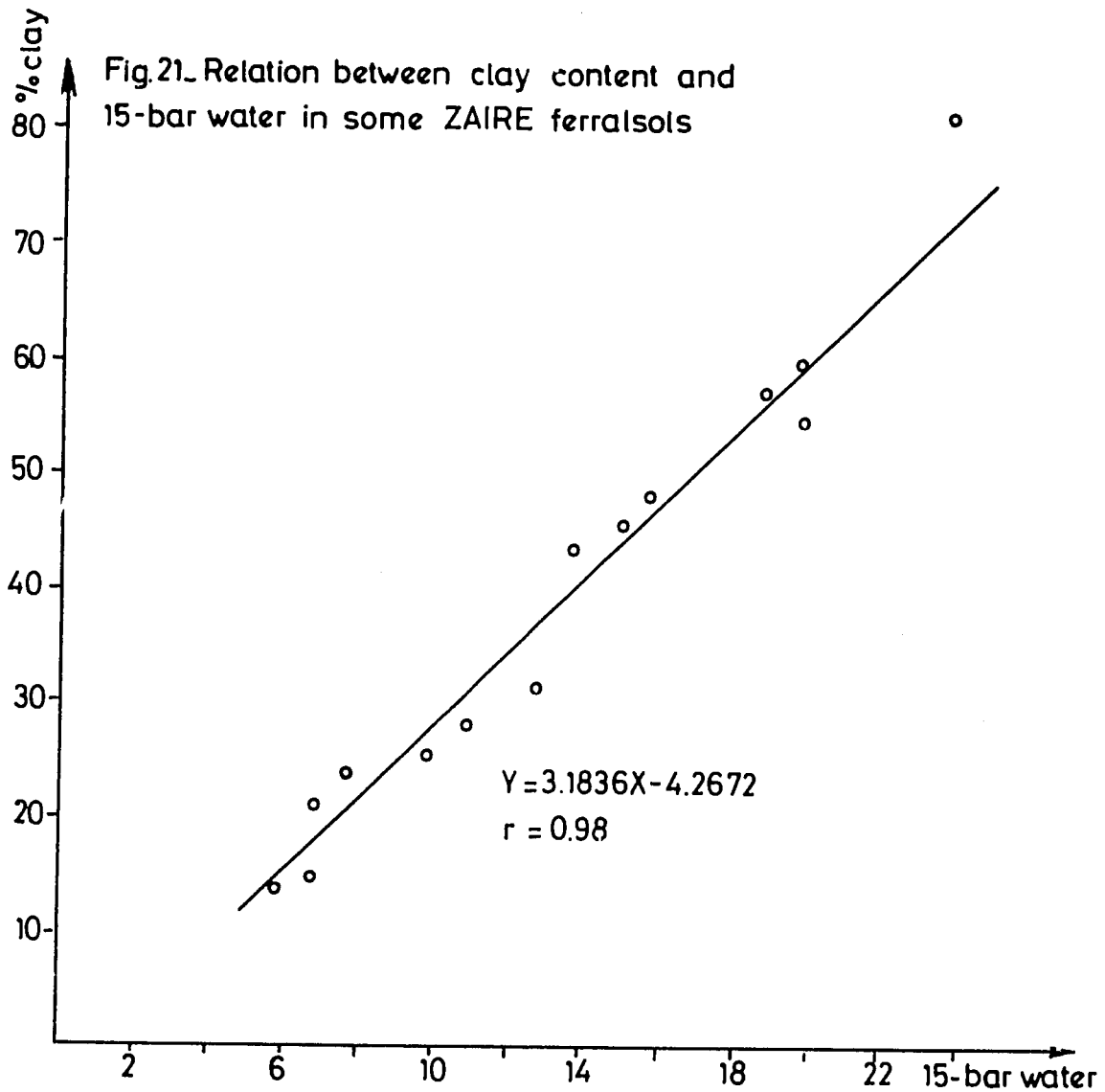


Fig. 21_ Relation between clay content and 15-bar water in some ZAIRE ferralsols

Under a rain forest base saturation is low (15-30%), but it may increase up to 40-50% in some savanna Ferralsols under an ustic moisture regime.

The net charge is negative in most cases. Only very exceptionally have Ferralsols with a net positive charge been found.

The Organic Matter

The development of the organic top soil and the quantity of organic matter in the profile is at a broad geographic level related to the climatic factor temperature.

The soils of low altitudes normally have 0.8 to 1.5% C in the upper 15 cm and include around 100-120 tons C per ha down to a depth of 1 m.

The variation in organic matter content in the low altitude zone varies according to weathering stage (Table 3) and within the Ferralsols with texture and color (Table 4). On the same lithologic unit the Ferralsols have a lower organic matter content than the less weathered Ferrisols.

Within the Ferralsols the organic matter content is highest in the fine-textured soil and lowest in the sandy soils. Red soils normally have more organic matter than yellow soils.

Between 1,500 and 2,000 m of altitude the A1 horizon is prominant up to 30-50 cm thick. The carbon content in the upper 15 cm is over 1.5% and often more than 2%. The profile to a depth of 1 m normally has more than 20 tons of organic carbon per ha.

Over 2,000 m altitude the soils are highly humiferous and even peat may accumulate at the surface under humid mountain rain forests.

Table 3. Mean carbon content (in %) of surface horizons (0-10 cm) in Central Africa with regard to parent rock and weathering stage.

Parent material	Carbon content (%) in upper 10 cm for following weathering stages		
	Recent	Intermediary	Ultimate
Shaba province, Zaire (S)			
- Sandy clay on conglomerate	1.41	1.15	0.94
- Clay on shales	2.02	1.69	1.67
- Clay on dolomites	3.08	-	2.09

Table 3 (cont'd)

Parent material	Carbon content (%) in upper 10 cm for following weathering stages		
	Recent	Intermediary	Ultimate
Central Zaire basin			
- Yangambi sediments ca. 20% clayey Oxisol			1.16
Kwango area			
- Kalahari sand ca. 5% clayey Quartzipsamment			0.42

Table 4. Carbon content (tons/ha/50 cm) of red and yellow soils of the Lubumbashi area (Zaire).

Soil material	Carbon content (T/ha/50 cm)	
	Red soils	Yellow soils
Clay on limestone	79	65
Clay on shales	71	55
Sandy clay on conglomerate	61	47
Mean values	70	56

Phosphorus

Available phosphorus levels of Ferralsols are low, and most analytical results mention "traces." Total phosphorus in the top 15 cm in typic savanna Ferralsols ranges from 100 to 150 mg P_2O_5/100 g. Organic P is about 70 to 75% of total P.

The soils have a high phosphorus fixation capacity. P-adsorption isotherms of Ferralsols with 55 to 60% clay (Fig. 22) indicate that a profile (P49K) after clearing adsorbs 250 ppm of P at a concentration of 0.1 ppm in the solution. This represents some 650 kg P/Ha for the top 20 cm.

P-adsorption decreased to 150 ppm of P (P34K) or 390 kg P per ha after 4 years of cultivation with an annual P_2O_5 application of about 120 kg/ha.

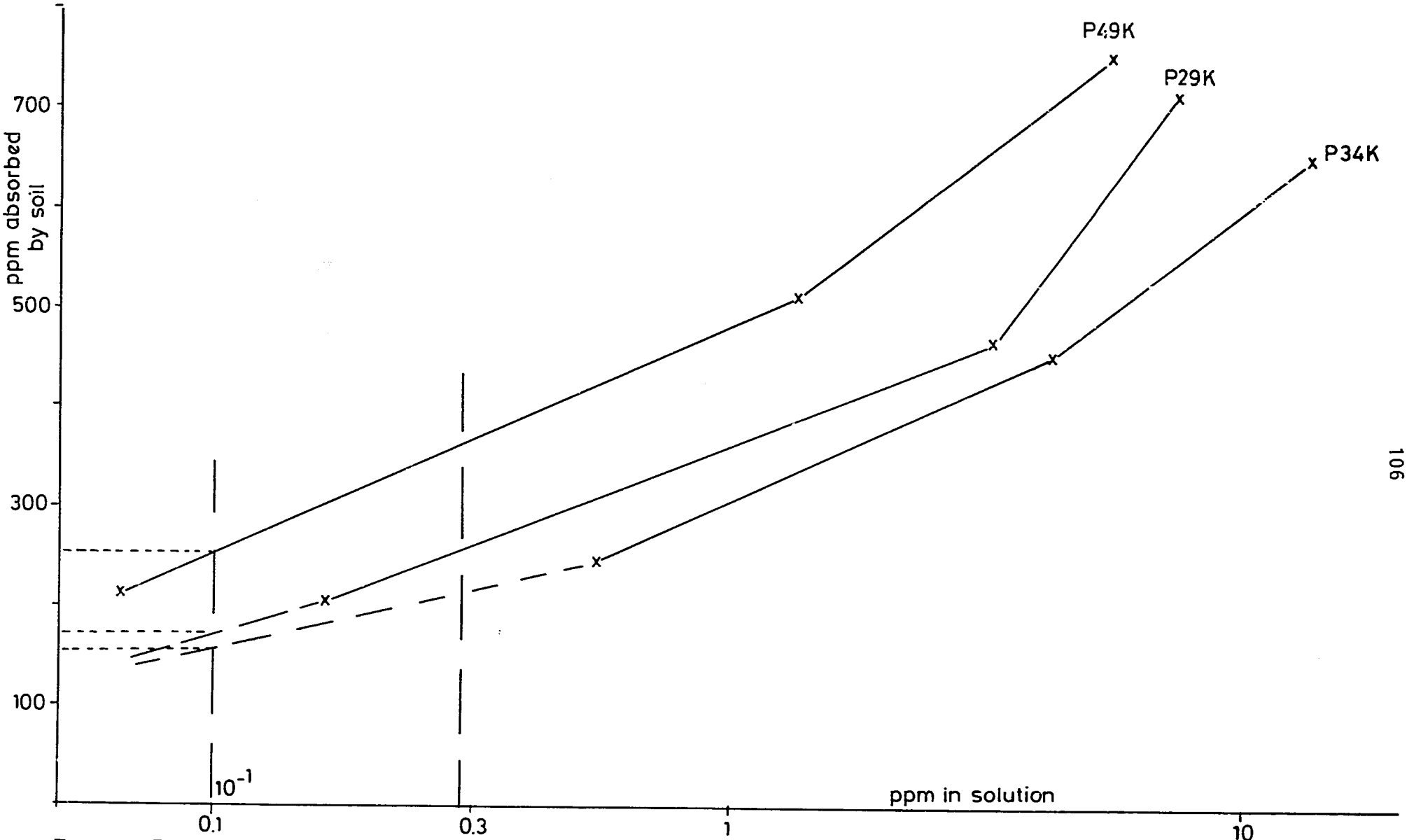


Fig.22 - P-adsorption isotherms of Ferralsols (HERBILLON, 1979)

Trace Elements

Most Ferralsols of Zaire are low in Zn and Cu. Zinc varies between 0.3 to 1.7 ppm and copper from 1.8 to 4.8 ppm. The Mn level generally varies from 60 to 100 ppm but on highly weathered soils on basic rocks, the toxicity level of 200 ppm may be exceeded.

THE CLASSIFICATION OF FERRALSOLS IN SOIL TAXONOMY

The B horizon of the Ferralsols have all mineralogical and physico-chemical characteristics of the oxic horizon:

- apparent CEC is less than 16 meq/100 g;
- no weatherable minerals are present;
- absence of clear cutans and a weak macrostructure is associated with a very strong micro-aggregation so that only few water-dispersible clays are present.

Therefore we have the tendency to correlate these soils with the Oxisols. However the clear clay increase in some profiles is the reason that some soil scientists have correlated such profiles (with clay differentiation) with the Ultisols, notwithstanding the absence of cutans and the complete immobility of the clays.

Clay skins in tropical soils are a good indication of the weathering stage; when they are present the clay is mobile and may move. However in the initial stage of soil formation the movement has not necessarily been intensive enough to satisfy the criteria of the argillic horizon, particularly on fine-textured materials.

Therefore we believe that in this initial stage of soil formation, in addition to the presence of cutans a textural differentiation should be required to call a B horizon argillic or it has to be assumed that the eluvial horizon has been eroded.

At the transition "intermediate" and "ultimate" stages of weathering we believe that clay increase should no longer be considered; all subsurface horizons, having the physico-chemical and mineralogical characteristics of the oxic horizon and in addition no or only thin patchy clay skins in the upper 20 cm of the B, should be considered as oxic horizons whatever

the textural profile may be. This textural profile is indeed so variable within "natural land units" that it becomes difficult to apply any definition set up with regard to clay increase.

A suggestion for the interpretation of subsurface B-horizons in low activity clay soils is formulated in Table 5. According to this criteria only a minor change in the definition of the argillic and oxic horizon is required to solve the whole Ultisol-Oxisol transition problem.

If defined as such, clear physical soil characteristics related to the soil-water relationship (infiltration rate, available water) will be associated with the distinction between cambic and argillic horizons on the one hand and oxic horizons on the other hand.

Table 5. Suggestion for classification of B horizons in low activity clay soils.

Weathering stage and associated clay mobility	clay increase	
	does not satisfy the increase for argillic horizon	satisfies for argillic horizon
Intermediary: clear cutans on peds; clays are mobile	CAMBIC or ARGILLIC according to past erosion →	ARGILLIC
Ultimate: no or only thin patchy cutans in upper 20 cm of B; clays are immobilized in micro-aggregates	↓ OXIC	↓ OXIC

DISCUSSION

Q. A. Jaribu: 1. What is the difference in the degree of weathering between the Ferralsols and the Areno-Ferralsols. In the presence of the Areno-Ferralsols, the order of Kaolisols lessivés seems to be justified. 2. What are the causes and origin of the B2c horizon and what is the relation of this horizon to the B2t?

A. C. Sys: 1. The difference between Ferralsols and Areno-Ferralsols is not based on weathering but on texture. Both groups have a difference in weathering within the definition of ferralsolic material. The Kaolisol lessivés order was intended to include the Kaolisols with

bleached sandy spots below the A1. Testing has shown, however, that this order is not justified as such soils are of very limited extent. 2. The B2c represents the upper part of the oxic horizon in Ferralsols. We believe that the harder consistence of this horizon is related to the drying out of the soil in the dry season. I think there is no relation between the B2c and the B2t, the B2c being an oxic and the B2t an argillic horizon.

Q. E. Schlichting: If the argillans in the B are neither formed by illuviation nor by swelling/shrinking of the soil, how far does the clay migrate in the B?

A. C. Sys: I believe that the clay movement from A to B is limited to the upper 60 to 80 cm of the B2t horizon. Clay increase is only noted in the upper part of the B2t and below this depth the clay content decreases very gradually. Cutans observed in the deeper horizons indicate mobility of clay and some movement of clay may occur. However, no increase in clay was noted in the deeper horizon. Rather, there is a decrease in clay due to a less advanced stage of weathering.

Q. M. Ali: In your definition of Ferralsols as representing the ultimate stage of weathering, one of the characteristics is "dominance of low activity clays." 1. Do you insist on the 16 meq/100 g clay limit even if the horizon concerned has more than 2% organic carbon which accounts for the higher CEC? 2. Should the total thickness of the oxic horizon of 50 cm occur within 1.25 m below the soil surface?

A. C. Sys: 1. Dominance of kaolinite is one characteristic to define the ultimate stage of weathering, but in addition other characteristics are required, such as absence of weatherable minerals, low silt:clay ratio, and absence of cutans. We do not use the 16 meq limit but all of the soils at the ultimate stage of weathering have an apparent CEC of less than 16 meq/100 g clay after correcting for organic matter. 2. I believe the oxic horizon should occur immediately below an A3 or eluvial horizon and have a thickness of at least 30 cm if the soil is deeper than 50 cm. If a lithic contact occurs within 50 cm, a thickness of 10 cm seems satisfactory to me.

Q. K. Matungulu Kande: 1. Could you repeat the relation between texture and degree of alteration? 2. Could you clarify the concept of a lithologic discontinuity in the case of Ferralsols?

A. C. Sys: 1. With progressive weathering the clay content increases and

the silt content decreases. 2. The lithologic discontinuity in the case of Ferralsols consists mainly of a layer of superficial deposits over a gravel layer formed at the top of saprolite.

Q. J. Bennema: Do you also find low silt:clay ratios in Oxisols on basic rocks? In such soils in Brazil, the ratios can be relatively high due to resistant minerals in the silt fraction.

A. C. Sys: In all of the Ferralsols on basic rocks which we have studied the silt:clay ratio is very low. I do not know of any exceptions in Zaire, but they may occur in other areas. In central Africa this parameter seems to work quite well as an expression of the weathering stage, but I should not recommend to generalize its use elsewhere before comprehensive testing.

Q. J.A. Comerma: What kind of cutans do you find in the Ferralsols you mentioned? Are they caused by stress or illuviation? Is there a relation in these soils between the presence or absence of cutans and 2:1 and 1:1 clays as indicated in a paper by Dr. Van Wambeke presented at the Dalabe Conference in 1954?

A. C. Sys: The cutans present in Ferralsols are oriented ferri-argillans and illuvial cutans. When the cutans disappear with progressive weathering, the amount of 2:1 clay minerals decreases. However, in Ferralsols on shales some illite may still be present after complete disappearance of the clay skins.

OXISOLS OF BRAZIL

J. Bennema

INTRODUCTION

Oxisols occur to a great extent in Brazil; the total area of typical Oxisols in that country is probably greater than the total area in the rest of the world.

Many soil descriptions and laboratory data can be found in publications, mostly in those by the Servico Nacional de Levantamento e Conservacao de Solos (SNLCS). The laboratory data include the SiO_2, Al_2O_3, Fe_2O_3 and TiO_2 percentages, obtained after boiling the fine earth with a H_2SO_4 solution of high concentration (Vettori, 1959). The data for Fe_2O_3 and TiO_2 in Oxisols are practically the same as the total contents, while those for SiO_2 and Al_2O_3 are similar to the total contents found in the clay fraction (Bennema, 1974). These data form an important source of information for understanding the genesis of these soils.

PARENT MATERIALS

Oxisols in Brazil are found partly on sediments as "parent rock." The soils on flat parts of these sedimentary areas are autochthonous or, if the areas are dissected and the sediments are deep, pseudo-autochthonous because the soil material will have been partly or wholly moved along the slope.

The term pseudo-autochthonous (Camargo et al., 1962) is being used in Brazil for materials which have been moved but have not left the area with the same country rock. In the areas of consolidated rocks, many old planation surfaces are present. On such planation surfaces the kind of soil changes often with the country rock, indicating that pseudo-autochthonous

soil materials are present here too. Stone lines in these areas are mostly of biogenetic origin. Without taking the biogenetic influences into consideration, the formation of these soils cannot be understood. The situation in Brazil is different in this respect from that in Africa, where the "dry glacial climate" with strong sedimentation and erosion (forming stone layers as a basal conglomerate) had much more influence. Also, volcanic influences as in East Africa were not present in most of Brazil.

The formation of the Oxisol material in Brazil is strongly integrated with two kinds of geogenetic processes:

1. The retreat of slopes of older planation surfaces on which soils with deep regolith had already formed;
2. A very slow wearing down of the planation surfaces during a long time (realize that 1 mm loss during 100 years, is 10 m loss during a million years).

The planation surfaces were probably covered with soils already for a very long time. The wearing down of the surfaces occurred together with the change in soils, in which, as was mentioned, biogenetic influences played a great role. The idea that the Oxisols were formed on deposited material is according to the author not the right one. A strong integration of pedo- and geogenesis has to be the starting point of the theory about the genesis of these soils in these areas.

GENESIS

An example is given in Fig. 1 (based on data from Lemos et al., 1960) of the most common vertical sequence of the "attackable" main mineral components of a typical Oxisol (Components profiles).

The following zones can be recognized:

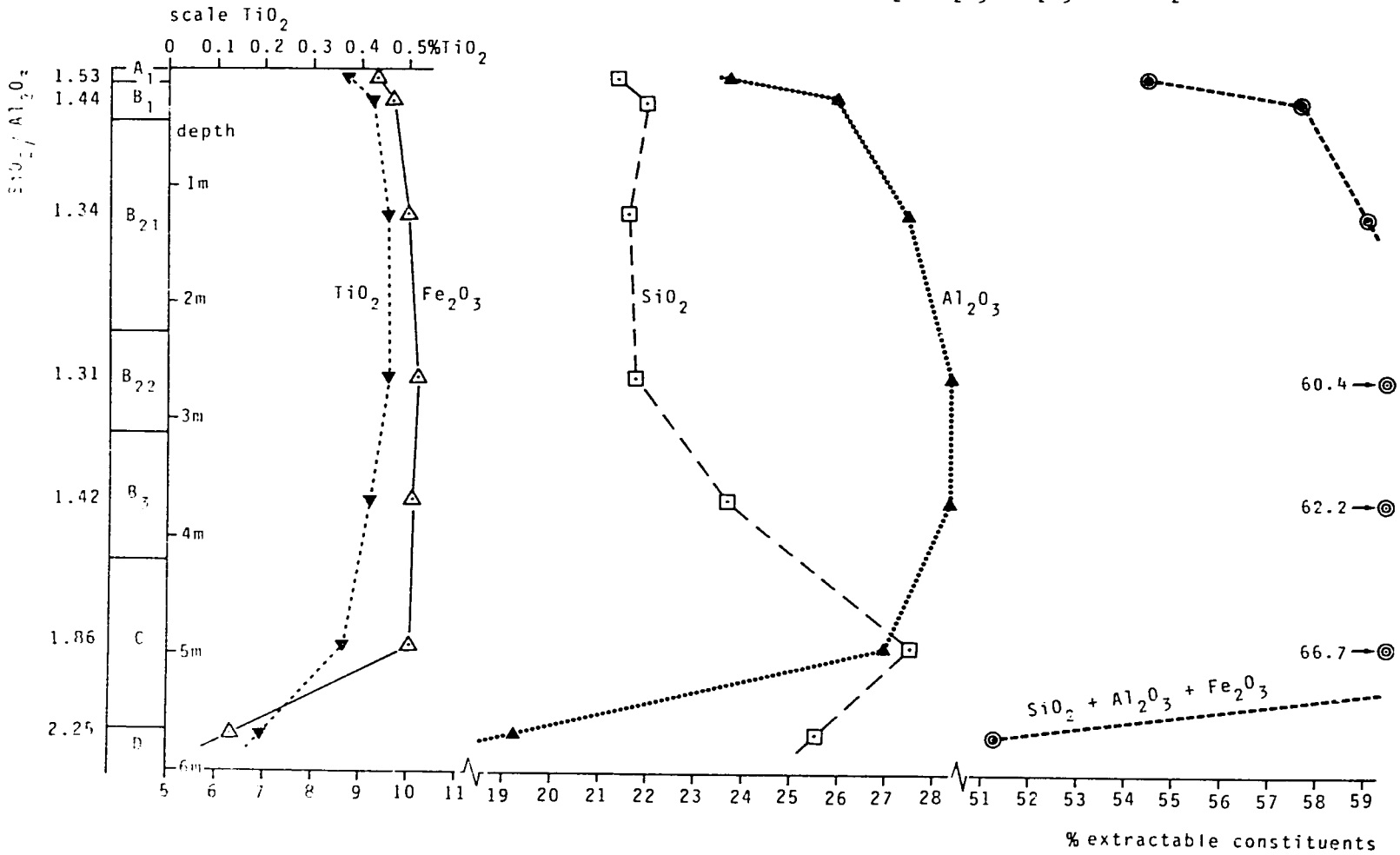
(a) A zone in which not all of the primary weatherable minerals are decomposed; this results in relatively low amounts of the main "attackable" components.

(b) A zone in the lower part of the solum, in which the maximum of attackable components are found and in which silica decreases in the higher part of the zone. It is a zone of desilication.

Fig. 1

DARK RED LATOSOL on CLAYSTONE SÃO PAULO sp.39

percentages with H_2SO_4 D 1.47 "extractable" SiO_2, Al_2O_3, Fe_2O_3 and TiO_2



(c) A zone, including the top layer, where normally all or at least most of the attackable elements decrease to the surface. Al_2O_3 shows mostly the highest loss perhaps due to cheluviation, while in wet moisture regimes Fe_2O_3 shows the highest loss due to reduction. The explanation of the loss of all the finer components is probably that a combination of erosion and solution is active over a long time period. Further, the activity of ants and termites, also influence the distribution of the fine particles in the profile. This process can best be described with the term impoverishment, the equivalent of the well-known French term "apprauvrissement." This process should be well distinguished from clay illuviation and ferrolysis.

BRAZILIAN OXISOLS

Aquox

After this general part, different kinds of Brazilian Oxisols are discussed and examples are given. First some profiles of Aquox found near Brasilia are discussed (de Freitas, 1978) (profiles 1 and 2). Important is the loss of iron, which leads to an Oxic horizon with colors of 2Y 8/2. A definition is given which fits this kind of Aquox:

Aquox have: either an aquic moisture regime or are artificially drained and have one or both of the following characteristics associated with wetness:

(1) mottling in a horizon having colors of 2Y or yellower;

(2) a horizon without mottling with colors of 2Y or yellower together with an umbric or histic epipedon.

Akrox

Different Oxisols with akric properties, delta pH (pH KCL - pH H_2O) of -0.2 or greater and an ECEC of less than 1.5 meq occur in Brazil. They have either a high iron content and at least some gibbsite (a small part of the Terra roxa legitima or Dusky Red Latosols belongs to this group) or extremely high gibbsite content with some Fe_2O_3 (see also under Aquox profile 2). This indicates that besides iron, gibbsite has an impact on

the charge characteristics of these soils.

Some doubt is presented by the writer if Akrox (the non-hydromorphic Oxisols with akric properties) is a convenient group to distinguish at the suborder level, because:

(a) the presence of a relative high delta pH (greater than 0.2) in subsoil is not of so much importance for its use. Especially the iron-rich Akrox can with present day knowledge be seen as fairly good agriculture soils;

(b) they will be difficult to map;

(c) too much is expected from the exactness of the data on ECEC and delta pH of the different laboratories.

Two examples of Akrox are given, profile 3 (de Freitas, 1978) and 4 (Lemos et al., 1960). One with high iron content; the other one with extremely high gibbsite content.

Yellow Latosols on Sediments with Low Iron Contents

Till now orders were discussed as proposed by Eswaran in his circular letter no. 6/80 August 1980. In the following part the Brazilian Classification (of the SNLCS), will be the main base.

Yellow Latosols with Low Sesquioxide Content on Sediments

These soils have a great extension in the lower Amazon valley, along the coast and on some river terraces. The clay is predominantly kaolinite and the sand fraction quartz. They have a yellow color (Xanthic Ferralsols in the FAO classification) and the texture varies from coarse to extremely fine.

Their chemical and physical characteristics are very specific. The low sesquioxide content influences the charge characteristics, while the physical properties are also strongly affected. They belong to the most unstable Oxisols and can easily deteriorate as well under anthropogenic influences as in nature (especially if a dry season is present). They should be handled as a group apart and well on a high level, because also the geographical extension is very specific. These soils could be defined as having in the B a hue of 10 YR or 7.5 YR with a value of 5 to 7 and a high chroma, while the SiO_2/Al_2O_3 is relatively high, 1.7 or higher, and

the free iron content is low. The base saturation of the soil under natural conditions is always low.

The clay content increases with depth till 1 m or more as in most Oxisols (except in some iron-rich Oxisols on basic rocks). This increase is linear with log (depth +1) as shown in Fig. 2 (data marked AM from Sombroek, 1966). (Oxisols of this kind should, if this increase is more than 40% (within 30 cm) in soils of medium texture, not be expelled from this order. In this way alike soils would be divided at the highest level.)

One example (see profile 5; Sombroek, 1966) of such a soil is given; others can be found (written in English) in the literature. A special great soil group has been proposed for this group, Oligo or shortened Oli great groups (meaning poor in sesquioxide content).

Latosols with a High Iron Content

These are soils mainly derived from basaltic rocks and are tentatively above 19% free iron. All kinds of intergrades occur to other soils, but the description will in the first place deal with the more typical members. Some soils with high iron contents were already classified as Akrox; of course they do not belong to the group under discussion. These soils can be divided into:

The Dusky Red Latosols (Terra roxa legitima), the color being due to the presence of hematite and finely divided MnO;

The Dark Red variant of the Dusky Red Latosols, in which the MnO is probably more segregated;

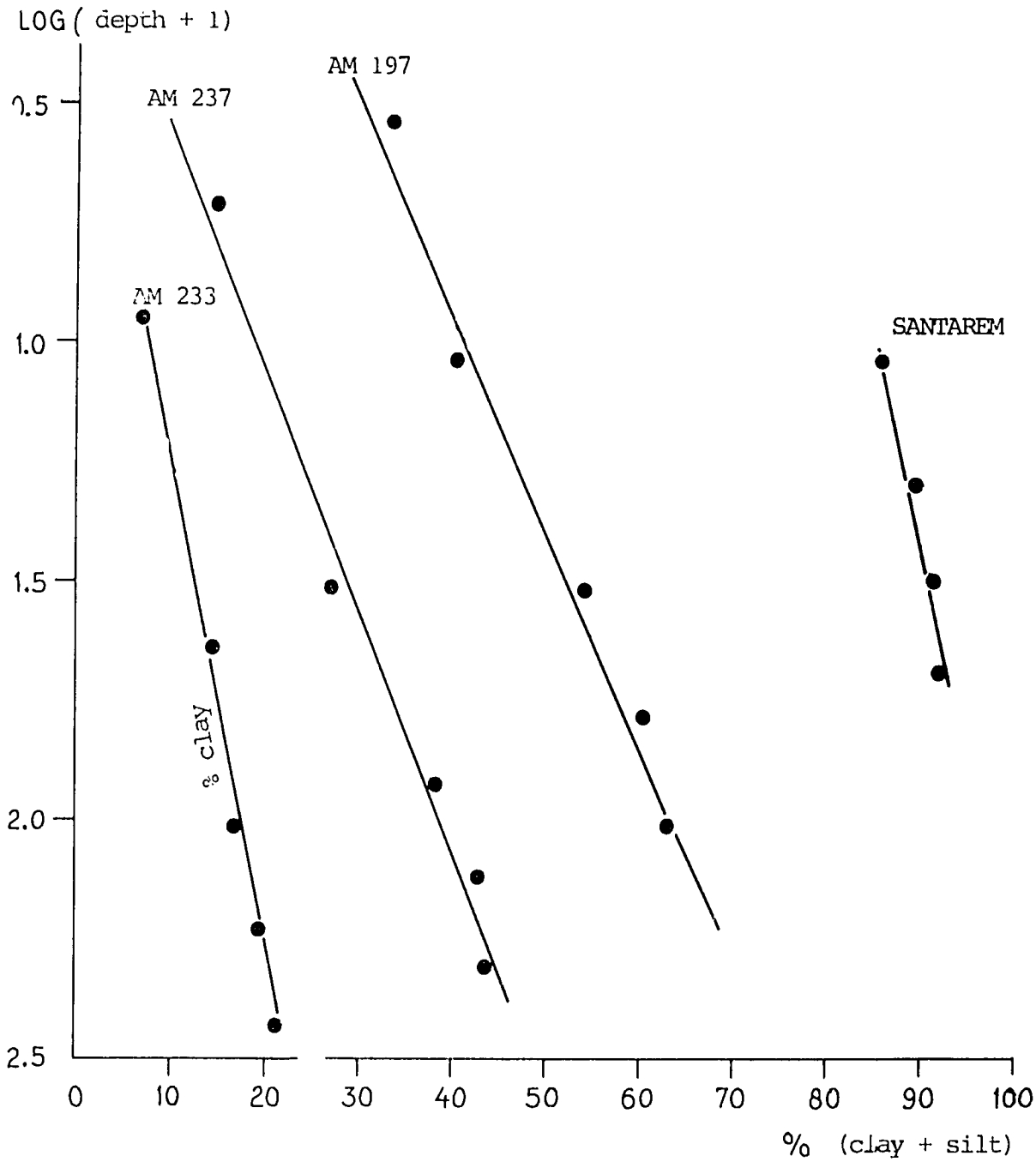
The Brown Latosols, in which the iron coloring the soils is predominantly goethite.

The last soils are mainly found south of the Capricorn under a subtropical forest or subtropical grassland with a perudic moisture regime. The color of the B has a hue of 5 YR or 7.5 YR and the value as well as the chroma is normally rather low, e.g. 3/4 or 4/4. The soils, as all the soils in this chapter, are clayey.

A special variant of these soils is found under the perudic conditions in South Bahia, a part of the soils described as Una belong to this group. Also Brown Latosols may probably occur in other climates under imperfect drainage conditions.

Fig. 2

% (clay + silt) AS A FUNCTION OF LOG (depth)^{x} ON SEDIMENTS IN THE LOWER AMAZONE REGION (AM) AND ON SEDIMENTS IN SURINAME (S)



NOTE: X and Y axes are reversed so we can recognize it as a profile

The Dusky Red Latosols are the only ones of which Eutric members occur next to Dystric members. The latter might have a lower or higher Al^{+++} saturation. It is interesting to note that the Eutric members may have a positive delta pH, and that in some cases the pH_0 is above 6. The Brown Latosols in subtropical regions often have an Umbric epipedon and would partly be classified as Humox in Soil Taxonomy. The clay fraction in the Brown Latosols and also in the Dark Red variant of the Dusky Red Latosol consist of kaolinite and iron oxides as in many other Latosols, but they have next to these clay minerals often higher amounts of interstratified clay minerals and a relatively high amount of amorphous materials.

The soils with high iron content form a continuum with the soils known as Nitosols in the legend of the "FAO-Unesco Map of the World." The Eutric Dusky Red Latosols intergrade to the Eutric Nitosols (Alfisols) and the Dystric Latosols to the Dystric or Humic Nitosols.

Some examples are given of this group of iron rich Latosols, profiles 6 (Lemos, 1967), 7 and 8 (EMBRAPA, SNLCS) and 9 (Lemos, 1967).

The Dark Red and Red-Yellow Latosols

The Dark Red Latosols have a medium content of iron which colors the soil dark red; the iron content depends on the texture and also on the size of the iron particles, but is mostly between 8 and 19% for fine-textured soils. The texture varies between coarse to fine textured. The sand fraction is normally quartz. They often are derived from claystone, shales, some schists, etc. Most of them are Dystrophic but also Eutrophic members occur. As a variant a yellow colored "Dark Red Latosol" occurs. The latter soils occur in a perudic moisture regime, with goethite as the main iron component. The same variant may occur in imperfectly drained soils.

The Red and Yellow Latosols have relatively low iron content, but the total sesquioxide content is higher as in the soils described as Yellow Latosols with low sesquioxide content. They have a great variety of colors in the B from yellow to red, but they never have a hue redder than 5 YR together with a value less than 4. The texture varies again greatly; the sand is mainly quartz.

As well as the Dark Red, the Red-Yellow Latosols may occur as Eutric or Dystrophic, although most of them are Dystric. These Dystric ones may have a higher or lower Al^{+++} saturation. The Eutric ones are in particular

found with drier moisture regimes.

PROBLEM OF SOILS WITH HUMIC PROPERTIES

Many different kinds of Latosols occur in Brasil with a high amount of organic matter. They are often found locally. A listing of the different kinds shows that these soils with humic properties often have not much in common, beside the higher organic matter content and the darker color of the A.

The following soils occur with a high organic matter content:

(a) Brown or Dark Red variant of Dusky Oxisols in the subtropical areas with normal organic matter profile (decreasing with depth). The kind of decrease depends on the kind of vegetation, forest or natural grassland.

(b) Dark Red or Red Yellow Latosols with a normal distribution of the organic matter profiles with depth, sometimes (rarely) found at a somewhat higher altitude.

(c) Dark Red or Red Yellow Latosols with an abnormal distribution of the organic matter profiles in a situation, where cumulic profiles can be expected.

(d) Red Yellow or Brown Latosols with an abnormal distribution of the organic matter profiles in areas where possibly a younger A horizon has been developed over an older buried A horizon (is comparable to the case of a Sombric horizon, only a lighter colored horizon is absent between the two A horizons).

(e) Soils developed very locally on flat Red Yellow Latosols in savannah regions, showing a deep A horizon. The soils are extremely poor as is the vegetation. This kind of soil has still no explanation.

(f) Soils developed on sedimentary terraces in Yellow Latosols with low sesquioxide contents, known as Brown Soils of the Indians. The black soils have a "black" anthropogenic A horizon. The status of the brown A horizon, which is found around the "black soils" is still not well known. The P_2O_5 status is too low to call them anthropogenic.

If we consider further that in the tropics the organic matter content may change rather rapidly, if the soils are used for agriculture, then the con-

clusion must be that it is better not to use organic matter content or the color of the A horizon at a very high level of the classification. It is proposed to delete the Humox and then classify them as extragrades within the soils discussed before.

CONCLUSION IN RELATION TO CLASSIFICATION

In the foregoing a review of Brazilian Oxisols was given. Not all of the aspects used in the Brazilian classification til' now could be brought forward, e.g. the high amount of lateritic gravel. Furthermore, a division of the development of the A horizons was worked out in more detail than was given here. Also, shallow subgroups were sometimes distinguished.

It should be clear from this review that soil color is a characteristic that should be used with great care in soil classification. Oxisols with dark red colors include quite different soils as do Oxisols with yellow colors. Color can therefore not be used at higher levels than subgroups.

The proposal which follows here must be seen as strictly personal; no possibility existed due to lack of time to consult the staff of SNLCS. It is added because in the foregoing building stones are given for a classification, but how they could be used is quite another question. It is a proposal which deals only with Brazilian Oxisols and can be seen as an example of a classification suitable for the Brazilian Oxisols.

TENTATIVE SCHEME FOR THE CLASSIFICATION OF BRAZILIAN OXISOLS SUBORDERS AQUOX, AKROX, ORTHOX, USTOX AND TORROX (HUMOX OMITTED)

Key to Great Groups of the Orthox (See also Bennema and Camargo, 1979).

(1) Soils on sediments with low sesquioxide content and "yellow" colors - Oliorthox

(2) Soils having high amounts of iron oxides and dusky red or dark red color, mainly derived from basic rock - Roxorthox

(3) Soils having high amounts of iron oxides and having brown color - Brunorthox

(4) Soils having medium amounts of iron oxides and having mostly dark red or yellow colors - Rhodorthox

(5) Soils having medium amounts of iron oxides - Haplorthox

The Kurorthox, Sombriorthox and Paleorthox in the proposal of Eswaran have been omitted. They can better be handled at a lower level of the classification. The iron content could be further defined in relation to the clay content.

The following subgroups of the great groups of the Orthox could, for example, be recognized (not complete):

(1) Oliorthox
1. Typic (=Allic)
2. Petroferric
3. Dystric
4. Anthropic
5. Umbric
6. Psammentic

(2) Roxorthox
1. Typic
2. Rhodic
3. Eutric
4. Allic
5. Leptic
6. Psammentic
7. Alfic
8. Ultic

(3) Brunorthox
1. Typic (=Allic)
2. Dystric
3. Tropic
4. Humic
5. Ultic

(4) Rhodorthox
1. Typic
2. Brunic
3. Petroferric
4. Eutric
5. Allic
6. Humic
7. Cumulic
8. Psammentic
9. Alfic
10. Ultic

(5) Haplorthox
1. Typic
2. Petroferric
3. Eutric
4. Allic
5. Humic
6. Cumulic
7. Psammentic
8. Alfic

Alfic and Ultic subgroups are especially meant for clayey soils. Intergrades between Ultisols and Alfisols and Oxisols with lower clay content could better be handled with the Ultisols and Alfisols.

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DISCUSSION

Q. J.A. Comerma: What significance do you assign to the presence or absence of an A2 horizon for separating Oxisols from other soils such as Ultisols?

A. J. Bennema: The presence or absence of an A2 horizon is used as a field criterion in regions of typical podzolic soils as in São Paulo State of Brazil. It goes together more with a stronger than gradual clay increase and shallower profiles such as the Red Yellow Latosols.

Q. R. Schargel: What levels of Fe_2O_3 contents would you use to separate great groups of Oxisols?

A. J. Bennema: For clayey soils I would tentatively suggest the following limits:

1. More than 19%
2. 8 or 9 to 19%
3. <8 or 9%, with gibbsite and SiO_2/Al_2O_3 ratio less than 1.7
4. < 8%, without or with small amounts of gibbsite, and SiO_2/Al_2O_3 normally less than 1.7

APPENDIX

List of Profiles

Brazilian Classification	Soil Taxonomy (1-4) Proposed Scheme (5-9)
1. Allic Humic-Gley Soil	Haplaquox
2. Dystrophic Ground-water Laterite	Acraquox or Plinthaquox
3. Red-Yellow Allic Latosol	Akrox
4. Terra roxa legitima (Dusky Red Latosol)	Akrox
5. Kaolinitic Yellow Latosol	(Typic Oliorthox)
6. Dusky Red Latosol--Dystric	(Typic Rhoxorthox)
7. Dusky Red Latosol--Eutric	(Eutric Rhoxorthox)
8. Brown Latosol--Humic	(Humic Brunorthox)
9. Brown Latosol--Humic	(Humic-Ultic Brunorthox)

ACKNOWLEDGEMENT

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Profile 1 (perfil complementar DF 41). Data 23/4/77

Classification	:	Allic Humic-Gley Soil phase wet grassland on well, topography gentle undulating
Locality	:	Federal District Brasil
Situation and slope	:	upperpart of a slope of 8%
Altitude	:	1160 m
Parent materials	:	Quaternary sediments
Topography	:	gentle undulating
Drainage class	:	very poorly drained
Vegetation	:	well grassland with palm trees (Buriti)

A1 :

0-40 cm	:	Black (N 2/0); clay loam; slightly plastic and slightly sticky
Cg 40-70 cm	:	White (2.5 Y 8/2); sandy clay; massive, plastic, sticky

Observation : on weathered quartzite

Profile no. 1

SNLCS

horizon	depth cm	gravel >20mm %	gravel 20-2mm %	particle size analysis NaOH % sand 2-.20 mm	sand .20-.05mm	silt .05-.002mm	clay <.002 mm	water disp clay %	floc degree %	silt/clay	AVLB PHOS pp m
A1	0-40	0	0	15	25	27	33	15	55	0.82	2
Cg	-70	0	1	21	36	8	35	2	94	0.23	1

pH(1:2.5) H2O	pH(1:2.5) KCl N	extractable bases mE/100g Ca^{++}	Mg^{++}	K^{+}	Na^{+}	sum extr	ext acty mE/100g Al^{+++}	H^{+}	cat exch mE/100g	base sat %	$100.Al^{+++}/(Al^{+++}+S)$
5.0	4.5	0.2		0.20	0.14	0.5	2.5	17.9	20.9	2	83
5.0	4.5	0.2		0.02	0.02	0.2	0.4	2.5	3.1	6	67

org C %	N %	C/N	attack by H2 SO4 (d=1.47) % SiO2	Al2O3	Fe2O3	TiO2	P2O5	Na2CO3 (5%)	SiO2/Al2O3 molecular ratio	SiO2/R2O3 molecular ratio	Al2O3/Fe2O3 molecular ratio
10.86	0.67	16	9.5	14.9	1.4	0.36			1.08	1.02	16.60
0.78	0.07	11	4.9	19.3	0.6	0.49			0.43	0.42	49.79

No weatherable clay minerals in sand fraction

Profile 2 (perfil DF 18). Date: 21/3/77

Classification	: Clayey Dystrophic Ground-Water Laterite, phase wet grassland on a spring level, level topography with a concretionary substratum
Locality	: Federal District Brasil
Situation and slope	: 1% slope in level area with grassland
Altitude	: 1240 m
Parent material	: Clay cover over tertiair basal conglomerate of Laterites
Drainage class	: poor
Present use	: natural grassland

A1 : 0-8 cm	dark grey, 10 YR 4/1 and grey 10 YR 5/1 rubbed; fine texture with gravel; weak fine to medium granular; friable, plastic, slightly sticky; transition level and clear.
A3g : 8-20 cm	grey brown, 10 YR 5/2 and pale brown 10 YR 6/3 rubbed; very fine with gravel; weak medium granular; friable, plastic and slightly sticky, transition level and clear.
B1gcn : 20-30 cm	white, 2.5 Y 8/2; yellow mottling; very fine texture with gravel; moderate fine to medium subangular blocky; hard, plastic and sticky; transition level and clear.
B2gcn : 30-45 cm	white 2.5 Y 8/2, reddish mottling; clayey-skeletal; massive, very hard, plastic, sticky; transition level and abrupt.
Cg cnpl : 45-60 cm	mixed colors, composed of white (N 8/6) and red (2.5 YR 5/6): very fine textured with gravel, massive, hard, plastic and sticky.
Observations :	Pit till 60 cm depth, Groundwater-level at 45 cm depth. Many roots in the A_1, common in the $A3_g$ and rare in B_1g cn. Many small and medium pores in the A_1, common in $A3_g$ and few in B1g cn.

Profile no. 2

SNLCS

horizon	depth cm	gravel >20mm %	gravel 20-2mm %	particle size analysis NaOH % sand 2-.20 mm	sand .20-.05mm	silt .05-.002mm	clay <.002 mm	water disp clay %	floc degree %	silt/clay	AVLB PHOS pp m
A1	0- 8	0	7	13	13	23	51	15	71	0.45	1
A3g	-20	0	7	9	10	19	62	36	42	0.32	1
B1gcn	-30	0	24	12	10	16	62	0	100	0.26	1
B2gcn	-45	0	58	25	10	13	52	0	100	0.25	1
1Cgcnp1	-60+	0	13	11	3	12	74	0	100	0.16	< 1

pH(1:2.5) H2O	pH(1:2.5) KCl N	extractable bases mE/100g Ca^{++}	Mg^{++}	K^{+}	Na^{+}	sum extr	ext acty mE/100g Al^{+++}	H^{+}	cat exch mE/100g	base sat %	$100.Al^{+++}/(Al^{+++}+S)$
5.5	4.5	0.5	0.11	0.06	0.7	0.4	9.4	10.5	7	36
5.6	4.8	0.4	0.06	0.05	0.5	0.1	5.5	6.1	8	17
5.9	5.7	0.4	0.02	0.03	0.5	0	2.1	2.6	19	0
5.7	5.9	0.3	0.02	0.02	0.3	0	2.1	2.4	13	0
5.7	5.4	0.3	0.02	0.03	0.4	0.4	1.5	2.0	20	20

org C %	N %	C/N	attack by H2 SO4 (d=1.47) % SiO2	Al2O3	Fe2O3	TiO2	P2O5	SiO2/Al2O3 molecular ratio	SiO2/R2O3 molecular ratio	Al2O3/Fe2O3 molecular ratio
4.13	0.34	12	5.4	38.9	2.8	0.81		0.24	0.23	21.79
2.46	0.21	12	4.7	42.6	2.4	0.83		0.19	0.18	27.84
1.02	0.09	11	5.4	44.6	3.2	0.82		0.21	0.20	21.87
0.79	0.08	10	9.8	43.2	4.4	0.65		0.39	0.36	15.40
0.38	0.05	8	27.4	40.5	6.2	0.66		1.15	1.05	10.23

No weatherable clay minerals in sand fraction

Profile 3 (Perfil DF 16), Date - 21/3/77

Classification : Red-Yellow Allic Latosol, "open cerrado" phase with level Topography

Localisation : District Federal, Brasil

Situation and slope : Pit on top of elevation with 1 % slope, with vegetation of grasses

Altitude : 1.330 m

Parent material: Clayey layer over basal-conglomerate of old "laterite" from Tertiair

Erosion : Slight sheet erosion

Well to moderately well drained

Natural vegetation : "Open cerrado"

Land use : Natural grassland

A1 0-8 cm : dark brown (6 YR 3/2) and dark brown (9 YR 3/4) crushed; clay; moderate small to medium granular; very friable, plastic and sticky; transition level and clear

A3 8-20 cm : dark brown (6.5 YR 4/4) and dark brown (7.5 YR 4/4) crushed; fine clayey; weak small to medium granular; very friable, plastic and sticky; transition level and clear.

B1 20-40 cm : brown (7.5 YR 5/4); very clayey, weak very fine granular with the aspect of massive porous with little coherence; very friable, plastic sticky; transition level and gradual.

B21 40-95 cm : yellowish-red (5 YR 5/8); fine clayey, weak very fine granular with the aspect of massive porous with little coherence; friable, plastic and sticky; transition level and difuse.

B22 95-145 cm : very fine granular with the aspect of massive porous with little coherence; friable, plastic, sticky; transition level and gradual

B23 145-200 cm : red (3.5 YR 4/8); fine clayey; weak very fine to fine granular, plastic sticky

B3 200-280 cm : red (1 YR 5/6); fine clayey, plastic and very sticky.

Observations: Till the B22 much "pseudo sand" which makes it difficult to estimate the texture. Some nodules with a diameter around 3 cm in B22 and many in B23.

In the sand fraction 50 to 75% quartz further also many clayey concretions no weatherable minerals

Profile no. 3

SNLCS

horizon	depth cm	gravel >20mm %	gravel 20-2mm %	particle size analysis NaOH % sand 2-.20 mm	sand .20-.05mm	silt .05-.002mm	clay <.002 mm	water disp clay %	floc degree %	silt/clay	AVLB PHOS pp m
A1	0- 8	0	1	15	12	18	55	16	71	0.33	2
A3	- 20	0	1	12	12	12	64	17	17	0.19	2
B1	- 40	0	1	9	10	13	68	33	33	0.19	1
B21	- 95	0	1	9	9	10	72	1	1	0.14	1
B22	-140	0	1	6	8	14	72	0	0	0.19	1
B23	-200	0	1	5	8	13	74	14	14	0.18	1
B3	-280+	0	1	5	8	12	75	42	42	0.16	16

pH(1:2.5) H2O	pH(1:2.5) KCl N	extractable bases mE/100g Ca^{++}	Mg^{++}	K^{+}	Na^{+}	sum extr	ext acty mE/100g Al^{+++}	H^{+}	cat exch mE/100g	base sat %	$100.Al^{+++}/(Al^{+++}+S)$
4.9	4.4	0.2		0.06	0.02	0.3	0.7	8.4	9.4	3	70
5.1	4.7	0.1		0.03	0.02	0.2	0.2	6.0	6.4	3	50
5.2	5.1	0.1		0.02	0.03	0.2	0.1	5.0	5.3	4	33
5.3	5.6	0.1		0.01	0.02	0.1	0	3.3	3.4	3	0
5.6	6.0	0.1		0.01	0.04	0.2	0	2.0	2.2	9	0
5.7	6.4	0.1		0.01	0.06	0.2	0	1.2	1.4	14	0
5.8	6.6	0.1		0.01	0.05	0.2	0	1.1	1.3	15	0

org C %	N %	C/N	attack by H_2SO_4 (d=1.47) % SiO_2	Al_2O_3	Fe_2O_3	TiO_2	P_2O_5	SiO_2/Al_2O_3 molecular ratio	SiO_2/R_2O_3	Al_2O_3/Fe_2O_3
3.20	0.20	16	5.4	36.0	12.8	1.00		0.26	0.21	4.41
2.20	0.14	16	5.0	35.6	12.7	1.06		0.24	0.19	4.40
1.79	0.12	15	4.9	37.6	13.7	1.07		0.22	0.18	4.31
1.10	0.07	16	5.2	38.2	14.0	1.08		0.23	0.19	4.28
0.89	0.06	15	5.4	40.1	14.5	1.07		0.23	0.19	4.34
0.63	0.05	13	6.8	40.0	14.6	1.10		0.29	0.23	4.30
0.48	0.04	17	9.6	39.7	14.3	1.11		0.41	0.33	4.35

Profile 4

Sp. no. 36 : SNCLS Date 1958

Classification :	Terra roxa legitima (Dusky red Latosol)
Locality :	State São Paulo, Brasil
Situation :	Roadcut, halfway on a hill with 5% slope
Altitude :	420 m
Topography :	Gentle undulating
Parent rocks :	Basalts
Vegetation :	Grassland
	Original Broadleaf Tropical Forest
Drainage :	Well drained

A_1 :		Dark reddish brown (2.5 YR 3/3)
0-40 cm		Yellowish red, crushed (2.5 YR 3/6); clay; weak fine granular; soft , friable, slightly plastic and sticky; transition level and difuse; roots abundant.
A_3		
40-65 cm	:	dark reddish brown (2.5 YR 3/4) yellowish red, dry crushed (5 YR 4/6); clay; weak fine granular; soft, friable; slightly plastic and sticky; transition level and difuse; roots abundant.
B_{21}	:	dark red (2.5 YR 3/5); clay; massive porous breaking down in weak very fine granular; soft, friable, slightly plastic and sticky; transition level and plastic; roots rare.
65-90 cm		
B_{22}		
90-120 cm+	:	like B_{21}

Coarse sand fraction 20-40% quartz iron rich concretions 40-57%; 20-25%magnetite. No easy weatherable minerals.

Profile no. 4

SNLCS

horizon	depth cm	gravel >20mm %	gravel 20-2mm %	particle size analysis NaOH % sand 2-.20 mm	sand .20-.05mm	silt .05-.002mm	clay <.002 mm	water disp clay %	floc degree %	silt/clay	AVLB PHOS pp m
A1	0-40	0	1.2	7.0	14.4	16.9	61.7	0.3	100	0.28	<10
A3	40-65	0	1.1	5.9	15.3	17.5	61.3	0.1	100	0.29	<10
B21	65-90	0	1.5	6.7	13.8	17.4	62.1	0.2	100	0.28	<10
B22	90-120+	0	4.0	6.4	15.5	17.7	60.4	5.2	91	0.29	<10

pH(1:2.5) H2O	pH(1:2.5) KCl N	extractable bases mE/100g Ca^{++}	Mg^{++}	K^{+}	Na^{+}	sum extr	ext acty mE/100g Al^{+++}	H^{+}	cat exch mE/100g	base sat %	$100.Al^{+++}/(Al^{+++}+S)$
5.1	4.6	0.51	0.31	0.04	0.04	0.90	4.91		5.81	15.49	
5.3	4.8	0.32	0.17	0.03	0.02	0.54	4.16		4.70	11.49	
5.7	5.1	0.34	0.20	0.04	0.05	0.63	3.59		4.22	14.93	
5.8	5.7	0.38	0.15	0.03	0.02	0.58	2.38		2.96	19.59	

org C %	N %	C/N	attack by H2 SO4 (d=1.47) % SiO2	Al2O3	Fe2O3	Na2CO3 (5%) TiO2	P2O5	SiO2/Al2O3 molecular ratio	SiO2/R2O3 molecular ratio	Al2O3/Fe2O3 molecular ratio
0.94	0.08	11.8	14.63	26.45	25.52	4.47	0.19	0.94	0.58	1.63
0.75	0.06	12.5	14.62	26.77	25.66	4.39	0.17	0.93	0.58	1.63
0.63	0.06	10.5	14.61	27.10	25.74	4.56	0.15	0.92	0.57	1.56
0.44	0.04	11.0	14.36	27.60	26.25	4.74	0.14	0.88	0.55	1.60

Profile 5

Classification : Kaolinitic Yellow Latosol, (Ortho), medium textured (KYL_m)

Location : Along highway BR-14, km 12.7 S of São Miguel do Guamá

Relief and drainage : Flat top of terrace, about 55 cm above nearby river. Well-drained. Alt. 65 m.

Parent material: Pleistocene fluviatile(?) sediments

Vegetative cover : Tropical forest with medium timber volume (150 m^3/ha ca.) At the spot probably once or twice attacked by fire.

A_1 : 0-20 cm — Brown (10 YR 4/3) coarse sand. Single grains and a few, weak, fine crumbs. Moist, loose. Not sticky and not plastic when wet. Soft when dry. Very many, mainly fine roots. Transition gradual.

A_3 : 20-70 cm — Yellowish brown (10 YR 5/4) light coarse sandy loam. Little coherent massive, to weak, medium to fine subangular blocky structure. Moist, very friable. Not sticky and not plastic when wet. Slightly hard when dry. Slightly more resistant to penetration than other horizons. Common pores. Many roots. Some pieces of charcoal. Transition diffuse.

B_1 : 70-140 cm — Brownish yellow (10 YR 6/6) coarse sandy loam. Weak, medium to fine subangular blocky structure. Moist, very friable. Not sticky and not plastic when wet. Slightly hard, to hard when dry. Common pores. Many roots. Transition diffuse.

B_{21} : 140-220 cm — Reddish yellow (7.5 YR 6/6) heavy coarse sandy loam. Little coherent massive, to weak, medium to fine subangular blocky structure. Moist, very friable. Not sticky and slightly plastic when wet. Slightly hard, to hard when dry. Common, to few pores. Few roots. Transition diffuse.

B_{22} : 220-320 cm — Reddish yellow (7.5 YR 6/6) light coarse sandy clay loam. Little coherent massive. Moist, very friable. Not sticky and slightly plastic when wet. Hard when dry. Few pores. Very few roots.

Profile no. 5

SNLCS

horizon	depth cm	gravel >20mm %	gravel 20-2mm %	particle size analysis NaOH % sand 2-20 mm	sand 20-.05mm	silt .05-.002mm	clay <.002 mm	water disp clay %	floc degree %	silt/clay	AVLB PHOS pp m
A_1	0-20	0	0	79.1	13.2	1.0	6.7	1.8	73	0.15	11
A_3	-70	0	0	68.4	16.4	0.8	14.4	7.9	45	0.06	6
B_1	-140	0	0	68.5	14.3	0.4	16.8	10.1	40	0.03	2
B_{21}	-220	0	0	62.7	16.5	1.0	19.8	0	100	0.05	2
B_{22}	-320	0	0	62.2	16.4	0.4	21.0	0	100	0.02	1

pH(1:1) H2O	pH(1:1) KCl N	extractable bases mE/100g Ca^{++}	Mg^{++}	K^+	Na^+	sum extr	ext acty mE/100g Al^{+++}	$H^+ + Al^{+++}$	cat exch mE/100g	base sat %	$100.Al^{+++}/(Al^{+++}+S)$
4.6	3.9	0.48		0.06	0.03	0.57	0.72	3.63	4.20	13.6	56
4.6	3.9	0.32		0.08	0.04	0.44	0.93	3.23	3.67	12.0	68
4.5	3.8	0.28		0.06	0.03	0.37	0.73	2.22	2.59	14.3	66
4.5	3.8	0.28		0.07	0.03	0.38	0.64	1.61	1.99	19.1	63
4.5	3.8	0.28		0.06	0.03	0.37	0.64	1.01	1.38	26.8	63

org C %	N %	C/N	attack by H2 SO4 (d=1.47) % SiO2	Al2O3	Fe2O3	Na2CO3 (5%) TiO2	P2O5	SiO2/Al2O3 molecular ratio	SiO2/R2O3	Al2O3/Fe2O3
0.88	0.06	14.7	4.11	3.80	1.21	0.34	0.03	1.84	1.52	4.39
0.42	0.03	14.0	6.95	6.29	1.72	0.57	0.03	1.88	1.60	5.47
0.25	0.03	8.3	8.62	7.77	1.72	0.67	0.03	1.89	1.65	7.09
0.18	0.02	9.0	9.31	8.55	1.92	0.64	0.03	1.85	1.62	6.99
0.13	0.02	6.5	9.44	8.69	1.82	0.64	0.03	1.85	1.63	8.14

Profile 6

Prefile no 35 SNCLS
Rio Grande do Sul

Classification : Dusky-Red Latosol, Dystric
Location : Municipality Sante Angelo, 6 km from Sante Angelo along the road, Sante Angelo, Sao Luiz Gonzaga. 20°22' sout, 54°17' east.
Situation : Roadcut half way up a slope of 5%
Altitude : Between 300 and 400 m
Reliëf : Gentle undulating
Lithology : Basic igneous rocks of the trapp formation
Landuse : Shrubs.
Original vegetation : Partly natural grassland, partly forest
Climate : Cfa Köppen, annual temperature 19.5°C, annual precipitation 1750 mm, without marked dry season
Drainage class : Well drained

A_1 0-40 cm : moist dark reddish brown (2.5 YR 3/4), moist crushed dark red (2.5 YR 3/6), dry dark red (2.5 YR 3/6) and dry crushed yellowish red (5 YR 4/8); clay ; weak fine and medium granular; porous with small pores; slightly hard, firm, plastic and slightly plastic; boundary diffuse and level; roots occupy 5% of the cross-section of the horizon.

B_1 40-80 cm : moist dark red (2.5 YR 3/6), moist crushed dark reddish brown (2.5 YR 3/4), dry dark red (2.5 YR 3/6) and dry crushed (2.5 YR 4/6); clay ; moderate fine and medium subangular; few weak clay skins; not very porous; hard, firm, slightly plastic and non sticky; boundary gradual and level; roots occupy 2% of the cross-section.

B_2 80-120 cm : moist and moist crushed dark reddish brown (2.5 YR 3/4), dry dark reddish brown (2.5 YR 3/5), and dry crushed red (2.5 YR 4/6); clay; weak; coarse subangular with the aspect of massive coherent in place; few weak clay skins; porous with small pores; very hard, firm to friable, slightly plastic and non sticky; boundary diffuse and level; roots occupy 1% of the surface of the cross section of the horizon.

B_{31} : moist and moist crushed dark red (2.5 YR 3/6), dry
120-170 cm dark red (2.5 YR 3/5), and dry crushed yellowish red (5 YR 4/6); clay; weak coarse subangular with aspect of massive coherent in place; very porous with small pores; very hard, friable, slightly plastic to non plastic and non sticky; boundary diffuse and level roots absent.

B_{32} : moist and moist crushed dark reddish brown (2.5 YR 3/4),
170-210 cm+ dry dark red (2.5 YR 3/6) and dry crushed yellowish red (5 YR 4/6); clay; weak very coarse angular and subangula with aspect of massive weakly coherent in place; very porous with small pores; very hard, friable, slightly plastic and non sticky,; roots absent.

Profile no. 6

SNLCS

horizon	depth cm	gravel >20mm %	gravel 20-2mm %	particle size analysis NaOH % sand 2-.20 mm	sand .20-.05mm	silt .05-.002mm	clay <.002 mm	water disp clay %	floc degree %	silt/clay	AVLB PHOS pp m
A_1	0-40	0	x	7.3	5.8	25.0	61.9	27.9	55	0.40	2
B_1	-80	0	x	4.7	4.3	19.4	71.6	0	100	0.27	1
B_2	-120	0	x	4.6	4.2	17.6	73.6	0	100	0.24	1
B_{31}	-170	0	x	4.0	4.2	14.4	77.4	0	100	0.19	1
B_{32}	-210	0	x	3.7	4.5	16.7	75.1	0	100	0.22	1

pH(1:2.5)		extractable bases mE/100g					ext acty mE/100g		cat exch mE/100g	base sat %	$100.Al^{+++}/(Al^{+++}+S)$
H2O	KCl N	Ca^{++}	Mg^{++}	K^+	Na^+	sum extr	Al^{+++}	H^+			
5.3	4.4	1.72	0.92	0.39	0.01	3.04	0.84	4.94	8.82	34.5	20
5.4	4.5	1.20	0.44	0.04	0.01	1.69	0.67	3.32	5.68	29.8	29
5.4	4.4	1.07	0.48	0.04	0.02	1.61	1.05	3.58	6.24	25.8	41
5.4	4.3	0.75	0.29	0.04	0.02	1.10	1.22	3.20	5.52	19.9	52
5.5	4.3	0.63	0.40	0.04	0.02	1.09	1.26	3.17	5.52	18.7	54

org C %	N %	C/N	attack by H_2SO_4 (d=1.47) % SiO2	Al2O3	Fe2O3	TiO2	P2O5	SiO2/Al2O3 molecular ratio	SiO2/R2O3 molecular ratio	Al2O3/Fe2O3 molecular ratio
1.23	0.12	10.3	24.47	21.06	24.59	4.47	0.22	1.95	1.12	1.35
0.53	0.06	8.8	26.41	22.94	23.13	3.92	0.20	1.94	1.18	1.55
0.51	0.06	8.5	26.85	23.67	22.70	3.84	0.21	1.91	1.18	1.63
0.31	0.04	7.8	27.88	24.54	21.45	3.69	0.19	1.91	1.23	1.80
0.33	0.04	8.3	27.28	23.55	22.10	3.63	0.21	1.95	1.22	1.68

MnO 0.40 cm, 0.29%; 80-120 cm, 0.28%; thin slides 60 cm) no argillans
105 cm)

Profile no. 7 (Perfil 20 pr area 1) Date 10/06/78 SNCLS

Classification : Dusky Red Latosol, phase: moist deciduous tropical forest. In Soil Taxonomy Typic Eutrorthox.
Locality : Cambira, Parana, Brasil
Situation and slope : half way up the slope of 5%
Parent rock : basalts
Topography : gentle undulating with long slopes
Altitude: 850 m
Drainage class : somewhat excessively drained
Erosion : Moderate to strong sheet erosion (?)
Actual use : Coffee and mais

Ap 0-16 cm : very dusky red (10 YR 3/4); fine clayey; weak fine and medium granular with aspect of massive porous, friable, plastic, stick; transition gradual and level.

B_1 16-44 cm : very dusky red (10 YR 3/4), fine clayey; moderate medium and large subangular blocky and strong very fine granular, friable, plastic and sticky; transition diffuse and level.

B_{21} 44-73 cm : (10 YR 3/5) further like B_1

B_{22} 73-146 cm : like B_{21}

B_3 146-240 cm : like B_{21} but transition clear and level.

B_3/C 240-270 cm : very dusky red (10 YR 3/5) and colors of the weathered parent material.

Observations: Many roots in Ap and B_1, common in B_{21} and rare in the other horizons.
Many fine and very fine pores in the whole profile.

SNLCS

horizon	depth cm	gravel >20mm %	gravel 20-2mm %	particle size analysis NaOH % sand 2-.20 mm	sand .20-.05mm	silt .05-.002mm	clay <.002 mm	water disp clay %	floc degree %	silt/clay	AVLB PHOS pp m
Ap	0-16	0	0	7	7	19	67	30	55	0.28	6
B_1	-44	0	0	6	5	12	77	0	100	0.16	< 1
B_{21}	-73	0	0	5	5	10	80	0	100	0.13	1
B_{22}	-146	0	0	5	6	13	76	0	100	0.17	< 1
B_3	-240	0	1	5	6	12	77	0	100	0.16	< 1
B_3/C	-270+	0	0	7	12	33	48	0	100	0.69	1

pH(1:2.5) H2O	pH(1:2.5) KCl N	extractable bases mE/100g Ca^{++}	Mg^{++}	K^+	Na^+	sum extr	ext acty mE/100g Al^{+++}	H^+	cat exch mE/100g	base sat %	$100.Al^{+++}/(Al^{+++}+S)$
5.3	4.3	2.7	5.9	0.76	0.02	9.4	0.3	5.8	31	61	3
5.1	4.4	1.7	4.4	0.74	0.02	6.9	0.3	4.3	36	60	4
5.1	4.5	0.8	3.8	0.16	0.02	4.8	0.2	3.7	37	55	4
5.0	4.7	0.7	3.3	0.20	0.01	4.2	0.2	3.2	34	55	5
5.2	5.0	0.3	2.5	0.04	0.02	2.9	0.1	2.5	36	53	3
4.7	4.1	0.5	4.8	0.10	0.03	5.4	1.5	2.5	38	57	22

org C %	N %	C/N	attack by H_2SO_4 (d=1.47) % SiO_2	Al_2O_3	Fe_2O_3	TiO_2	Na2CO3 (5%)	SiO_2/Al_2O_3 molecular ratio	SiO_2/R_2O_3	Al_2O_3/Fe_2O_3
1.79	0.20	9	20.1	20.7	31.8	4.70		1.65	0.83	1.02
1.12	0.16	7	21.1	22.8	31.0	3.94		1.57	0.84	1.15
0.84	0.10	8	21.1	24.6	30.0	3.77		1.46	0.82	1.29
0.53	0.07	8	20.1	25.5	32.7	4.09		1.34	0.74	1.22
0.35	0.05	7	20.1	26.3	30.4	4.13		1.30	0.75	1.36
0.17	0.04	4	26.7	25.2	28.7	3.40		1.80	1.04	1.38

Profile no 8 (perfil 38, Parana, area 9) Date 24/05/78 SNCLS

Classification : Brown Latosol, Allic, fine textured, subtropical evergreen forest, gentle undulating. In Soil Taxonomy : Humox.
Locality : Guarapuava, Parana, Brasil
Situation and slope: On top of elevation with 5 to 6% slope
Parent rock : Andesite?
Topography : gentle undulating
Altitude : 1,080 m
Drainage class : somewhat excessively drained.
Erosion : no observable erosion
Natural and actual vegetation: evergreen tropical forest

O_1 3-0 cm : partly decomposed litter

A_{11} 0-24 cm : dark reddish brown (5 YR 3/2); fine clayey; weak and moderate, medium granular; firm, plastic, and sticky; transition gradual and level.

A_{12} 24-45 cm : dark reddish brown; weak fine and medium granular and weak small and medium subangular blocky; friable, plastic and sticky; transition diffuse and level.

A_3 45-83 cm : dark reddish brown (5 YR 3/3.5); fine clayey; weak medium subangular blocky and strong very small granular; friable, plastic and sticky; transition gradual and level.

B_1 83-110 cm : dark reddish brown (5 YR 3/4): see A_3

B_{21} 110-140 cm : dark reddish brown (5 YR 3/5), diffuse and level transition further see A_3

B_{22} 140-200 cm : dark red (3.5 YR 3.5/5) very fine clayey, moderate medium subangular blocks; firm, plastic and sticky; glazes weak and few.

Observations: many roots in A horizon, few in the B horizon.
Many pores, medium, small and very small in all horizons

Profile no. 8

SNLCS

horizon	depth cm	gravel >20mm %	gravel 20-2mm %	particle size analysis NaOH % sand 2-20 mm	sand .20-.05mm	silt .05-.002mm	clay <.002 mm	water disp clay %	floc degree %	silt/clay	AVLB PHOS pp m
A_{11}	0-24	0	0	2	3	20	75	29	61	0.27	1
A_{12}	-45	0	0	2	3	19	76	37	51	0.25	< 1
A_3	-83	0	0	1	3	19	77	39	49	0.25	< 1
B_1	-110	0	0	1	2	17	80	45	44	0.21	< 1
B_{21}	-140	0	1	1	3	17	79	0	100	0.22	< 1
B_{22}	-200+	0	1	1	4	17	78	0	100	0.22	1

pH(1:2.5) H2O	pH(1:2.5) KCl N	extractable bases mE/100g Ca^{++}	Mg^{++}	K^{+}	Na^{+}	sum extr	ext acty mE/100g Al^{+++}	H^{+}	cat exch mE/100g	base sat %	$100.Al^{+++}/(Al^{+++}+S)$
4.4	3.8	0.9		0.12	0.06	1.1	4.3	13.3	39	6	80
4.6	3.9	0.7		0.08	0.06	0.8	3.5	9.9	37	6	81
4.8	4.0	0.4		0.04	0.05	0.5	2.7	7.6	36	5	84
4.9	4.2	0.6		0.03	0.06	0.7	2.1	6.7	36	7	75
5.1	4.4	0.4		0.03	0.04	0.5	0.6	4.7	38	9	55
5.2	4.3	0.4		0.02	0.04	0.5	0.2	3.9	38	11	29

org C %	N %	C/N	attack by H2 SO4 (d=1.47) % SiO2	Al2O3	Fe2O3	TiO2	Na2CO3 (5%)	SiO2/Al2O3 molecular ratio	SiO2/R2O3	Al2O3/Fe2O3
3.67	0.31	12	18.9	21.9	24.9	5.61		1.47	0.85	1.38
2.45	0.20	12	18.7	22.9	27.0	6.13		1.39	0.79	1.33
1.64	0.13	13	19.1	24.0	28.7	6.24		1.35	0.77	1.31
1.33	0.12	11	20.1	24.7	29.6	6.33		1.38	0.78	1.31
0.63	0.08	8	20.9	24.9	28.2	6.40		1.43	0.83	1.38
0.31	0.07	4	22.0	25.4	29.8	6.51		1.47	0.84	1.34

Profile no 9 (perfil rp-5) Date 14/01/76 SNCLS

Classification : Brown Latosol (Vacaria)
Locality : Experimental Station of Vacaria Rio Grande do Sul, Brasil.
Situation : Top of elevation
Parent rock : Basalt
Topography : Undulating
Altitude : ± 900 m and latitude about 29° S
Erosion : slight
Drainage class : well drained
Vegetation : natural grassland
Use : grassland

A_1 0-24 cm : Dark reddish brown (5 YR 3/3.5, moist; 5 YR 3/4, dry); clay; strong small and medium granular, medium and large subangular blocky and single grains; many small, medium and large pores; hard and very hard, friable, plastic and sticky, transition level and gradual, many roots.

A_3 24-45 cm : dark reddish brown (5 YR 3/4, moist), yellowish red (5 YR 4/6, dry); clay; strong medium and large subangular blocky and single grains; many small, medium and large pores; hard, friable, plastic and sticky, transition level and diffuse, few roots.

B_1 45-68 cm : (5 YR 3/5 moist); fine clayey, strong medium and large subangular blocky; many small, medium and large pores; weak developed glazes; hard friable plastic and very sticky; transition level and gradual; roots rare.

B_{22} 170-270 cm : yellowish red (5 YR 4/8 moist); fine clay; hard, friable, plastic and very sticky.

Observations: From a similar profile with glazes samples of thin slides did not show argillans.

Profile no. 9
Sample no.

SNLCS

horizon	depth cm	gravel >20mm %	gravel 20-2mm %	particle size analysis NaOH % sand 2-.20 mm	sand .20-.05mm	silt .05-.002mm	clay <.002 mm	water disp clay %	floc degree %	silt/clay	AVLB PHOS pp m
A_1	0- 24	0	0	3	23	16	58	32	45	0.28	3
A_3	- 45	0	x	2	20	12	66	36	45	0.18	6
B_1	- 68	0	x	2	16	11	71	48	32	0.15	1
B_{21}	-170	0	x	2	19	12	67	0	100	0.18	3
B_{22}	-270+	0	x	3	15	13	69	0	100	0.19	3

pH(1:2.5) H2O	pH(1:2.5) KCl N	extractable bases mE/100g Ca^{++}	Mg^{++}	K^+	Na^+	sum extr	ext acty mE/100g Al^{+++}	H^+	cat exch mE/100g	base sat %	$100.Al^{+++}/(Al^{+++}+S)$
5.1	3.8	1.6	1.4	0.14	0.01	3.2	3.7	9.8	19	19	54
5.0	3.8	0.8	1.2	0.05	0.02	2.1	4.4	7.6	15	15	68
5.0	3.8	0.5	1.4	0.03	0.02	2.0	4.5	6.4	16	16	69
5.0	4.0	0.3	1.4	0.02	0.01	1.7	3.0	4.1	19	19	64
5.1	4.0	0.4	1.6	0.02	0.01	2.0	2.8	3.7	24	24	58

org C %	N %	C/N	attack by H_2SO_4 (d=1.47) % SiO2	Al2O3	Fe2O3	TiO2	P_2O_5	SiO2/Al2O3 molecular ratio	SiO2/R2O3	Al2O3/Fe2O3
2.64	0.21	13	17.6	16.0	14.4	2.08	0.13	1.87	1.19	1.74
2.03	0.12	17	19.8	17.9	15.8	2.19	0.11	1.88	1.20	1.78
1.64	0.10	16	22.9	20.5	16.5	2.17	0.11	1.90	1.26	1.95
0.93	0.07	13	22.6	19.6	16.4	2.28	0.11	1.96	1.28	1.88
0.53	0.07	8	21.5	18.8	17.2	2.60	0.10	1.94	1.23	1.71

THE STATUS OF THE INTERNATIONAL COMMITTEE ON THE CLASSIFICATION OF ANDISOLS

M.L. Leamy

ABSTRACT

Activity since the inception of ICOMAND in 1978 has been reviewed and it is concluded that workshops and meetings have been far more productive than Circular Letters. Deficiencies in the geographic data base for testing the Andisol proposal are outlined. Information is required from large parts of Africa, Southeast Asia, and Latin America before a final compilation can be contemplated.

Output from the New Zealand workshop in February 1981 is summarized. Currently the major points of debate include the definition of andic and vitric soil properties, the relevance of bulk density as a classification criterion, the validity of the concept and elements of ECDAM, the use of temperature regime at suborder level, and the definition of the boundaries between Andisols and other orders.

The future strategy of ICOMAND is outlined, the most important element of which is the conclusion that without a significant financial input, which does not seem to be available from traditional sources, the goal of a comprehensive, widely accepted Andisol proposal within the next five years will not be achieved.

REVIEW OF ACTIVITY

Since its inception in 1978 the International Committee on the Classification of Andisols (ICOMAND) has been active through circulars and workshops. There have been three circulars distributed to an international audience of about 100 scientists. Approximately 20 people have responded

to these, a few of them with contributions of substantial import to the concerns of the Committee.

The workshops have been far more productive. The first was informally arranged and was held in Tokyo in 1978 at the headquarters of the National Institute for Agricultural Sciences. It involved some 30 people in a probing discussion on the new proposals which resulted in a critical examination of some of the key taxa for temperate-zone volcanic ash soils. For instance, the necessity for a great group of Melanaquands was effectively argued by Japanese soil scientists, and subsequently demonstrated in the field in a way that decades of correspondence could not have achieved.

The second workshop took place in Palmerston North, N.Z. on the occasion of the International Conference on Soils with Variable Charge. It was attended by more than 80 scientists from 23 countries, and the output indicated clearly the advantages of bringing people together for discussion rather than trying to conduct a scientific debate through the tortuous channels of the international mailing system.

It is crystal clear from this experience that if advances toward a globally acceptable classification of soils are to be made, they will not happen through the postal services. Scientists are sometimes accused of being naive about technologies ot than their own and about the realities of the potential economic input of their science. From my experience it is inescapable that reliance on anything other than regular scientist-to-scientist contact in an appropriate environment will not only be ineffective--it will doom the goal of an International Soil Classification System to at least the next century--which may be about 10 years too late for a humanity which needs it now.

The constraint is clearly financial. Given only a fraction of the defense budgets of the world's leading nations, we soil scientists could develop systems of productivity which would ensure that no politician would be obliged to worry about excesses of population in the world. More importantly, Third World countries could shake off any reliance which has been forced on them by policies imposed by larger, richer, nations seeking to expand the markets of the world at the expense of the people of the Third World.

Soil scientists have in their grasp one of the keys to ensuring that every nation on earth can optimize its land resources. If we are constrained from using that key by national or multinational financial policies, we should become a little militant about that. What we know, and what we can do, are commercial properties. Let us sell ourselves for the good of mankind.

GEOGRAPHIC DATA BASE FOR ANDISOLS

When Soil Taxonomy was written, the data base for the Andepts was confined to the Western U.S., Alaska and Hawaii. The global distribution of soils formed on volcanic ash includes large parts of Latin America (e.g. Mexico, Costa Rica, Peru, Ecuador, Chile, Argentina); Africa (e.g. Cameroon, Kenya, Rwanda, Uganda); Southeast Asia (Indonesia, Philippines, Korea); the Pacific (Papua-New Guinea, Fiji, Samoa); and even Europe (Spain, Germany, Italy). Since ICOMAND commenced deliberations, considerable data has been injected from Japan and New Zealand. But there is still a long way to go.

What needs to be done, technically, is clear. How to do it, technically, is possible. How sad it is that we are constrained from reaching these goals by an economic system that is so unresponsive to one of the real needs of the modern world.

OUTPUT FROM THE NEW ZEALAND WORKSHOP

Simple definitions were the main thrust of the New Zealand meetings. Compelling proposals for defining Andisols in terms of "andic soil properties" or "vitric soil properties" were advanced.

The proposed definition of "andic soil properties," developed by a New Zealand pedologist (B.R. Purdie) captured the imagination of participants because it unraveled the complicated terminology of the current definition. In essence the definition of andic soil properties is of properties which extend to 35 cm or more and which meet the requirements of spe-

cific particle size/mineralogy classes, i.e. medial or hydrous.

"Vitric soil properties" would be identified by definitions coinciding with the particle-sized mineralogy classes: pumiceous, cindery or ashy.

Definition of ECDAM

The definition of 'medial' and 'hydrous' requires the exchange complex to be dominated by amorphous materials (ECDAM). The definition of ECDAM has been criticized on the grounds that bulk density of less than 0.85 gm/cc is too low and not as relevant as measurements of void ratio or total porosity. Many apparent Andisols do appear to have BD values greater than .85, but doubts were expressed by soil stratigraphers as to whether those Andisols were correctly identified as being totally formed from volcanic ash, or whether there was a detectable and significant content of nonvolcanic loess in their parent material. This is a critically important threshold in the identification of soils from volcanic ash, because an input of nonvolcanic material can substantially affect the properties of these soils. However, loess is a temperate zone phenomenon, and there is evidence from intertropical regions, particularly Kenya and Mexico, which suggests that high amounts of amorphous silica from some volcanic sources will result in a bulk density value greater than 0.85 gm/cc.

There were also comments on pH in NaF. This is a useful measurement because there is a field test available to determine it. It also appears to be unquestionably a sign of high variable charge that is not easily confused with criteria for other orders, with the notable exception of Spodosols. Many spodic horizons have high pH values in NaF, but other factors such as morphology, stratigraphy and provenance are usually sufficient to identify the appropriate order.

The phosphate retention value has considerable attraction because this is a value which leads to little confusion with other taxa, but has also considerable utility in terms of immediate land use application.

The fourth element in the proposed redefinition of ECDAM is variable charge. The proposed method for determining this is by subtracting bases + exchangeable Al from CEC at pH 8.2. A criticism that has been levelled is that bases + exchangeable Al may not always represent natural field pH. Perhaps the arbitrary selection of a reasonable value for field pH, which should not be beyond the capabilities of competent taxonomists, may satis-

fy this criticism.

However, a very strong recommendation emanating from the N.Z. meeting may overcome this criticism. This is that a measure of the acid oxalate-extractable aluminum (with a critical value of 2.4%) could be a more valid and a simpler measure of the high activity of Andisols.

ECDAM was heavily criticized by Japanese soil scientists who proposed an alternative value of ECDAHA--Exchange Complex Dominated by Active Hydrous Alumina. There is no question that so called "amorphous materials" are not amorphous by modern standards of instrumentation. But serious doubt exists as to whether these soils should be defined on the basis of conceived effects rather than measurable properties. For instance, there is at least the possibility that active iron compounds, such as ferrihydrite, may be present in some Andisols. Clearly, the concept and the elements of ECDAM require substantial review and modification.

Other Concepts

Another feature of the Andisol proposal which has excited considerable comment is the use of temperature regime at suborder level, particularly in the Tropands. The debate centers around the repetition of temperature regime at suborder and at family level, and the allegedly unwarranted emphasis on the importance of isotemperature regimes. The debate rages on with a minimum of data and practical land use experience to sustain it, and it is clear that the answer will emerge only through contributions from strategically located tropical countries such as Indonesia, Philippines, Ecuador and others.

There is some evidence of rhodic properties in Andisols, particularly in the Pacific nations of Fiji and the Solomon Islands, where soils on young, basic volcanic ash have red hues with low chromas, and also have remarkably high total phosphorus values.

An important concept that was emphasized at the New Zealand workshop was that not all soils on volcanic parent materials are Andisols. Andisols are one part of a sequence, architectured by time, climate and vegetation, existing between Entisols and other orders such as Alfisols, Spodosols and Oxisols. A primary aim of ICOMAND is to define the boundaries between Andisols and these other orders. Different regions of the world will be critical in deriving the appropriate parameters--for instance, the interface

between Entisols and Andisols is well expressed in the western U.S.; and that between Spodosols and Andisols in Alaska and New Zealand.

FUTURE STRATEGY FOR ICOMAND

The goal of a comprehensive, widely accepted Andisol proposal within the next 5 years will not be achieved by relying on circulars to generate data and debate. The emphasis must be on personal contact through visits, workshops or group study tours. ICOMAND does not have a financial budget. Apart from travel expenses for the Chairman to attend International Soil Classification Workshops, and some of the postage for circulars, both of which are funded through Soil Management Support Services, expenses are absorbed by the institutions to which members belong. Two meetings are being planned--one in Japan in 1982 sponsored by the Japanese Society for the Promotion of Science, and initiated by a group of Japanese soil scientists; and an International Soil Classification Workshop sponsored by SMSS in South America. There will need to be more contacts than this in many other parts of the world, and the final compilation of the proposal will require, in my estimation, at least 6 months full time activity by one person. It is abundantly clear that if the goal is to be achieved, more finance will be required than is likely to be available from the traditional sources. To this end a proposition is being circulated suggesting that key, progressive transnational companies involved in some aspect of food or fibre production might accept, as a research investment, a proposal that they fund part of the ICOMAND program. The benefit for the investor would be access to information about the properties and distribution of productive soils, and a very real contribution to solving the food supply problems of many developing countries.

The problems that assail ICOMAND are common to most ICOM's. This approach to funding might achieve greater success if the combined weight of all the International Committees were thrown behind it.

MINERALOGY AND MICROMORPHOLOGY OF SOME ANDISOLS OF RWANDA

G. Stoops

INTRODUCTION

The northern and northwestern territories of Rwanda are part of the East African Rift system and are characterized by relatively young volcanic materials. It is therefore obvious that Andisols form a quite important soil group in these areas (Van Wambeke, 1961). For the present workshop four profiles with andic characteristics were sampled by H. Neel, and their micromorphological and mineralogical characteristics studied in the Laboratory of Mineralogy, Petrography and Micropedology at the State University of Ghent, Belgium.

Whereas several review papers exist on the clay mineralogy of Andisols, nothing comparable has been published with regard to their micromorphology. As such knowledge can be very important with respect to the classification of soils, an attempt is made here to retrace and define the typical micromorphological characteristics of andic soil materials as described by different authors and to select a few characteristics which can be considered as diagnostic.

MICROMORPHOLOGICAL CHARACTERISTICS OF ANDISOLS

Introduction

Although Andisols have been investigated intensively in several countries, information on their micromorphological characteristics is relatively scarce. Moreover, practically all descriptions published concern Typic Dystrandepts, and no information at all is available on some of the other great groups (e.g. Durandepts).

For this review of literature, mainly the following papers have been used: Kawai (1969), Stoops (1972), Aguilar & Delgado (1973), Benayas et al. (1973), Fernandez Caldas et al. (1975), Tejedor Salguero et al. (1975), Fernandez Caldas & Tejedor Salguero (1975), Bech-Borras et al. (1977), Tejedor et al. (1978), and information from some internal reports of our laboratory.

Microstructure

The low bulk density, which characterizes Andisols, and their friable consistency, already point to a specific microstructure. Practically all descriptions of Dystrandepts indicate a very porous microstructure, ranging from spongy to fine crumbly. Most commonly the soil material is built up of a loose packing of aggregates. In general, three types of aggregates can be recognized (Bech-Borras et al., 1977): (i) rounded micropeds of about 50 m, frequently associated with biopores, (ii) rounded secondary aggregates, about 400 m in diameter, with residual packing pores, and (iii) larger aggregates, up to a few mm, built up of a denser packing of the former types. The porosity pattern is dominated by compound packing pores, interconnected cavities and channels. In somewhat denser soil materials (e.g. with a spongy microstructure, mainly found in the mid of the profile or in the epipedon), irregular rough fissures may be found, resulting from the air-drying of the sample (Shin, 1978).

The formation of the micro-aggregates is not yet well understood. Most of the small rounded pellets found in the higher part of the profile are clearly of faunal origin, but for the larger micropeds, and specially those found in the lower horizons, a biological origin is less evident. Stoops (1972) describes spheroidal micropeds of 300-400 m diameter in the C_2 of a Dystrandept, with a weakly developed concentric fabric, and mostly with a mineral grain or rock fragment as nucleus. Weak birefringent rings indicate that some weathering occurred previous to the formation of the actual micropeds. It is remarkable that even in arid soils on volcanic ash (ACSAD, 1980, profile R1) a similar microstructure is observed.

Shin (1978) concluded that the micro-aggregates are very stable, both with regard to wet sieving and to slaking in different solutions (water, Tamm's reagent and Na-Hypobromite). The latter solution seemed most ef-

fective in destroying the aggregates, which only partly confirms the supposition of Bech-Borras et al. (1977) that monomorphous organic matter is the binding substance in the micro-aggregates.

In a Typic Hydrandept from Korea, Shin (1978) describes an irregular jointed and fragmented microstructure, with cavities as intrapedal pores.

Coarse Material

By coarse materials are meant here particles larger than about 5 m. They consist mainly of fragments of rocks, primary minerals, volcanic glass and phytolites.

The rock-fragments are essentially of volcanic origin and may give precise information as to the nature of the parent material (petrography and crystallinity). Moreover, the differential weathering of their different constituents may be a useful indicator for estimating the degree and type of weathering of the material (Eswaran et al., 1973).

The most common primary minerals are fieldspars, olivine, augite, oxihornblende, quartz, magnetite and ilmenite. The latter two minerals generally occur in the silt or fine sand fractions. In most cases no *in situ* weathering products are observed in thin sections. The transformation of olivine to iddingsite seems rather an alteration than a weathering process. The presence of minerals, typic for plutonic or metamorphic environments, may indicate a colluvial or solian transport although it should not be excluded that they may originate from the underlying basement. Secondary minerals, like gibbsite, may be present, but mainly form larger features, which will be discussed later.

Volcanic glass may be the dominant constituent of some profiles (e.g. Vitrandepts). It is in general more weatherable than the primary minerals, and therefore may decrease towards the soil surface. Basic volcanic glass (sideromelane), characterised by a positive relief and a darker colour, may be totally or partially transformed to orange-yellow palagonite. This process should not be mistaken for a pedogenetic weathering of the glass, as erroneously has been done by some authors.

According to our experience, phytolites are relatively abundant in most andic soil materials. In how far this is the result of a higher opal production by the vegetation, or a better conservation in the soil, is not

yet clear.

Fine Material

Practically throughout the profile the fine material has a dark brown colour, decreasing in intensity with depth. In general it is cloudy or dotted, and composed of an intimate mixture of clay and amorphous or very finely dispersed organic matter. One of its most important characteristics is its optical isotropy, giving rise to an undifferentiated or at the most weakly scaly birefringent fabric (Stoops, 1978).

Organic Matter

Highly fragmented organic material seems to be abundant in most Andisols. Fragmentation generally increases with depth, whereas the total amount of organic residues gradually decreases with depth. No detailed descriptions of the morphology of organic matter in Andisols were published up to now. A typical phenomenon observed in all Andisols is the intimate mixture of the organic residues of different sizes, both with the fine and the coarse mineral material. This feature points undeniably to a high biological activity.

Most authors mention the presence of fungal hyphae in the A horizons of Dystrandepts, but not sufficient data were available to relate their presence to other factors.

C/f-Related Distribution

Depending on the relative amounts of fine and coarse material present, different types of c/f-related distributions may occur. In most cases, however, a porphyric c/f-R.D. is noticed inside the aggregates. They then consist of an intimate mixture of clay, minerals of different sizes and fragmented organic matter. When the coarse fraction is dominant, the fine material may form pellets, randomly distributed between the grains (enaulic), or even adhere as a coating around the grains (chitonic). This is probably a first stage in the formation of concentric micropeds.

Pedogenetic Features

Pedogenetic features are rather scarce in Andisols. The most common feature, although still relatively rare, is the occurrence of gibbsitic new formations. Gibbsite may occur as pseudomorphs after feldspars, as microcrystalline nodules, or as coatings on the walls of cavities, indicating a relative mobility of aluminum in the soils.

Some authors record the presence of clay coatings on ped surfaces and pores in the B horizons, but it seems questionable how such soils still can be classified as Andisols.

Discussion

From the above it may be deduced that the following micromorphological characteristics are diagnostic for Andisols, and partly also for other andic soil materials, if they occur together:

- a very porous microstructure, consisting in most cases of a loose packing of more or less spherical microaggregates of different sizes, grading in some cases to a spongy microstructure;
- an intimate mixture of finely fragmented organic matter with fine and coarse mineral material in the upper horizons as a result of an intense biological activity;
- an undifferentiated (isotropic), or at the most very weakly scaly birefringent fabric throughout the profile;
- the presence of relative fresh volcanic minerals and/or volcanic glass in sand and silt fraction.

MICROMORPHOLOGY OF ANDIC MATERIALS FROM RWANDA

Prof. R7, Hor. A_p, A_{12} & A_{13} (Typic Dystrandept)[1]

A crumbly microstructure is observed throughout the profile, but less expressed in the A_{13}. The loosely packed aggregates range in size from 250 to 1500 m, the larger being composed of a dense packing of small (50

[1]Profile numbers and horizons refer to the description in the Tour Guide.

m) micropeds (Plate I, 1 and 2). Biopores and pedotubules indicate a high biological activity (Plate I, 3). The coarse material consists mainly of rare grains of fresh augite, feldspar and glass. The dominant fine material is dark brown to opaque in the A_p, brown to dark brown in the A_1 horizons, but always isotropic. The fragmented organic matter is homogeneously dispersed in the fine mass. Phytolites commonly occur, and fungal hyphae are occasionally observed in the top horizon.

Prof. R8, Hor. A_{11}, A_{12} & B_{21} (Udic Eutrandept)

A crumbly microstructure is found throughout the profile. Rounded micropeds, 50 to 100 m in diameter are loosely packed (Plate II, 1 and 3). Larger aggregates seem to consist of welded pellets. The packing of the micropeds is denser in the A_{11} than in the underlying horizons.

In the A_{11} horizon the dark coloured, isotropic fine material is strongly dominant over the coarse material, which consists mainly of silt-sized fragments of volcanic glass. Few coarser grains of augite, feldspar and palagonite (Plate II, 3) are noticed. In the underlying horizons, the fine material is somewhat less dark, but always isotropic. A porphyric c/f-related distribution is noted throughout the profile. Silt-sized phytolites are frequently observed throughout the profile. Occasionally fungal hyphae were noticed (Plate II, 2).

Prof. R6, Hor. A_3 & B_{22} (Andic Humitropept)

In this profile the crumbly structure is less developed than in the two former profiles, although still present, especially in the deeper horizons (Plate III, 1). The coarse material, which is dominant over the fine, consists mainly of volcanic rock fragments (Plate III, 1) and grains of feldspar, augite and olivine (Plate III, 2 and 3). The dark brown fine material is isotropic. The abundance of fecal pellets and the intimate mixture of organic and mineral compounds points to a high biological activity. The B_{22} horizon is characterized by the presence of thin clay illuviation coatings on the walls of cavities in its spongy part.

Prof. R9, Hor. A_{p1}, A_{p2}, A_{13}, A_{14} & A_{16} (Udic Eutrandept)

The A_p shows a spongy microstructure with mammillated cavities, grad-

ing to a more crumbly microstructure in the A_{13} and A_{14}, becoming irregularly jointed in the A_{16}. Heterogeneity of the material, and presence of stratified accumulations of silt and/or clay in the A_{14} may indicate some disturbance of the profile. The coarse fraction of the A_{16} consists mainly of quartz and weathered biotite. These minerals decrease towards the top of the profile, where augite and feldspar become more important. The fine material is brownish and intimately mixed with fine organic fragments, especially in the A_p. An open porphyric c/f-related distribution is noticed throughout. The top layers have an undifferentiated b-fabric, but in the A_{16} a weakly scaly fabric may be noticed. Phytolites are less common than in the other profiles.

MINERALOGY OF ANDIC MATERIALS FROM RWANDA

Prof. R7, Hor. A_{12} & A_{13}

X-ray diffraction of the clay fraction shows no distinct lines, except for low amounts of feldspar and traces of a 10 Angstrom mineral. The high bulge in the background clearly indicates a dominance of allophane, as confirmed by a continuous loss of a large quantity of water during thermogravimetry. T.E.M. also confirms the presence of allophane and imogolite. The silt fraction has a composition similar to the clay fraction, except for a higher feldspar content. Augite (mainly purple) is practically the only heavy mineral found in the sand fraction.

Prof. R8, Hor. A_{12} & B_{21}

X-ray diffraction of the clay fraction gives no recognizable lines, except for traces of feldspar, and a broad bulge near 7.5 Angstroms. T.G. indicates a continuous loss of water between 20 and 1000 degrees C. A very broad and very weak endotherm near 500 degrees C on the D.T.A. may point to an incipient formation of halloysite or kaolinite in the dominant allophanic mass. T.E.M. confirms the dominance of the latter, even as the presence of imogolite. The diffractogram of the silt fraction shows also a very important background (allophane), some lines of feldspar and enstatite and traces of a 10 Angstrom component. Idiomorphic enstatite with opaque

inclusions dominates the heavy mineral fraction of this soil, with some additional grains of augite.

Prof. R6, Hor. A_3 & B_{22}

A distinct peak of mica and a few smaller feldspar peaks are superimposed on an important background of amorphous material. In the A_3 horizon, some small peaks indicating weakly crystalline kaolinite or halloysite are added to this. The presence of this mineral is confirmed by a clear endothermic peak near 500 degrees C in the D.T.A. curve. T.E.M. investigations proved the presence of halloysite. T.G. curves show a continuous loss of water, confirming the dominance of allophane.

The silt fraction has a similar composition, but here the presence of feldspar is better expressed. Amongst the heavy minerals of the sand fraction, augite is the most important one. Few biotite flakes are observed.

Prof. R9, Hor. A_{p2}, A_{13} & A_{14}

The important background on the X-ray diffractograms indicates the presence of allophanic material. Superimposed on this, distinct peaks of kaolinite or halloysite and a weathering mica are observed. These lines are less clear in the A_{14} horizon than in the higher ones. A weak and broad endothermic peak near 520 degrees in the D.T.A. curve and T.E.M. observations confirm the presence of halloysite. The continuous loss of water shown in the T.G. curve indicates an important allophane content.

The silt fraction has a similar composition, but here the halloysite peaks are more clear on the diffractogram. The sand fraction contains the following heavy minerals: rather fresh augite (dominant), tourmaline, staurolite and sillimanite.

DISCUSSION

Profiles R7 and R8 have been respectively classified as Typic Dystrandept and Udic Eutrandept. Both profiles show the typical characteristics of Andepts with respect to composition of their clay fraction (allophane,

imogolite) and to their micromorphological aspects (micropedal structure, isotropic fine material, coarse fraction composed of volcanic minerals and glass, high biological activity).

Profiles R6 and R9 were both classified respectively as Andic Humitropept and Udic Eutrandept. Although allophane is no longer the only clay mineral present, it is still the most important one, giving andic properties to the soil material. The micromorphological aspects of profile R6 are still close to those of the Andepts, although less pronounced. The formation of clay cutans in the B horizons indicates an incipient illuviation process. In profile 9 only part of the andic characteristics are preserved in the top layers; the deeper part of the profile is clearly non-andic (jointed microstructure, scaly b-fabric, coarse fraction composed mainly of quartz and weathered biotite).

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DISCUSSION

Q. F.N. Muchena: 1. One would normally expect to have pellety or granular microstructure in soils with high biological activity. Is the pellety structure in Andisols attributable to a high biological activity or what is its origin? 2. Why is organic matter not considered as a pedologic feature?

A. G. Stoops: 1. The pellety microstructure in the top layer might be of biological origin, but this cannot be extended to the deeper horizons. Physical processes, combined with the typical physiochemical properties of the soil material, are probably responsible for this microstructure typical of the Andisols. 2. Although Brewer (1964) is not considering organic matter as being part of the soil material, we just considered it as a soil constituent on the same level as the mineral components. However, organic matter does not meet the requirements of Brewer's definition of pedological features.

Q. M.L. Leamy: Can imogolite be used as a diagnostic feature as determined by thin section analysis?

A. G. Stoops: Due to its very small size, imogolite cannot be recognized in thin sections; it is far beyond the resolving power of an optical microscope.

FIGURE CAPTIONS

Plate I Profile R7

1. Loose packing of aggregates and micro-aggregates in A_p. Plain light.
2. Detail of micrograph 1. Larger aggregate composed of welded micropeds. Note the presence of phytolites (P). Plain light.
3. Pedotubule in A_{13}. Note the pellety microstructure of the material. Plain light.

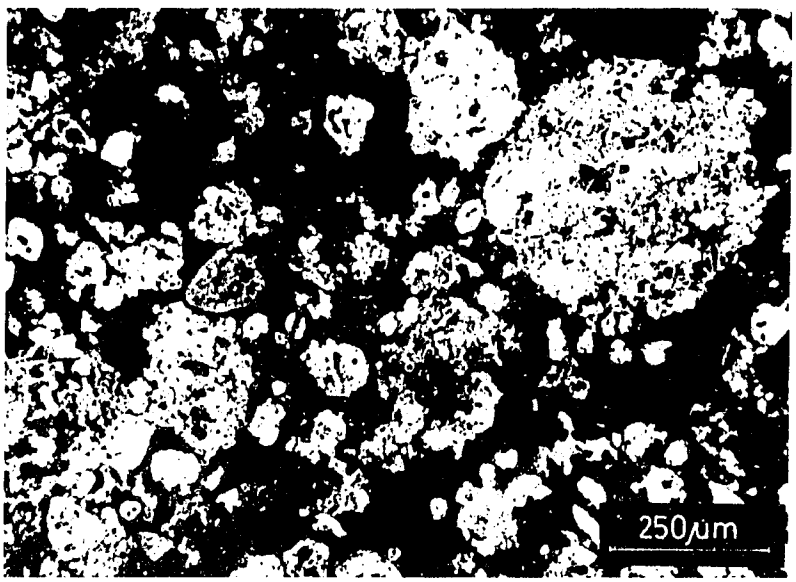
Plate II Profile R8

1. Loose packing of micropeds in A_{11}. Plain light.
2. Detail of micrograph 1. Note individual micropeds, phytolites (P) and fungal hyphae (H). Plain light.

Plate III Profile R6

1. Micropeds and fragments of basalt (B) in B_{22}. Plain light.
2. Detail of matrix from B_{22}. Note composition of the coarse fraction: volcanic glass (G), augite (A), feldspar (F) and olivine (O). Plain light.
3. Idem. Crossed polarizers.

PLATE I



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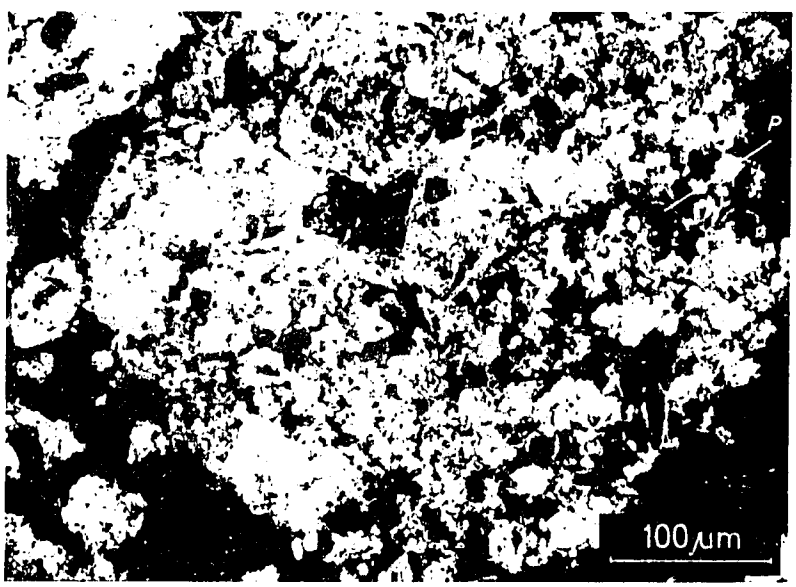

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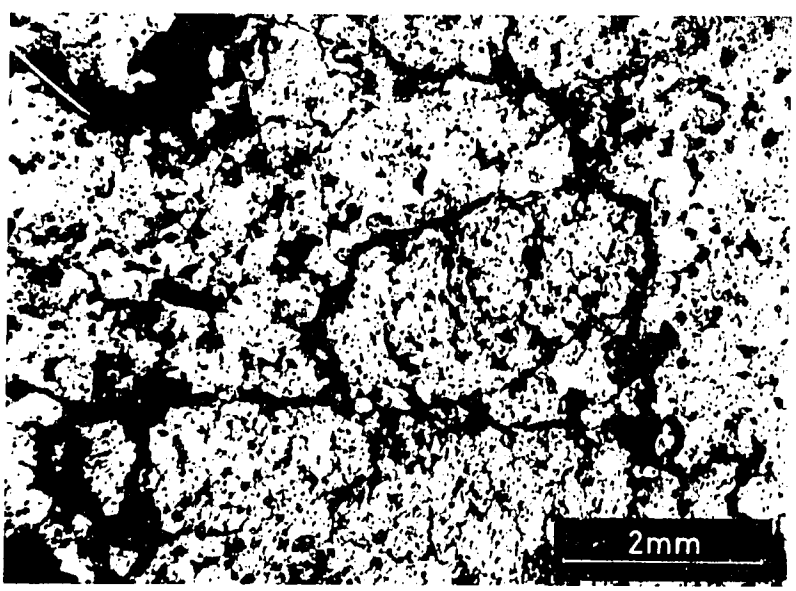

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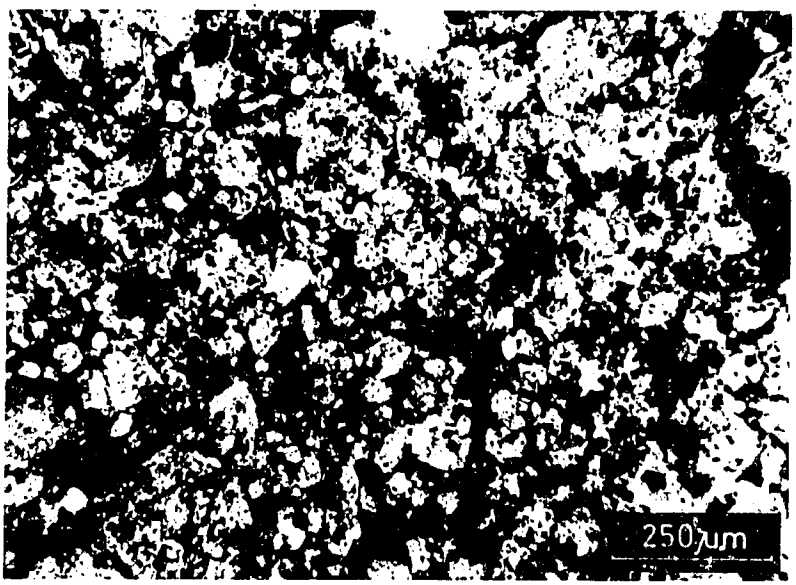

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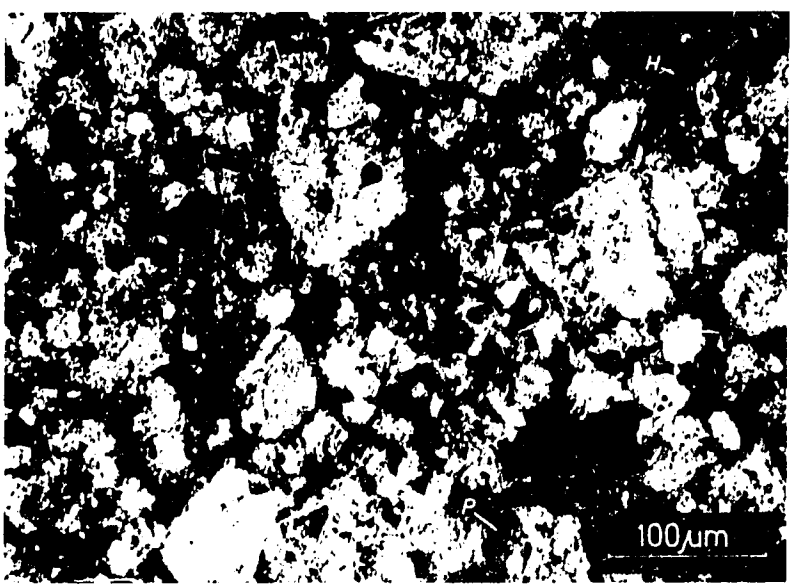

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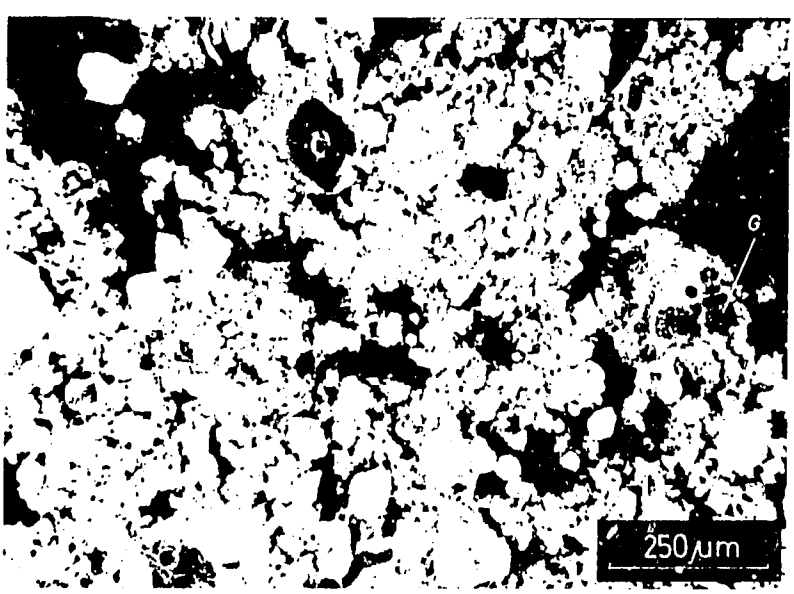

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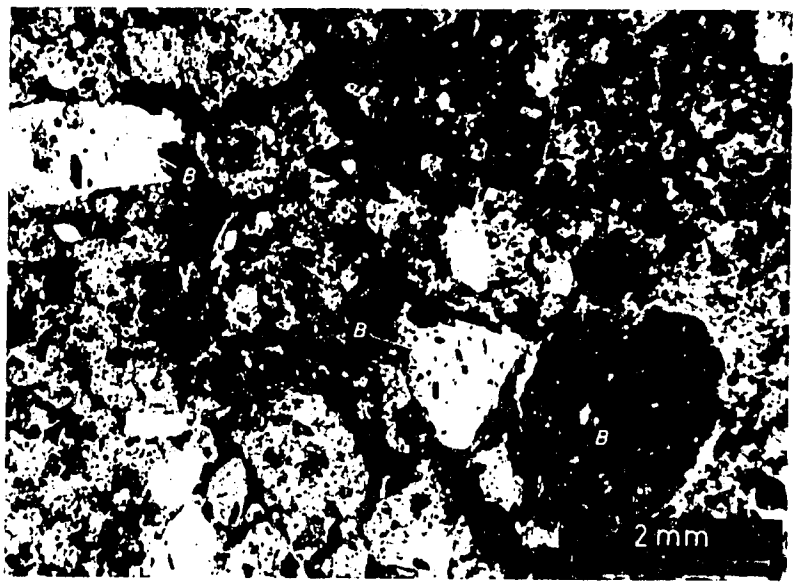

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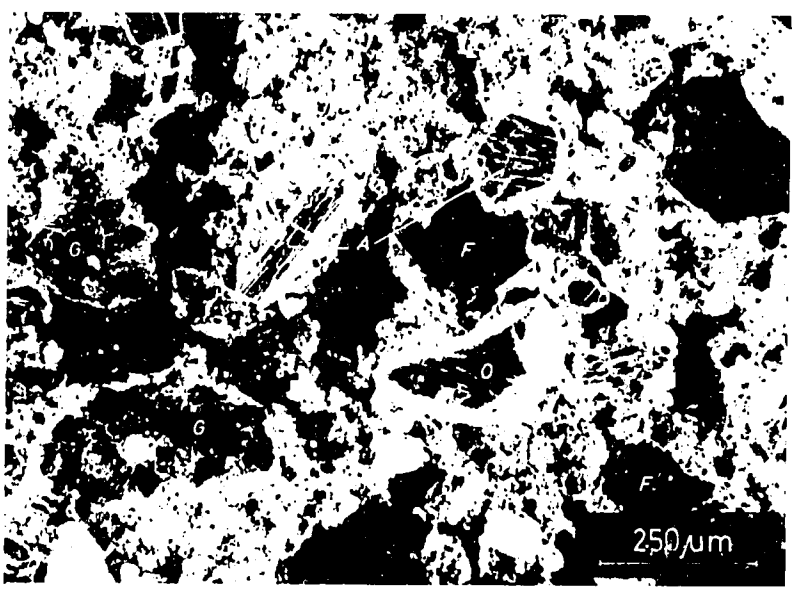

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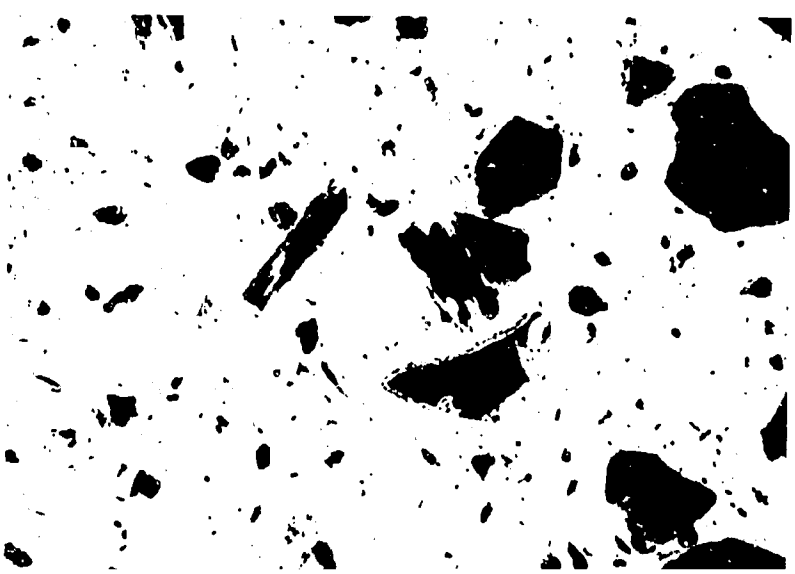

3

THE ANDISOLS OF CAMEROON

E.M.T. Awa and E.T. Awah

INTRODUCTION

Andisols cover only a limited land area in Cameroon, about 600,000 ha (Fig. 1). Because of their high production potential, they have achieved remarkable importance in the agricultural development of Cameroon. By Andisols here we will refer simply to soils developed on volcanic materials. Andisols as proposed will be more definitive.

There appears to be a weak belt of Andisols stretching in a northeasterly direction into Cameroon. It is realized from the soils and historical studies that this highland plateau area was not formed as a result of one sudden uplift, but of a series of eruptions from the Tertiary epoch through the Quarternary to the present. Some of the basement complexes and rhyolite intrusions may have taken place during the Precambrian (Hawkins and Martin, 1964), but there have been considerable eruptions and outpourings of modern times. Cameroon Mountain was termed the "Chariot of Gods" by the Carthaginians (about 500 BC) as a result of the explosive eruptions during this period. Several smaller lava and ash outpourings have been recorded in modern times.

Aside from the differences in the age of the parent rock material, significant differences in the soil types are also a reflection of the climates. The Andisols here range from the humid tropics, with over 11,000 mm of rainfall (12 months) and thick forests of huge mahogany trees, through shrub savannas and savannas of the mountain plateau to the Sahelian North with two seasons: a short wet torrential season of 2-3 months and long dry season of 8-9 months. The variations and evolution of the climate factor over the ages, and the probability that this change is being influenced by human interferences, has been a subject of some discussion (Siefferman, 1973).

The volcanic soils have constituted the bread basket of Cameroon. Some of our major plantation undertakings have been sited on these soils, and the yields are very outstanding.

LAND USE

The uses to which these soils have been put are varied. While the economics of production and marketing have to some extent dictated the various choices, the climate, topography, vegetation, soil types, and social preferences have been quite important in the traditional decisions as to land use.

In the forest zones where the temperature and rainfall are high (in excess of 7,000 mm rainfall in places) and the soil is generally young and fertile, the native farmers plant various root crops--yams, cassava, cocoyams and corn. Plantation agriculture involving tree crops is a major land use: rubber, oil palm, bananas, cocoa and robusta coffee. While the large plantations will go for large chunks of suitable land, the smaller holders and food cultivators can do with small pockets of fertile land. The very steep slopes and inaccessible areas are under forests and bush.

The savannah zone occupies the higher elevations--thanks to the volcanism. These areas are said to have been under forests (Hawkins and Martin, 1964), but over the years the climate has changed to give them their present savannah grasslands. Here the climate is less intense as the temperatures are modified by the elevations. The main crops here include cereals, legumes and a host of temperate vegetables (corn, rice, groundnuts, beans, Irish potatoes, cabbages, carrots, leeks, etc.). A very profitable livestock industry is predominant on this rich grassland (cattle, goats, sheep, poultry).

CHARACTERISTICS OF ANDISOLS OF CAMEROON

Van Barneveld (1979) saw Andisols as including soils developed on thick deposits of volcanic ash and other pyroclastic materials in general.

Such soils have characteristics which include:

(a) freely drained, young profiles with little profile development and horizon differentiation other than that caused by depositional stratification;

(b) very light and porous soil materials with low bulk densities (0.85/cm) and high water-holding capacities;

(c) deep topsoils, dark brown to brown in colour, with high organic matter contents due to humic compounds which are relatively resistent to microbial decomposition--allophane;

(d) dark-coloured subsoils with often smeary consistencies (thixotropism) and the tendency sometimes to dry out irreversibly;

(e) a clay fraction dominated by amorphous material that includes allophane. Allophane has a high exchange capacity, high pH-dependent surface charge and is usually difficult to disperse;

(f) variable supply of bases, depending on the mineralogy of the parent ash, climate (leaching) and age (weathering). Due to p-fixation the available phsophorus levels are generally low.

Only a few of the soils developed on volcanic ash in Cameroon will fit neatly within these limits. Within the lowland on a few areas around the slopes of Cameroon Mountain and in the Tombel-Nyombe area, they are estimated to cover not more than 150,000 ha of land. Within the Bafoussam-Bamenda Highlands (Haute Plateau) they may cover another 240,000 ha of land.

Around Cameroon Mountain, these are on gentle steppes and gently sloping lands. They are usually deep to moderately deep except when rocky outcrops are encountered. Within the Moungo-Kupe area (Njombe-Tombel), they are found on gentle slopes (5-8%). They are porous, very permeable, friable and have low bulk densities (0.5-0.85 gm/cm^3) and low available water retention capacity. They are thus droughty during the dry season (udic-ustic moisture regime), thixotropic throughout (Hydrandepts), and some have a placic horizon (Placandepts). The soils are moderately high in organic matter (5-15%), depending on altitude, rainfall and the nature of the parent ash. Many of the soils are formed in intermediate to basaltic ashes (50% silica).

These ashes have led to the formation of soils with higher pH values and higher base saturation values than normally found in Andisols of other areas. These differences are attributed to the higher contents of calcium-

and magnesium-bearing minerals (plagioclases, olivine and augite). However, in the very humid coastal areas, on more acidic and/or somewhat older ashes, the soils are low in available bases (Dystrandepts).

The Andisols of the Western and Bamenda highlands around Foumbot and Wum are formed in relatively young stratified coarse rhyolitic ash and fine scoria. The soils are very dark brown to almost black, have a sandy loam or "ashy" feel and are very porous and permeable, but due to their sandy character, the amount of available water is limited. The rhyolitic ashes are acidic in nature and the low exchangeable cations and base saturation values clearly show the influence of the parent material. The soils, however, are not particularly acid.

CLASSIFICATION OF VOLCANIC SOILS IN CAMEROON

It will be seen from the tables that these profiles do not fit neatly into any of the central concepts of Andisols as spelled out by Smith. The associated soils in the Ekona area have been classified as Typic Tropohumults but on examination of these series, the properties of an Andisol will be ignored.

Other limits for the classification of Andisols which were used here include (Awah, 1979):

1. A low soil temperature
2. pH (in NaF) of 9-9.2
3. P-retention values of >85%
4. Low bulk densities (1.0-1.15 g/cm^3) if soil has more than 80% clay
5. High amounts of extractable acidity.

The two other soil series described in this report--the Mussaka and Koutaba series--strongly express these properties. The Ekona series, Andic Argiudoll, has been included to show the difficulties encountered in the classification of these soils. Typically Udolls will be found in humid continental climatic areas in the mid latitudes, but some of the soil pedons here express a mollic epipedon and meet the necessary requirements of a Udoll. The andic subgroup has been used in this case to bring out its peculiar andic characteristic. The classification of the other pedons has followed the same reasoning.

SOIL EVOLUTION

The development of Andisols in Cameroon appears to be dominated by the climate. In the Bamenda-Wum area, where there are very distinctive rainy and dry seasons, the soils are subjected to seasonal wetting and drying. Within the mountain areas, and along the western slopes of Cameroon Mountain, the dry effect is minimized by cold humid temperatures and year-round wetness (perudis) respectively. Within this mountainous area it is seen that allophane is prominant within the clay fraction.

It is pointed out (Awah, 1979) that in the wet phase there is a reduction of Fe^{+++} oxides and consequent translocation of Fe^{++} to lower horizons. In the dry serated phase there is a preponderance of the Fe^{+++} concentrations. The textural composition of the soil material may be very diverse, depending on state of weathering and the fineness of original parent material (ash, cinder, pumice). Under the alternating wet and dry climatic zones (ustic), allophane is said (Van Barneveld, 1979) to be transformed first into hydrated halloysite, and then into metahalloysite and finally kaolinite. It is also pointed out (Sieffermann, 1973; FAO/UNDP) that this process may be accelerated when the parent materials have been retransported and redeposited through mudflows caused by heavy rainstorms. This transformation may result in a loss of the light, fluffy nature of the soils and an increase in the bulk densities.

SOME CONSTRAINTS TO CROP PRODUCTION

It has been acknowledged that the volcanic soils are among the most utililzed in Cameroon. The population within the areas overlain by lava or volcanic ash exceeds 60 persons to the hectare. This is the most densely populated and cultivated area with a good infrastructure network of roads. Both perennial and annual crops are widely cultivated by reason of their naturally high fertility levels and good tilth. Some of these soils have been cultivated for more than 10 years continuously and without

the use of fertilizers. The yields have not dropped appreciably after this intensive cultivation. On the older members,however, (Argiudults and Tropepts), the disappearance of the A_1 horizon through erosion or burning, drastically reduces their capability to produce important crops.

These soils exhibit a tendency to dry out irreversibly and it has been difficult to disperse them for particle-size analysis. This is particularly true for the young volcanic soils. The uneven distribution of rainfall, and the fact that these soils have low water-holding capacity, forces availability of moisture to become an important consideration. The high moisture-demanding crops (bananas) have to be irrigated during the dry season. Droughtiness is even severer on the shallower soils and for shallow-rooted crops.

The high CEC and exchangeable cations in the top horizons may be related to the organic matter content. Soil management therefore becomes of very great importance as mismanagement of the organic matter has quite often led to poor structure and abandonment of farms. Phosphorus fixation has been widely speculated for these soils. The organic matter affords a very important source of this nutrient. The available nitrogen and especially the C/N ratio is strongly tied to the proper management of the organic material.

MUSSAKA SERIES

The Mussaka Series groups a number of soils developed on old, clayey volcanic mudflows derived from basaltic pyroclastic materials. They characteristically have a well-developed argillic horizon, a high clay content and some excess water in the subsoil during the rainy season. The Mussaka Series is essentially a mapping unit and not a taxonomic unit, as the soils are difficult to classify into one single order. Many Mussaka soils are Argiudolls (Andic); others are Tropudalfs or Tropohumults.

Description of Typifying Pedon (430 m)

The profile is developed in an old volcanic mudflow; gently undulating

landscape, 1-3% slopes at 430 m a.s.l.

Parent material: volcanic mudflow material of basaltic origin.

Land use: mango orchard with grass undergrowth.

A11 00-04 cm : very dark brown (10YR 2.5/2) moist, very dark grayish brown (10YR 3/2) dry; clay; medium, moderate granular and subangular blocky structure; friable, slightly plastic, slightly sticky; very slightly acid; common fine and medium roots; many fine and few medium pores; clear, smooth boundary.

A12 04-20 cm : very dark brown (10YR 2.5/2) moist, dark brown (10YR 3/3) dry; clay; medium, moderate angular blocky structure; friable, plastic, sticky; very slightly acid; common, fine and medium roots; many fine and medium pores; gradual, smooth boundary.

B1t 20-40 cm : very dark grayish-brown (20YR 3/2) moist, dark brown (10YR 3/3) dry; clay; medium, moderate angular blocky structure; friable, sticky and plastic; slightly acid; few, fine, faint FeMn mottles; few, fine, discontinuous clayskins; few, fine roots; many fine and few medium pores; gradual, smooth boundary.

B21t 40-57cm : very dark grayish-brown to dark brown (10YR 3/2.5) moist, dark brown to brown (10YR 4/3) dry; clay; medium, moderate angular blocky structure, with a tendency to form prisms; friable, sticky and plastic; slightly acid; common, fine, faint FeMn mottles; common, fine, continuous clayskins; few, fine roots; many fine and very fine pores; diffuse, smooth boundary.

B22t 57-110 cm : dark brown (10YR 3/3) moist, dark brown to brown (10YR 4/3) dry; clay; medium, weak irregular prisms breaking into medium, moderate angular blocky structure; friable, sticky and plastic; slightly acid; common, fine, faint FeMn mottles; few, fine FeMn concretions; many fine and continuous clayskins; very few, fine roots; many fine and very fine pores; basalt stones and gravel up to 7 cm take 20% of soil volume; diffuse, smooth boundary.

Table 1. Selected properties of andosolic soils of Cameroon.

Horizon	Depth (cm)	B.D.	OM (%)	C/N	CEC[1]	Ca	Mg	K	Na	TEB	BS (%)	---pH--- H_2O	KCl	av.p[2]	
A. EKONA SERIES (Andic Argiudoll, very fine clayey, halloysitic, isohyperthermic) 550 m, 2400 mm rainfall (Mt. Cameroon area)															
A11	00-16	0.95	4.3	9.7	24.0	8.3	4.2	3.9	0.3	16.7	69.6	5.8	5.0	40	75.3
A12	16-30	1.01	2.8	9.0	19.4	9.5	2.5	4.0	0.3	16.3	80.2	5.8	5.0	17	81.7
B1	30-50	1.05	2.1	8.6	17.4	7.6	2.9	3.9	0.3	14.8	85.0	5.6	4.8	13	80.3
B21t	50-75	1.08	1.6	7.9	16.2	8.2	3.1	1.9	0.3	13.5	83.5	5.5	4.8	13	80.4
B22t	80-150	1.03	1.3	9.3	19.1	6.8	3.1	1.4	0.4	11.7	61.3	5.4	4.6	-	81.3
B. MUSSAKA SERIES (Andic Tropohumult, very fine clayey, halloysitic, isohyperthermic) 430 m, 2400 mm rainfall (Mt. Cameroon area)															
A11	00-04	1.10	6.36	10.6	34.0	15.3	3.2	1.58	0.03	20.11	59.2	6.2	5.2	34	54.1
A12	04-20	1.10	2.29	7.8	26.3	7.3	2.3	1.45	0.01	11.06	42.1	6.0	4.8	20	68.1
B1t	20-40	1.17	1.55	10.0	24.6	3.0	1.7	1.68	0.02	6.40	26.0	5.4	4.4	15	79.9
B21t	40-57	1.17	1.15	8.4	25.2	2.2	1.4	2.15	0.02	5.77	22.9	5.4	4.6	12	82.0
B22t	57-110	1.10	1.07	7.7	22.2	1.7	1.2	2.51	0.02	5.43	24.5	5.4	4.5	-	83.0
B23t	110+	-	0.84	8.1	23.5	1.2	0.9	2.23	0.01	4.41	18.6	5.2	4.2		86.0
C. KOUTABA SERIES (Andic Ustoxic Palehumult, fine clayey, kaolinitic, isothermic) 1215 m, 2050 mm rainfall (Western Highlands)															
A1	00-09	0.88	5.69	33.1	17.2	0.1	0.3	0.12	0.00	0.52	38.2	5.2	4.3		1
B1	09-14	0.94	4.23	27.3	13.3	0.0	0.6	0.03	0.00	0.63	55.2	5.2	4.4		0
B21	20-40	0.95	2.34	19.4	9.3	0.0	0.7	0.05	0.03	0.78	87.6	6.2	5.6		0
B22	74-200	-	1.69	19.6	9.4	0.0	0.4	0.08	0.01	0.49	87.5	6.8	6.0		0
D. HAUTE PENJA SERIES (Hydric Dystrandept, thixotropic, isohyperthermic) 8385 m, 3657 mm (Tombel)															
A1	00-13		7.57	7.6	52.6	15.7	6.0	2.35	0.06	24.1	45.8	5.8	5.0	44	
B1	13-21		5.35	7.4	44.8	10.8	3.1	0.85	0.07	14.8	33.1	5.7	4.8	14	
B2	60-80		3.39	8.6	49.6	5.0	1.9	0.41	0.05	7.4	14.8	5.2	4.6	12	
B31	115-130		2.52	9.2	47.7	3.5	3.3	0.41	0.12	7.3	15.4	5.6	5.0	4	
B32	190-240		1.69	8.9	55.3	6.4	5.8	0.74	0.09	13.0	23.6	5.6	4.6	-	

Table 2 (cont'd)

Horizon	Depth (cm)	B.D.	OM (%)	C/N	CEC[1]	Ca	Mg	K	Na	TEB	BS (%)	---pH--- H_2O	KCl	av.p[2]
E. BAKINGILI SERIES (Typic Hydrandept, thixotropic, isohyperthermic) 9.879 mm														
A1	00-16		4.24	3.9	29.2	1.0	1.1	0.42	0.19	3.4	11.6	4.8	4.3	19
B1	16-29		3.24	4.2	20.2	0.6	0.6	0.21	0.13	1.5	7.4	5.2	4.7	3
B21	35-50		2.47	4.7	16.4	0.4	0.6	0.10	0.15	1.5	9.1	5.8	5.2	2
B22	60-75		2.25	4.3	15.4	0.8	1.11	0.09	0.18	2.2	14.3	5.9	5.4	2
Soils do not disperse well. Dries out irreversibly.														

[1] CEC = NH_4OAc, pH 7

[2] av.p = Kurz-Bray II (0.03 NH_4P, 0.1 N.RC_1

B23t : dark brown to dark yellowish-brown (10YR 3/3.5) moist, dark
110-150 cm(+) yellowish-brown (10YR 3/4) dry; clay; medium, moderate angular blocky structure; friable, sticky and plastic; acid; few, fine faint mottles; few, fine discontinuous clayskins; very few, fine roots; basalt stones and gravel up to 20 cm take 40-50% of soil volume.

Drainage, Permeability and Erosion

The soils of the Mussaka Series are moderately well-drained with some excess subsurface water during the rainy season, due to fairly slow infiltration in the rather dense subsoil (stagno-gley); runoff is medium/slow. The soils are not eroded, except in a few steep areas where the topsoil has been partly removed. The susceptibility to erosion is slight to moderate.

Range in Characteristics

Most soils of the Mussaka Series are deep; some, however, are moderately deep or even shallow. The topsoils (50-70% clay) vary in thickness between 20-30 cm and are invariably followed by a 10-20 cm thick B1 horizon very clayey (60-80% clay). The subsoils include a deep and well-developed argillic horizon with a rather dense, weak prismatic structure, difficult to penetrate by the banana roots. The subsoils are generally mottled, locally with few, fine FeMn concretions, indicating excess water after heavy rains. In the very deep Mussaka soils, a buried older profile may be found between 120-150 cm from the surface. The deeper subsoil is often slightly thixotropic.

Related Soils and Their Differentia

Related soils are in the Ekona Series, which are developed on somewhat younger mudflows. The Ekona soils have less-developed argillic horizons and are well drained.

Classification

Soil Taxonomy. All Mussaka soils have well-developed argillic hori-

zons and epipedons which are generally mollic but sometimes umbric. Some have base saturation values (NH_4OAc) of 50% or more in the entire argillic horizon (Argiudolls). Others have lower base saturation values. In some of the latter the base saturation (sum of bases) is over 35% (Tropudalfs); in others it is less than 35% (Tropohumults). Andic subgroups are hereby proposed to classify these soils properly. More data are required to establish criteria for these subgroups. All soils are in fine clayey, halloysitic, isohyperthermic families. It is not possible to map the Argiudolls, Tropudalfs and Tropohumults individually.

French CPCS. Sols brun lessivés eutrophes, tropicaux, andiques.

UNESCO/FAO. Mostly Luvic Phaeozems; some are Humic Nitosols.

HAUTE PENJA SERIES

The Haute Penja Series is a member of the thixotropic, isohyperthermic family of the Hydric Dystrandepts. Typically, Haute Penja soils have deep, uniform dark brown, well-drained profiles, with an exceptionally light and fluffy tilth (low bulk densities). The Haute Penja soils are formed in several meters of volcanic ash and very fine scoria over basalt. On hand feeling, they have a loamy texture and are very thixotropic.

Description of Typifying Pedon

Profile T5. 5.5 km SSW CDC Tombel Estate Office and 800 m E of Edibindjock Camp, South West Province.

4 degrees 42' N, 9 degrees 39' E, 385 m above sea level.

Soil was moist when described. Land use: mature rubber estate and bananas.

A1 00-13 cm : dark brown (10YR 3/3) moist, dark brown to brown (10YR 4/3) dry; clay loam; medium and fine, moderate granular and some subangular blocky structure, very light and fluffy; friable, sticky, slightly plastic, thixotropic; slightly acid; many fine and medium roots; many fine and medium pores; clear, smooth boundary.

B1 13-32 cm : dark brown (10YR 3/3) moist, dark yellowish-brown (10YR 3/4) dry; clay loam; medium moderate subangular blocky and

some fine granular structure, very light and fluffy; friable, sticky, slightly plastic, thixotropic; slightly acid; many fine and medium roots; many fine and medium pores; gradual, smooth boundary.

B2 : dark yellowish-brown (10YR 3/4) moist and dry (10YR 3/5);
32-105 cm loam to clay loam with very few, fine, partly weathered scoria particles; medium, moderate to weak subangular and angular blocky structure; friable, sticky, slightly plastic, thixotropic; acid; many, fine and medium roots; many fine and medium pores; few, thin discontinuous cutans on ped surfaces; gradual, smooth boundary.

B31 : dark yellowish-brown (10YR 3/4) moist and dry (10YR 3/5);
105-180 cm loam with up to 30% (vol.) fine to very fine partly weathered scoria; medium, weak angular blocky structure; friable, sticky, slightly plastic, very thixotropic; slightly acid; common, fine and medium roots; common, fine and medium pores; gradual, smooth boundary.

B32 : dark yellowish-brown (10YR 3/4) moist and dry (10YR 3/5);
180 cm(+) loam with 10% (vol.) fine to very fine, partly weathered scoria; medium and coarse, weak angular blocky structure; friable, sticky, slightly plastic thixotropic; slightly acid; few, fine and medium roots; common, fine and medium pores.

Remark. This soil does not disperse well. Hence, particle-size analysis was not made. Only field estimates are given (hand feeling).

Range in Characteristics

The thickness of the solum is not known but probably exceeds 3-4 m. The gravelly and stony phases are less deep. The horizon has very low bulk densities (below 0.6). The B2 horizon sometimes has thin, discontinuous cutans, which may be clay films. The presence of fine, partly weathered scoria is a common feature of the Haute Penja soils. It is more common in the subsoil where it can reach 30-40% by volume, but some very fine scoria may also be present in the topsoil.

Phases

Gravelly phase and stony phase.

Competing Series and Their Differentia

Related soils are in the Cocoa Camp, Tombel, Mile Eighteen, Edibinjock and Kola Camp Series. Cocoa Camp and Tombel soils have scoria layers in the subsoil, are slightly less fluffy and are less acid. Mile Eighteen soils are also very fluffy and less acid but are mixed with scoria material almost from the surface. Edibinjock and Kola Camp soils have a clayey texture (hand feeling), have higher bulk densities and are less thixotropic.

Setting

Haute Penja Soils are formed in several meters of fine pyroclastic materials, which cover the lava plateau around Haute Penja and Loum-Chantiers (370-450 m) in the Littoral Province. In the South West Province, these soils cover only a few hundred hectares.

Drainage and Erosion

Well-drained, medium runoff, moderately rapid permeability. The soils are not or only slightly eroded; erodibility ranges from slight to moderate.

Land Use and Vegetation

Native vegetation is lower montane tropical rain forest, but this has disappeared completely. Soils are intensively used for banana plantations, some rubber and permanent smallholders' farms with foodcrops and some coffee and cocoa.

Classification

Soil Taxonomy. Hydric Dystrandepts, thixotropic, isohyperthermic.
French CPCS. Andosols diffenciés, désaturés, chromiques.
UNESCO/FAO. Humic Andosols.

KOUTABA SERIES

The Koutaba Series is a member of the very fine clayey, kaolinitic, isothermic family of the Andic Ustoxic Palehumults.[1] Typically, Koutaba soils have very deep, well-drained, gravel-free profiles developed in Pleistocene volcanic ash. They have dark reddish-brown, loamy topsoils and dark red, clayey subsoils. They have excellent physical properties, including a very fine structured fluffy topsoil, but they are very leached and contain few nutrients.

Mapping symbol: Kt.

Description of Typifying Pedon

1215 m above sea level; 2052 mm near Nkounja, Foumban, Division Western Highlands.

Hyparrhenia grassland, used for extensive grazing. Soil was humid when described.

A1 00-09 cm : dark reddish-brown (2.5YR 3/3) moist, reddish-brown (2.5YR 4/3) dry; clayey; fine and very fine, strong granular and subangular blocky structure with moderate amounts of pseudosands and microaggregates; friable, sticky and plastic; acid; many, fine grassroots; very porous; clear, smooth boundary.

B1 09-24 cm : dark reddish-brown (2.5YR 3/4) moist, reddish-brown (2.5YR 4/4) dry; clayey; medium, moderate subangular to angular blocky structure, friable, sticky and plastic; acid; many, fine grassroots; many fine and medium pores; clear, smooth boundary.

B21t 24-74 cm : reddish dark brown to dark red (2.5YR 3/5) moist, reddish-brown to red (2.5YR 4/5) dry; clayey; medium, moderate angular blocky structure with a slight tendency to form prisms; friable, sticky and plastic; very slightly acid;

[1]The Andic Subgroup has been created to express the volcanic ash character of the soil (bulk density 0.9; P-retention 80%; pH NaF 9.2).

few, thin continuous and discontinuous clay films on ped faces; many, fine roots; many fine and common medium pores; few, fine weakly cemented durinodes; diffuse, smooth boundary.

B22t 74-200 cm : dark red (2.5YR 3/6) moist, red (2.5YR 4/6) dry; clayey; medium, moderate angular blocky structure, arranged in weak compound prisms; friable, sticky and plastic; neutral; common, thin continuous and discontinuous clay skins on ped faces; common, fine roots, many fine and common medium pores; few, fine weakly cemented durinodes; clear, smooth boundary.

B3 200 cm (+) : basaltic gravel and scoria layer (less than 40% soil material).

Range in Characteristics

The Koutaba soils are developed in 2-3 meters of Pleistocene volcanic ash; below this depth there are layers of basaltic gravel and scoria overlying old basaltic lava flows.

The topsoils are 15-30 cm deep (average 20 cm) and can be subdivided in an A1 horizon of 7 cm (average) and a transitional B1 horizon of 13 cm (average). The topsoils are invariably dark reddish-brown in colour and have a very light, fluffy structure, partly consisting of pseudosands and microaggregates. The topsoils have 5-8% organic matter, are always acid, leached and poor in nutrients, particularly in phosphorus and calcium.

The subsoils are homogeneous with very clayey textures and blocky to weak prismatic structures and features indicating clay illuviation. They are slightly to very slightly acid (pH 6.0-6.8), still relatively high in organic matter, but otherwise they are leached and poor in nutrients, particularly in phosphorus, calcium and potassium. The subsoils typically have low bulk densities and are very permeable.

Phases

Flat and nearly flat (Kt.0), very gently undulating (Kt.1) and sloping (Kt.2).

Competing Series and Their Differentia

Related soils are in the Bamindjin and Bagam series, all belonging

to the Andic Ustoxic Palehumults. The Bamindjin soils are developed in the weathering products of mixtures of basaltic and metamorphic rocks with only the topsoils being developed in volcanic ash. The Bemindjin soils have higher soil fertility levels. The Bagam soils are similar to the Koutaba soils, but they are found in a rolling peneplain landscape.

Setting

The Koutaba soils are found on the gently undulating plain of Koutaba, including the lower slopes of most of the volcanic cones found on the plain.

Drainage and Erosion

Well-drained, slow to almost no runoff, rapid permeability and a limited water-holding capacity of approximately 80-100 mm in the first 80 cm of the profile. The soils are not eroded, but they are somewhat susceptible to wind erosion during the dry season.

Land Use and Vegetation

Vegetation consists of an almost treeless hyparrhenia grass savanna, used for extensive grazing. Part of the lands are used for mechanized maize cultivation (Westcorn).

Classification

Soil Taxonomy. Andic Ustoxic Palehumults.
French CPCS. Sols ferrallitiques fortement désaturés, humiques.
UNESCO/FAO. Humic Nitosols.

BAKINGILI SERIES

The Bakingili Series is a member of the thixotropic, isohyperthermic family of the Typic Hydrandepts. Typically, Bakingili soils have uniform dark brown profiles developed in thin mudflows derived from pyroclastic materials over basalt. They are normally stony and often very stony and have a limited soil depth. On hand feeling, they have a loamy texture.

Description of Typifying Pedon

Profile WC7. 2500 m SE CDC Debundscha Palms Estate Office, West Coast, S.W. Province.

4 degrees 6'N, 9 degrees 1'E, approx. 85 m above sea level.

Described by: E.T. Awah, G.W. van Barneveld. Soil was moist when described. Land use: lowland tropical rain forest.

A11 00-04 cm : very dark brown (10YR 2/2) moist; loam to clay loam; medium, moderate granular and fine, moderate subangular blocky structure; friable, slightly sticky, slightly plastic, thixotropic; acid; many fine roots; many fine and medium pores; horizon with some partly decomposed plant material; clear, smooth boundary.

A12 04-16 cm : very dark brown (10YR 2/2) moist; loam to clay loam; medium, moderate subangular blocky and granular structure; friable, slightly sticky, slightly plastic, thixotropic; acid; many fine and common medium roots; many fine and common medium pores; clear, smooth boundary.

B1 16-29 cm : very dark grayish-brown (10YR 3/2) moist; loam to clay loam; medium, moderate subangular to angular blocky structure, friable, slightly sticky, slightly plastic, thixotropic; acid; common fine and medium roots; common fine and medium pores; gradual, smooth boundary.

B21 29-60 cm : dark brown (10YR 3/3) moist, loam to clay loam; medium, moderate angular blocky structure; friable, slightly sticky, slightly plastic, thixotropic; slightly acid; traces of thin, discontinuous cutans (?) on ped surfaces; common fine and few medium roots; common fine and medium pores; gradual, wavy to irregular boundary.

Remark

Under natural conditions the soil never dries out due to the extremely high rainfall. In the laboratory the soil dries out irreversibly into sand-size particles and does not disperse well. Hence, dry colours are not given and particle-size analysis was not made. The texture classes

refers to field estimates (hand feeling).

Range in Characteristics

The thickness of the solum ranges from 10-150 cm approx. The profiles with a depth of less than 50 cm are grouped into the shallow phase (Lithic Hydrandepts). The shallow profiles generally are stony as well. The A horizon ranges from 5-15 cm and has uniform very dark brown to very dark grayish-brown colours.

It has a granular to subangular blocky structure, with a light fluffy tilth (bulk densities below approx. 0.6). The transitional horizon is mostly a B1 horizon, but sometimes it is an A3 horizon and ranges from 10-25 cm. The B2 horizon sometimes shows few, thin, discontinuous cutans on ped surfaces, but it is not clear whether these cutans are clay films or water films with organic matter. The thickness of the B2 horizon and to a lesser extent the B1 horizon depends on the thickness of the profile. Some profiles may have some fine scoria in the B horizons; these soils are intergrades to the Njonji Series.

Phases

Sloping phase (3-8% slopes, stony)
Moderately steep phase (8-12% slopes, very stony and rocky).
Steep phase (12% slopes, rocky).

Competing Series and Their Differentia

Related soils are in the Batoke and Njonji series. Batoke soils are very similar, but genetically they are more developed and are slightly less thixotropic. Njonji soils have subsoils with scoria layers.

Drainage and Erosion

Bakingili soils are well-drained, but always humid and never dry out. Runoff is medium to rapid and permeability is moderately rapid to rapid. Locally, the soils are slightly eroded; erodibility is moderate to high.

Setting

Bakingili soils are found on the lower SW slopes of the Mount Cameroon in the West Coast area. The soils cover a limited area only.

Land Use and Vegetation

Native vegetation is the lowland and lower montane tropical rainforest. The soils are sparsely used for oilpalm plantation.

Classification

Soil Taxonomy. Typic Hydrandepts, thixotropic, isohyperthermic family.
French CPCS. Andosols différenciés, désaturés, perhydratés, chromique.
UNESCO/FAO. Humic Andosols.

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THE ANDISOLS OF CENTRAL AND SOUTH AMERICA

F. Colmet-Daage

INTRODUCTION

To help in understanding the Andisols, we have divided them into the following groups based on simplified climo-toposequences:

1. Tropical regions of altitude with a relatively constant temperature (e.g. Ecuador, Columbia)
2. Temperate regions with an alternating temperature regime
3. Hot, tropical regions (Caribbean)

TROPICAL AREAS OF ALTITUDE WITH RELATIVELY CONSTANT TEMPERATURE DURING THE YEAR

ISOTHERMIC--ISOMESIC--ISOFRIGID

Soils Formed From Volcanic Ash With Presence of Silt and Fine Sand

The rainfall and humidity increase progressively.

Mollisols and intergrades with Andisols in wetter areas (udic moisture regime--isothermic). For about 1-2 m, the soil is black (10 YR 2/1) and often blacker below the plow layer. It is a sandy silt to loamy, sandy silt. The bulk density is near one. The base saturation is more than 50%, often 80%. The organic matter content is high, about 4 to 6% in the top soil and 2% at one meter depth. In many cases there are several buried soils and distribution of organic matter in the whole profile is not always uniform. Humic acid is more abundant than fulvic acid, especially in the deep layers.

One can observe several variations:

1. About 50 cm to 1 m depth, one can clearly observe shiny coatings with a little feeling of clay in depth. The clay may come from transloca-

tion of clay from the upper layer and more intensive weathering of the older and deeper ash deposits. Probably this second phenomena is most important. The halloysitic clay is evident in the less than two microns fractions. Dr. Smith thinks that there is an argillic horizon so that this soil might be an Argiudoll or an Argic Tropudoll.

2. The soil is very uniform, without coatings, not shiny nor with any feeling of clay. The base saturation varies from 60% to 90%, depending on the wetness of the zone. The soil does react to FNa Fieldes' Test, or slowly. In the less than two micron fractions one can clearly observe halloysitic clay by X-ray diffraction as the 10 Angstrom basal spacing is very distinct. The soil might be a Tropudoll. In Soil Taxonomy it is an Eutrandept.

3. The field appearance of the soil is exactly the same, but the less than two micron fraction does not show evidence of crystalline clay. X-ray diffraction shows a strong peak at 4.45 Angstroms which could be an indication of crystalline clays, but we do not observe any clear peak at 7 Angstroms or 14 Angstroms. Some of the X-rays do not appear clearly. Infrared spectrometry and electron microscopy do not give much complementary information.

Professor Yoshinaga of Ehime University in Japan thinks after examination of our results that there are irregular interstratifications of crystalline clays: halloysite, metahalloysite and montmorillonite. Dr. Smith thought we have to classify all these soils as Mollisols in spite of the difficulty of identifying clay mineral constituents. But in Soil Taxonomy, this is an Eutrandept.

Remark: Properties of Mollisol/Andisol intergrades. Some of the second and third soils described above without clay coating have all the properties of halloysitic soils. Other soils have weak andic properties of allophanic soils: a higher water content, a slightly higher water content at the same pH values on soil kept moist than on air-dried soil, a change in total cation exchange capacity with a change in pH of saturating solution, and occasionally a little reaction to Fieldes' sodium flouride test for allophane. In the field, it is impossible to detect any differences between these soils for mapping purposes.

Many times in other countries we have observed this high water content (80% at pH 2.5 or 3) in halloysitic soil and in soil which contains minerals of better organization than allophanic substances. In very young halloysitic clay, the 10 Angstrom X-ray peak is strong but infrared spectrometry diagrams do not present clear evidence of halloysitic clay. Electron microscopy shows concentric rounded particles or nothing really clear.

Andisols ("Haplotropand" and "Hydrotropand") in wet areas (udic moisture regime--isothermic temperature regime). The soil is wet throughout the year. One can observe the formation of allophanic soils deeply black: 2/3 meters depth, chroma 2 or 3. All the properties of allophanic soils are present and they can be classified as haplotropand or hydrotropand:

- High water retention and irreversible desiccation of air-dried soil, less than 100% water per 100 g of dried soil=haplotropand; more than 100%=hydrotropand;
- Variations of total cation exchange capacity with the pH of saturating solutions;
- Strong and rapid reaction with sodium flouride test, pH NaF 9.5;
- Percentage of base saturation near 50% or lower, sometimes very low.

Sometimes we can observe an intergrade which has properties of allophanic soils with little more than 50% base saturation. These soils are not extensive, just narrow transitional bands. The total exchangeable bases decrease in the wetter areas if some properties of allophane appear in the soils.

In Soil Taxonomy, most of these soils are Dystrandept or Hydrandept, only a few are Eutrandept.

Andisols ("hydrotropand, Haplotropand") in wet and cold areas (udic moisture regime--isomesic temperature regime). The higher the altitude, the more cloudiness, permanent humidity and low evapotranspiration. At very high altitudes, when the soil temperature is lower than 13 degrees C at 50 cm depth (isomesic), soils are very dark; chroma is 0 to 1. Organic matter content approaches 10 to 25% with slightly more parts of humic than fulvic acid.

In permanent very humid areas with constant cloudiness on fine silty sandy ash, we can observe very strongly hydrated allophanic soils. The

water content can reach 200 to 300 % of dry soil; the bulk density is about 0.25 to 0.35. There is not any cultivation when the soil temperature is lower than 10 degrees C isofrigid.

Soils Formed From Coarse Volcanic Ash Without Evidence of Silt

The slope of young volcanoes with deep ash or pumice deposits are often very regular. Climotoposequences are particularly evident. The content of clay minerals or allophanic substances is so small that it is sometimes very difficult to identify them; they generally do not have much influence on the soil properties.

Presence of halloysite, montmorillonite, or allophane is only an index of the climatic environment more important than the nature of the clay minerals for the soil properties. If the organic content of the top 20 cm layer is less than 1%, these soils are classified as Psamments. If the organic matter is more than 1% in the top layer, we classify a large part of these soils as Vitritropand. Any distinction between halloysitic soils or allophanic soils is difficult because the content of the less than two microns fractions is very low.

Soils Formed Partially From Very Fine Volcanic Ash in Wet and Cold Areas

The regions distant from the volcanoes only receive very fine ash. On the upper part of moderate slopes, cloudiness and low evapotranspiration help to keep the soil damp, which allows the vegetation to hold the fine ash, whereas on the dryer sides of the slopes, this ash is swept away by the wind.

Black soils are formed of varying thickness. They are very rich in organic material: 15-30% carbon. The very fine ash weathers quickly, and because of this, the primary minerals can rarely be identified.

These soils have all the properties of Andisols: high water retention (200-300%), instantaneous reaction to the Fieldes test, great variation in the exchange capacity in function of the pH, etc. Thus, these soils can be called organo-hydrotropand. Do any allophanic substances remain? Only miniscule quantities of mineral substances can be extracted: or Andi-

sols are mineral soils by definition. The allophanic substances existed, but then mostly disappeared, which explains why it is so difficult to extract mineral substances. The aluminum would have remained bound to the organic material. Perhaps this is one of the organic aluminum phases that Wada would like to have included in the Andisols because the "exchange complex is dominated by active hydroxyaluminum."

TEMPERATE AREAS WITH VARIATIONS OF THE TEMPERATURE DURING THE YEAR--THERMIC-MESIC

First Sequence: Vitrudand--Hydrudand--Gibbsitic Hydrudand--Intergrade Halloysite--Hapludalf

This sequence (cross-section) from the Osorno volcano to the Pacific perfectly illustrates the change from very young allophanic soils on the slopes of the volcano to the very hydrated allophanic soils without gibbsite, to older allophanic soils with gibbsite; and finally to the intergrade allophane/halloysite soils which contain crystalline halloysitic clay (or metahalloysite) also with some gibbsite.

Further to the west, there are heavy clayey red soils which are much older.

Young allophanic soils on the slopes of the volcano. These young sandy soils already have the characteristics of allophanic soils. Moisture retention reaches 75% at pH 3 on soil kept moist and falls rapidly when measured on previously air-dried soil. This soil gives a strong reaction with the Fieldes Test.

The evolution towards allophanic soils with high water content is thus already very clear, even though not much allophanic substance has been formed yet.

The very hydrated allophanic soils without gibbsite (Hydrudant) on the edge of the cultivated plain. The top layer, 30 cm thick, is dark chroma 2 with 15% organic matter. To 2 m depth, the organic content is about 6%, but the soil color is lighter (chroma 4) except for some buried organic horizons. In the whole profile, the soil crumbles easily. It is

soft, loamy, soapy.

The water retention of the soil kept moist is considerable, 160% water per 100 g of dried soil. If the water retention at different pH values is determined on previously air-dried soil, the water content is lower (30 to 40%). The decline is relatively more important in the always wet deep horizon than in the top layer which is sometimes temporarily drier in the field. The base saturation percentage is very low but the pH in water and KCl are about the same--a little bit higher than 6. The electron microscope reveals a lot of fiber and shapeless materials.

The very hydrated allophane with gibbsite. They are probably formed from an older ash deposit than in the last profile at least in the deep horizon. The morphological appearance of the soil and most of the physico-chemical characteristics are very close to those in the preceding profile without gibbsite.

Except for the cultivated top layer, which has undergone slight desiccation, all the horizons are very hydrated with 150 or 200% water content. The bulk density is constant about 0.4. The water content at several pF on previously air-dried soil samples is much lower (30-40%) than the water content at the same pF on soil samples always kept moist. The exchangeable base content and the base saturation are very low. However, the pH in water is about 5.5 and higher in potassium chloride. Gibbsite increases from the top to the bottom. At a depth of about 4 meters in the older deposits the percentage of gibbsite reaches its maximum and white elongated or rounded concretions of several millimeters of pure gibbsite are clearly visible.

Intergrades between allophanic and halloysitic soil near the coastal range. The top layer already has a clearly blocky structure and does not crumble finely as allophanic soils do. The sodium flouride reacts very little and very slowly. The soil gives a noticeable feeling of clay when you touch it. The water content at various pF's is considerably lower than in all the preceding allophanic soils we have described. The pH in water is definitely higher than the pH in KCl. There is halloysitic clay and other crystalline clay in noticeable quantity with some gibbsitic Ultisols.

Second Sequence: Young Soil--Hydrudand--Hapludand--Halloysitic Soils

This cross-section also shows clearly, from the East, near the volcano Antillanca, to the West, where rainfall decreases, the succession:

- from very young allophanic soil on the slopes of the volcano, where rainfall is very high: 3 or 4 meters per year,
- to very hydrated allophanic soils (Hydrudand),
- to the Trumaos soil, a less hydrated allophanic soil with a very friable particular field texture: rainfall is less than about 1.3 meters a year and decrease to the west,
- to the halicysitic soils--rainfall about 1 meter or less.

We did not find allophanic soils with gibbsite.

Young allophanic soils on the slopes of the volcano. Young allophanic soils have several layers of unweathered coarse pumice or scoria.

Hydrudand in the beginning of the cultivated plains. The soil is black in the first 40 to 50 cm with about 20% organic matter. Deeper, the soil is lighter still with 10% organic matter at 1 meter depth. Fulvic acids are very abundant. One can observe all the properties of very hydrated allophanic soils:

- water content of samples that have been kept moist is high, more than 150% at pF 2.5, with strong irreversible desiccation. There is a little desiccation of the upper horizons, and bulk density is a little higher (0.6) than in depth (0.35);
- the pH in KCl is higher than the pH in water, except in the top layer.

The electron microscope shows many fibers which are very similar to those observed on "so-called imogolite," in Japanese soils. Sometimes fibers are joined and juxtaposed. Electron diffraction clearly shows the typical rays of imogolite mineral at 1.4-2.1 at 2.7 Angstroms. According to Dr. Yoshinaga, we find here all the characteristics of so-called imogolite, a fiber mineral. (Some of this data was obtained by him on our clay samples.) There is a mixture of imogolite with other allophanic substances.

Hapludand Trumao osorno in the broad cultivated plains. There is less rainfall, a little more than 1 m. The soil is dark brown to about 20 cm

deep, chroma 2-3 (organic matter = 15% C/N = 10) then pale yellow, chroma 6-8, with 6% organic matter at 1 m depth. The main characteristic is the very friable structure of the B horizon. The soil seems composed of very fine round aggregates. The bulk density is about 0.5 to 0.6. The water content is still high with depth but no more than 100%. In the top horizon, water content is lower and the water at different pF values is the same on soil kept moist as on air-dried soil. The pH in water is a little higher than the pH in KCl. The AF/AH ratio is near one in the top layer but increases with depth.

Halloysitic soils near the Western Coastal Cordillera--Ultisols. Further to the west, rainfall is lower, less than 1 m per year. It is also an older deposit. The soil is loamy clay with an evident feeling of clay. The water content is low compared to the allophanic soils, and we obtain the same result at different pF values on soil kept moist as on air-dried soil. The bulk density approaches 1. The sodium flouride test gives a weak and slow reaction. X-ray diffraction shows a mixture of halloysitic and metahalloysite clays with a little goethite. Electron microscopy shows rounded concentric spherical particles with some swollen tubes of halloysite.

TROPICAL WARM LOWLAND AREAS WITH ISOTEMPERATURE REGIME

Main Sequence

Rusty brown halloysitic soils (typic halloysitic Tropudalf). Rainfall is about 1800 to 2000 mm and the dry season is pronounced. There is a lack of water for a few months at certain times of the year. The upper horizons partially dry out to varying depths. These conditions favor the synthesis of crystalline clay. One can observe halloysite formation. There are several types of halloysitic clay. In this sandy clay soil, clay coatings are especially distinct. I know of no other soils that have such evident shiny coatings. 10 Angstrom halloysite which is often associated with metahalloysite especially in the top layer. One cannot simply refer to halloysite, but to different forms of halloysite which correspond to soils

with very different properties.

Allophanic soil (Haplotropand) with temporary desiccation of the upper layers. In higher altitudes, there is little deficit of water throughout the year. The soils remain constantly moist or dry out only on the surface few cm. Soil moisture rarely falls below pF 4.2.

The A horizon is crumbly and dark colored to a depth of 10 to 15 cm but the thickness is often less in plowed and eroded areas.

The B or BC horizon might be 50 cm to 1 or 2 meters thick, sometimes with interbedding (or with) harder layers. The soil color is lighter (10YR 5/8) yellow beige. Air-dried soil is much lighter than moist soil, being nearly white in color. After prolonged air-drying, the soil turns a dark rusty brown. There are no coatings.

These soils can absorb a considerable amount of water and still remain quite crumbly. In the surface soil, moisture can reach 50 to 70% on air-dried soil basis. Soil moisture is much higher at a depth of around 1 m, reaching 90 to 100%. Once the soil has been left to air dry for several weeks it can no longer absorb as much water, even if it is left in contact with water for months.

These soils have good permeability. In over 1000 samples, we have found field moisture content very near pF 2.5 as measured on soil kept moist.

Allophanic soil more hydrated and always wet (Hydrotropand). Rainfall and cloudiness increase and evapotranspiration is reduced with altitude. One can observe: (1) an increase in the soil moisture, (2) an increase in organic matter content, (3) a reduction of exchangeable base content and (4) the soapy feeling of the soil becoming more and more pronounced.

The humic horizon is darker and richer in organic material but only about 15 cm thick. Deeper soils appear yellow.

Irreversible dehydration of air-dried soil is high. The results obtained at pF 3 and 4.2 on previously air-dried soil are much lower than those on soil kept moist. All the horizons are moist throughout the year.

We noted that the water content of the soil never fell below pF 4.2. There is always some rain.

Our laboratory analysis revealed that irreversible dehydration would only occur when the soil moisture value is less than that at pF 4.2.

Strongly hydrated allophanic soils (Hydrotropand) without gibbsite. Rainfall is higher with frequent cloudiness. The soils in higher altitudes have a very high water content. The organic matter content is high, 10 to 15% or more, in the upper 20 cm. The organic horizon is thin over the convex slopes and thick in the concave slopes. In the latter one occasionally finds soils which have become peaty.

The soils contain more than 150 or 200% water throughout the profile. They are very spongy and greasy and easily identified in the field. Desaturation is virtually complete, with less than 1 me/100 g of exchangeable bases. In the very cloudy regions, one often sees rusty-colored and light graying mottles around the roots. This phenomenon of iron reduction only occurs in such extremely wet soils. Sometimes, there appears to be placic horizon.

Other Sequence

Older soils--Allophanic soils with gibbsite. These soils are derived from older ash deposits. This gives an especially clear cartographical distinction which is useful for observing the behavior of phosphorous.

The soils closely resemble those in the preceding climo-toposequence.

There is a large, sometimes very large amount of gibbsite throughout the profile. It is especially abundant in the very wet mountain regions. It sometimes appears at some depth in the form of small pure white gibbsite concretions.

COMPARISON OF ANDISOLS WITH DIFFERENT TEMPERATURE REGIMES

Profile Characteristics

In the low altitude tropical warm areas and temperate areas with alternating seasons, the dark humic horizon is 15 to 20 cm thick. The deeper soil is yellow, chroma 4 to 8.

In the middle altitude, from 1500 to 2000 meters, the dark upper horizon is deeper, 50 to 60 cm.

In high altitude, about 2000 to 3500 meters, the whole profile is

black to a depth of 1 or 2 meters.

Chroma $\geq$ 2 if the soil temperature is warmer than 13 degrees C, and 0 or 1 if soil temperature is colder than 13 degrees C.

Fulvic Acid/Humic Acid Content

In tropical areas with constant temperature and in temperate areas with alternating temperature regime Andisols contain a lot of fulvic acid and little humic acid. It's the same in the wet temperate middle latitude of Chile (pyrophosphate extract).

In the tropical middle altitude, Andisols often contain more humic acid than fulvic acid.

In the higher altitudes in cold areas, the proportion of humic acid is high compared to fulvic if the permanent soil humidity is due more to a very low evapotranspiration and constant cloudiness rather than heavy rainfall.

On the other hand, if the rainfall is high, we observe a higher proportion of fulvic acid, but yet humic acid is dominant.

Soil pH

In the tropical areas with constant temperature and in temperate areas with an alternating temperature regime, the soil pH in water and in potassium chloride is very similar. Sometimes, the soil pH in potassium chloride is higher than pH in water.

In the higher altitude, soil pH in water is much higher than pH in potassium chloride. Possibly this is the influence of the nature of organic matter.

INTERGRADES BETWEEN ALLOPHANIC AND HALLOYSITIC SOILS

The change in the field from halloysitic soil to allophanic soil is mainly due to rainfall variations.

Tropical warm areas--isohyperthermic

This intergrade soil is a uniform dark brown through 60 to 80 cm, so

it seems like a deep organic rich soil. In the allophane soils found in slightly higher altitudes, on the other hand, the dark organic horizon is not very thick--15 to 20 cm. At greater depth the horizon is light yellow. This light yellow horizon usually contains more organic matter than the allophane-halloysite intergrades in horizons at the same depth. The dark color of the organic material does not come out in the allophane because of the M.O-allophane bonding. In contrast, in the allophane-halloysite intergrades, all the profile is dark-colored, which can be useful for soil cartography.

This less-than-two-micron clay gives the best X-ray diagram of halloysite that I have ever seen. The 10 Angstrom peak is extremely clear and much stronger than the 4.45 Angstrom peak. In contrast, the infrared diagram is rather poor. This young halloysite appears as round particles under the electron microscope.

In contrast, the X-ray diagrams of the older, more evolved halloysite soils are less characteristic (the 4.45 Angstrom peak is often stronger than the 10 Angstrom peak), but the infrared diagrams are much better defined. The tubular halloysite at first appears swollen and then shrinks to a well-formed tube.

Tropical Altitude Areas--Isothermic--Isomesic

The profiles of the Mollisols and the allophanic soils look alike, except when the coatings appear. Soil is deeply black.

In the less-than-two-micron fraction:

- either, there is not a well-identified clay; (The 4.45 Angstrom X-ray peak is strong, but the other X-ray peaks at 7 Angstroms, 10 Angstroms and 14 Angstroms are very weak. There is an irregular interstratification.)
- or the clay consists of well-formed X-ray diagram; halloysite with the 10 Angstrom peak very distinct and stronger than the 4.45 Angstrom peak.

SPECIAL PARTICULAR WATER RETENTION PROPERTIES OF ALLOPHANE AND ALLOPHANE-IMOGOLITE SOIL

Some of allophane-imogolite soils are very hydrated--between 150 oı 200% water content per 100 g of dried soil. Bulk density is about 0.3.

Some important differences in water retention can be observed betweeı these imogolite soils and typical allophanic soils:

1. The water content at pF 4.2 on samples kept moist is lower iı imogolite soils than on allophanic soils with an equivalent water content at the field capacity. There is a great difference between the water content at pF 3 (or pF 2.5) and pF 4.2 measured on soil kept moist. Thuı there is a great deal of available water.

These soils behave somewhat like a sponge which can reabsorb a large quantity of water after having lost some.

Table 1. Water content at pF 3 after drying the soil to different levels of humidity.

Soil was dried to this water content per 100 g of dried soil before the pF 3 measurement.	Allophane-Imogolite Soil			Allophanic Soils		
	E 319	E 384c	E 346c	E 370c	E 266c	S 59d
	-- Samples from Chile --			Chile	Ecuador	Antilles
Without desiccation	178	164	154	184	280	252
200				158	270	214
150		158			261	203
125	139	154	142			
100	147	149	142	155	236	190
75	115	139	138	134		
50		133	133		187	
air dry	80	82	95	35	44	37
dry 105 degrees		62	66	28	28	26
pF 4.2 on always wet soils, without desiccation	80	106	72	141	206	

2. For the samples studied, which contain imogolite, the water con-

tent at pF 3 (or pF 2.5), after air-drying still remains high, even after oven-heat desiccation. It is lower though than for samples which were kept wet, but much higher than with strongly hydrated allophanic soils of equivalent humidity at the field capacity.

So when compared to allophanic soil, the imogolite soils can lose a higher quantity of water. After air-drying, the imogolite layers can reabsorb a higher water quantity than allophanic soils do.

CLASSIFICATION

Before Dr. Guy Smith's trip to the French West Indies and Ecuador, we had classification difficulties with the Andisols, and particularly separating Andisols from Mollisols, Dystrandepts from Hydrandepts. The new proposition for the Andisols (Smith, 1978) has solved almost all the problems.

We suggest adding a gibbsitic subgroup to the Haplotropand, Hydrotropand, Hapludand, Hydrudand. Gibbsite in itself, in the quantity present, has no particular importance. Silica has had to be eliminated in order for gibbsite to appear. Gibbsite is, therefore, an indication of allophanic substances with a low silica/alumina ratio. Some of the properties are different from more siliceous allophane: high phosphorous fixation, possibility of alumina toxicity, etc.

Our results show that a part of allophanic soils of warm tropical countries have a phosphate fixation, estimated by the New Zealand method, of less than 90%. To come to a conclusion further studies would be necessary.

Some soils which present all the characteristics of isomesic, isothermic Hydrotropand are very rich in organic matter with more than 15% carbon content. A subgroup of rich organic matter hydrotropand could perhaps be created.

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DISCUSSION

Q. R. Tavernier: You mentioned that in isomesic or warmer iso-temperature regimes of Central and South America, the limit between the Andisols with low chrome (0 or 1) and those with higher chroma (more than 2) occurs at a temperature limit of about 13 degrees C. My question is if you find this transition at the same temperature limit in the areas with a xeric moisture regime in Chile. The reason for the question is that in the Meditteranean areas of Europe we find the transition at about 10 degrees C.

A. F. Comet-Daage: I have not studied Andisols with a xeric moisture regime in Chile.

Q. A. Rukaka: You said that gibbsitic Andisols should be recognized in the classification and that these kinds of Andisols sometimes exhibit certain plant toxicities. As gibbsite is not toxic to plants, the conclusion would be that the gibbsitic Andisols contain large quantities of exchangeable aluminum. Could extractable or exchangeable aluminum be used as a differentiating criterion?

A. F. Colmet-Daage: Gibbsite indicates allophanic substances with a low SiO_2/Al_2O_3 ratio. Some of the properties are the same, but others are different from the more siliceous allophane soils. Al toxicity, related to the deficiency in phosphorus, can be found in soils that have a low base saturation. In order to correct P deficiencies and to obtain the same levels of available P, much more phosphate has to be added to the gibbsitic Andisols than to the more siliceous allophane soils that have no gibbsite.

Q. H. Eswaran: What amount of gibbsite would you use as a diagnostic value in Andisols?

A. F. Colmet-Daage: The quantity of gibbsite is not important. It varies greatly in the profile and also depends on the size of the gibbsite particles. The presence of gibbsite shows that the silica was eliminated in large enough quantities to enable gibbsite to form in the soil. Gibbsite itself does not act upon the soil properties.

Comment. A.J. Herbillon: We have recently obtained results concerning the surface charge properties of allophanic clays (not soils). They completely support the conclusions by the author regarding the impor-

tance of gibbsite in Andisols from a soil management point of view. For details see Gonzalez, Batista et al. in Clays and Clay Minerals (in press).

Q. J.A. Comerma: You have stressed the difference between deep, dark Andisols of tropical highlands and the Andisols with yellow subsoils in the hot, tropical and temperate areas in Latin America. Doesn't this contradict the "Tropand" proposition?

A. F. Colmet-Daage: The aspect of the profile of the Andisols from hot tropical regions is indeed closer to that of the Andisols of the temperate regions with alternating seasons that to that of Andisols of the high altitudes of the tropics. The choice of "Tropand" was made in analogy with other orders and indicates that the soils can be cultivated year-round. Is this fact more important than the aspect of the profile? All of the Andisols in an isothermic and isomesic temperature regime that I know are deeply black throughout the profile when the soil temperature is less than 13 degrees C. The term 'melanic' is only useful if soils with yellow horizons exist in these areas.

Q. V. Ndoreyaho: As the leeward soils are dry and the windward soils are wet, the pedogenetic properties are different. Can this difference be noticed with regard to soil fertility?

A. F. Colmet-Daage: The fertility of a soil depends on the kind of crops, their need for nutrients and water, their resistance to deficiencies or toxicities, etc., all of which differ from place to place. Due to the close relationship between soils and climate, crops can be zoned by showing what the advantages and disadvantages are for a particular site.

Q. A.J. Herbillon: Do the Tropands, the Andisols rich in Al-humus compounds, show the same morphological features as those characteristic for what has been called in Rwanda "l'horizon socle"?

A. F. Colmet-Daage: We have often found hard, discontinuous blocks, similar to the socle horizon, in the deep, yellow horizons of well-hydrated allophane soils. Their origin is not clear. They may be a hard, weathered ash horizon which has not completely weathered, or they may have formed *in situ* due to increased "allophanic cohesion." Hydrated

allophane soils often have "allophanic cohesion" which is not found in the Mollisols that developed on the same materials. Even though this cohesion is very clear, it is usually rather weak, except for a few cases where the blocks have hardened enough to be cut with a knife.

THE CLASSIFICATION OF THE ANDEPTS OF HAWAII ACCORDING TO THE PROPOSED KEY TO ANDISOLS[1]

M.R. Recel, H. Ikawa, and G. Uehara

ABSTRACT

The Andepts of Hawaii were reclassified according to the definition of the proposed soil order Andisols using existing and new data. The two suborders in Hawaii are the Ustands and the Tropands. With slight modification in some of the proposed definitions and taxa descriptions, the Vitrandepts, Eutrandepts, Placandepts, Hydrandepts, and Dystrandepts were reclassified as Vitrustands, Haplustands, Placotropands, Hydrotropands, and Haplotropands, respectively. A tentative classification down to the family category is presented for 63 soil series. A list of recommendations is also made to the proposal.

INTRODUCTION

Andepts are volcanic ash soils having a low bulk density and appreciable amounts of allophane with a high cation exchange capacity or composed mostly of pyroclastic materials (USDA, 1975). This suborder of Soil Taxonomy, however, excludes some of the volcanic ash soils not meeting these requirements. Furthermore, the soil moisture regime is not used as a differentia in the Andepts as in the other soils. For these and other reasons, a proposal has been made to reclassify the Andepts and some andic subgroups into a new soil order Andisols (Smith, 1978).

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The purpose of this paper is to test the adequacy of the proposal to accommodate the Andepts of Hawaii.

Published and unpublished data as well as new data were used in this study. In particular, the data contained in the Soil Survey Investigation Report of Hawaii (USDA, 1976) and those of Recel (1980) were used. They included 17 soil series (some as paired pedons) representing one Vitrandept, five Eutrandepts, four Hydrandepts, and seven Dystrandepts. Other sources of data included thesis (Oshiro, 1969), dissertation (Hudnall, 1977), unpublished reports, and published articles (Hassan et al., 1975; Ikawa, 1979; Loganathan and Swindale, 1969).

Because new criteria are used in classifying the Andisols and additional data are needed, the present classification of the Andisols of Hawaii is only tentative. As more laboratory data are collected, an up-dated classification must be prepared.

DEFINITION OF ANDISOLS

As defined by Smith (1978), Andisols are mineral soils that do not have an aridic moisture regime or an argillic, natric, spodic, or oxic horizon unless it is a buried horizon, but have one or more of a histic, mollic, or umbric epipedon, or a cambic horizon, a placic horizon, or a duripan; or, the upper 18 cm, after mixing, have a color value, moist, of 3 or less and have 3% or more organic carbon in the fine earth; and, in addition, have one or more of the following combinations of characteristics:

1. Have, to a depth of 35 cm or more, or to a lithic or paralithic contact that is shallower than 35 cm but deeper than 18 cm, a bulk density of the fine earth fraction of less than 0.85 g/cc (at 1/3 bar water retention of undried samples) and the exchange complex is dominated by amorphous materials.

2. Have, in the major part of the soil between a depth of 25 cm and 1 m or a duripan, a placic horizon, or a lithic or paralithic contact that is deeper than 35 cm but shallower than 1 m, a bulk density of the fine earth fraction of less than 0.85 g/cc (at 1/3 bar water retention of undried samples) and the exchange complex is dominated by amorphous materials.

3. Have 60% or more, by weight, of noncalcareous vitric volcanic ash, pumice or pumice-like fragments, cinders, lapilli, or other vitric volcaniclastic materials either to a depth of 35 cm or more, or in the major part of the soil between 25 cm and 1 m or a lithic or paralithic contact that is shallower than 1 m, and the pH in the major part of these horizons of 1 g of fine earth in 50 ml of 1N NaF is 9.2 or more after two minutes.

4. Have a weighted average (by thickness of subhorizons) in the major part of the soil between a depth of 25 cm and 1 m or a duripan or paralithic or lithic contact shallower than 1 m, a water retention of undried fine earth at 15-bars pressure of 40% or more, an ustic moisture regime, and a bulk density of the fine earth fraction of less than 0.9; and in addition either a ratio of 15-bar water percentage (undried) to the meq of exchangeable bases that is 1.5 or less, or the pH of 1 g of fine earth in 50 ml of 1N NaF that is 9.4 or more after two minutes, or both (ICOMAND, 1979; Leamy et al., 1980).

Item 1 includes many of the soils presently classified as Andepts, while item 2 accommodates the thicker volcanic ash soils which may lack some of the properties of Andisols in the surface horizon. Item 3 is used to classify the vitric ash soils and Item 4 is proposed for soils such as the Eutrandepts which may be calcareous and where the NaF test is not relevant.

Aside from the low bulk density, one of the main requirements of Andisols is the presence of an exchange complex dominated by amorphous materials. As proposed by Blakemore (1978), some of the characteristics associated with amorphous materials are: (1) a pH of a suspension of 1 g of soil in 50 ml 1N NaF that is more than 9.4 after two minutes, (2) a phosphate retention value that is more than 90%, and (3) a variable charge that is more than 0.8 (ICOMAND, 1979) of the cation exchange capacity (CEC) of pH 8.2 (using $BaCl_2$). Variable charge is calculated by subtracting the bases and exchangeable aluminum from the CEC obtained with $BaCl_2$ at pH 8.2.

The key to the different categories is listed in the proposal by Smith (1978). This proposal must be consulted not only to use the key to the various categories but also to obtain the complete definitions of the modifiers as well as of other classes of combinations of particle size and mineralogy.

For the family differentiae, it should be noted that the hydrous class is proposed in place of the thixotropic class because of the difficulty in describing the latter. *Hydrous* is defined as: "Less than 35% (by vol-

ume) is greater than 2 mm; water retention at 15-bars is 100% or more on undried samples of the fine earth; the exchange complex is dominated by amorphous materials." Two other classes emphasize the unique moisture characteristics of the Andepts. *Medial* is defined as: "Less than 35% (by volume) is greater than 2 mm; water retention at 15-bars is 12% or more on previously dried samples; or water retention at 15-bars of undried samples is between 30 and 100%; the exchange complex is dominated by "amorphous materials." On the other hand, ashy is defined as: "More than 60% of the whole soil (by weight) volcanic ash, cinders, pumice, or other vitric volcaniclastics; less than 35% (by volume) is 2 mm in diameter or larger; less than 30% water retention at 15-bars on undried samples of fine earth, and less than 12% on air-dried samples."

CHARACTERISTICS OF THE ANDEPTS OF HAWAII

With the exception of one or two soils, all of the Andepts of Hawaii have bulk density values which are less than 0.85 g/cc. These values, however, are based on measurements taken at field moist condition. At the same time, for some selected soils, comparison shows that bulk density values at field moist condition and at 1/3-bar water retention are nearly alike. Thus, for soils with only one measurement, those with bulk density that is less than 0.85 g/cc at field moist condition are generally expected to have bulk density that is less than 0.85 g/cc at 1/3-bar water retention.

Vitrandepts

Only the data of the Apakuie soil was available and used to relate the Vitrandepts to the Andisols. The particular Apakuie series has appreciable amounts of vitric pyroclastic material and has a weighted average in the major part of the soil between a depth of 25 cm and a lithic or paralithic contact, a 15-bar water retention of the airdried sample of 18%. According to R.L. Fox (personal communication), the Apakuie soil also has appreciable amounts of phosphate sorption capacity.

Until such time that more data can be collected for the Vitrandepts of Hawaii, they will be classified tentatively as Andisols, based on the low bulk density requirement, a high phosphate sorption capacity, and a low 15-bar water retention.

Eutrandepts

The Eutrandepts have less phosphate retention than the Hydrandepts or the Dystrandepts as shown by phosphate sorption curves (Fox and Searle, 1978) and do not meet the phsophate retention requirement prescribed in the Andisol proposal. For three pedons of the Waimea series studied by Recel (1980), the phosphate retention values to a depth of 1 m or a lithic contact ranged from 58-75%, 65-81%, and 70-86%. The weighted averages for the same depth were 61%, 78%, and 77% respectively. For the same three Waimea pedons, the pH in 1N NaF was 9.4 or more between the depth of 25 cm and 1 m or a lithic contact.

The ratio of the 15-bar water percentage (undried samples) to the meq of exchangeable bases for 12 of 13 pedons (including the three Waimea pedons above and representing five soil series) was less than 1.5. One of the Naalehu pedons had a ratio of 1.6.

Seven of the 13 pedons of the Eutrandepts have a water retention of the undried fine earth at 15-bar pressure of 40% or more (weighted average). The remaining six, however, have water retention at 15-bar of less than 40%, although 35% or more.

Although the Eutrandepts that were examined meet the bulk density requirement (Items 1 and 2 of the definition of Andisols), they do not meet the requirement of the phosphate retention. Thus Item 4 of the definition is used to classify these soils. Again, although meeting the requirements of either the ratio of the 15-bar water percentage to the meq of the exchangeable bases or the pH in 1N NaF, or both, a significant number of the pedons do not meet the 40% requirement of the 15-bar water retention.

Because these Eutrandepts are not Mollisols or other soils, a recommendation is made to lower the 15-bar water retention requirement from 40% to 35% or even 30%. Such a recommendation is made because the Eutrandepts are generally "dry" soils. Furthermore, all of the Eutrandepts of Hawaii

are either medial, medial-skeletal, or medial over cindery family. A medial family, according to the proposed family definition, has a 15-bar water retention between 30 and 100% in undried samples which is inconsistent with the earlier requirement of 40%.

Placandepts

Andepts that are neither Cryandepts, Durandepts, nor Hydrandepts, and that have a placic horizon within 1 m of the soil surface in half or more of each pedon are called Placandepts. The Kahua series, a Placandept, is characterized by not only a placic horizon but also a low bulk density, large amounts of amorphous materials, and a 15-bar water retention of 62% (weighted average of undried samples) between a depth of 25 cm and 1 m (Oshiro, 1969).

Hydrandepts and Dystrandepts

Results of the various investigations (for example, Fox and Searle, 1978; Recel, 1980) reveal that the Andepts of Hawaii, especially the Hydrandepts and Dystrandepts, have an exchange complex dominated by amorphous or closely-related materials. They have high phosphate retention and high water retention at 15-bar pressure. In all measured samples, they have pH of over 9.4 in 1N NaF.

Based on this study, the Hydrandepts and the Dystrandepts easily meet the bulk density, phosphate retention and NaF requirements of the Andisols. No test of the variable charge ratio as prescribed by Blakemore (1978) was made because no data are available at present for the Andepts of Hawaii and the variable charge ratio does not seem to be appropriate.

According to Blakemore, the variable charge is calculated by subtracting the bases and exchangeable aluminum from the CEC obtained with $BaCl_2$ at pH 8.2. A ratio of the variable charge to the CEC with $BaCl_2$ at pH 8.2 in soils with amorphous materials is expected to exceed 0.8 (ICOMAND, 1979). The variable charge ratio is not appropriate because it incorrectly assumes that the exchangeable bases and aluminum correspond to permanent charge. A procedure for determining permanent charge in soils with permanent and variable charges has been reported by Uehara and Gillman (1980) and Gillman and Uehara (1980).

Reference is also made to the term "amorphous materials." Because many of the so-called amorphous materials, in addition to non-crystalline materials, contain allophane, imogolite, and other minerals with short range cystallographic order, it is recommended that the term "short range order materials" be used (R.C. Jones, personal communication). Thus, the exchange complex is dominated by short range order materials rather than by amorphous materials. Such recommendations are also made by others (ICOMAND, 1980).

CLASSIFICATION OF THE ANDISOLS OF HAWAII

According to the proposed key to the Andisols, the two suborders in Hawaii are the Ustands and Tropands. Ustands are Andisols that are not Aquands, Borands, or Xerands and that have an ustic moisture regime and/or a duripan. Tropands, on the other hand, are Andisols that are not Ustands and that have a hyperthermic or an isomesic or warmer iso-temperature regime. In general, the Vitrandepts and Eutrandepts are thus tentatively reclassified as Ustands, while the Placandepts, Hydrandepts, and Dystrandepts are reclassified as Tropands.

Vitrustands

Ustands that are not Durustands and that have a weighted 15-bar water retention of less than 15% for previously dried samples and of less than 30% for undried samples are classified as Vitrustands. These requirements apply to all horizons between 25 cm and 1 m, or between 25 cm and a lithic or paralithic contact that is shallower than 1 m.

Recognizing the need for data such as 15-bar water retention, the Apakuie series is classified as Vitrustands. This soil does not have 5% or more organic carbon throughout the upper 25 cm or does not have a subsurface horizon that has an upper boundary within 30 cm of the surface (a buried A1) that meets this requirement. The Apakuie series is, therefore, further classified as Entic Vitrustands and is a member of the medial, isomesic family.

Haplustands

Ustands not meeting the requirements of Durustands and Vitrustands are classified as Haplustands. The data of Io, Naalehu, Pakini, Waikaloa, and Waimea series were examined (USDA, 1976; Recel, 1980). The Waimea series represents the Typic Haplustands, although there may be some question on the organic carbon content in the upper 25 cm of the soil. The Io series also belongs to the Typic subgroup, but the Naalehu and the Pakini series are Entic Haplustands because the organic carbon is less than 5% in the upper 25 cm of the soil.

According to the present proposal, the Waikaloa series is classified as Ustollic Haplustands. Ustollic signifies the presence of a subhorizon containing soft, powdery secondary lime within 1.5 cm of the surface. The presence of such a lime, however, perhaps is better described by the calcic subgroup. The use of the word calcic will also avoid redundancy of the formative element "ust." The use of a mollic subgroup for soils with a lime horizon is not recommended because the typic subgroup should be one with the mollic epipedon. The rationale is that soils having a mollic epipedon commonly occur in the somewhat cool regions with ustic moisture regime like the Eutrandepts.

The Haplustands of Hawaii belong primarily to the medial and either the isohyperthermic, isothermic, or isomesic family. The Waimea series is an example of a member of a medial, isothermic family of Typic Haplustands.

Placotropands

Tropands that have a placic horizon within 1 m of the soil surface in half or more of each pedon are called Placotropands. The thixotropic, isomesic Typic Placandept, which includes the Kahua series, is correlated as hydrous, isomesic Typic Placotropand.

Hydrotropands

Tropands that are not Placotropands and that have a 15-bar water retention of undried samples of 100% or more on the weighted average of all horizons between 25 cm and 1 m or a lithic or paralithic contact shallower than 1 m are in turn Hydrotropands.

In addition, in this study, a requirement of a SiO_2/Al_2O_3 molar ratio of less than 0.85 is suggested for the Hydrotropands. Such a requirement is appropriate because it would help differentiate the Hydrandepts from the Hydric Dystrandepts of Hawaii which also have a 15-bar water retention of 100% or more in the undried samples.

The Akaka, Hilo, Honokaa, and Kealakekua are some of the series representing the Hydrotropands. Laboratory data (USDA, 1976) show that the Akaka and Hilo have positive delta-pH while the Honokaa and Kealakekua have negative delta-pH. These soils are thus classified as Acric Hydrotropands and Typic Hydrotropands, respectively. In this study, the acric subgroup refers to soils with zero or positive delta-pH and is preferred over the term *altic* proposed by Smith (1978). The term *acric* connotes extreme weathering and it is the extremely weathered soils that have zero or positive delta-pH.

These soils are members of the hydrous and either the isohyperthermic, isothermic, or isomesic family of the respective Hydrotropands. Although somewhat redundant, the hydrous class is used with the Hydrotropands in this study because the definition of this great group was modified previously with the inclusion of the SiO_2/Al_2O_3 ratio requirement. The Hilo series is an example of a member of the hydrous, isohyperthermic family of Acric Hydrotropands.

Haplotropands

According to the proposed key (Smith, 1978), Vitritropands are Tropands that are neither Placotropands nor Hydrotropands and that have a 15-bar water retention of less than 15% (previously dried samples) and of less than 30% (undried samples) on the weighted average of all horizons between 25 cm and 1 m or a lithic or paralithic contact that is shallower than 1 m.

If the Tropands are neither Vitritropands nor any of the other Tropands, they then classify as Haplotropands. The Hanipoe, Honuaulu, Kaipoioi, Maile, Paauhau, and Pane series (USDA, 1976), as well as the Kukaiau series (Ikawa, 1979; Recel, 1980) are some of the soils representing the Haplotropands. The Honuaulu, Maile, and Paauhau series have a positive

delta-pH in the subhorizons and are thus classified as Acric Haplotropands. On the other hand, the Hanipoe, Kaipoioi, and Kukaiau series are negative delta-pH soils and are classified as Typic Haplotropands. The Pane is also a Typic Haplotropand, if not an Oxic Haplotropand. The oxic definition, however, requires some change before being used for the Pane series.

At the family category, the Hanipoe, Kaipoioi, and Pane series belong to the medial class, while the Honuaulu, Kukaiau, Maile, and Paauhau series belong to the hydrous class. The temperature class is either isohyperthermic, isothermic, or isomesic. The Maile series is an example of a member of the hydrous, isomesic family of Acric Haplotropands.

This study shows that both the Hydric and Typic Dystrandepts are classified as Typic Haplotropands. However, because the Hydric Dystrandepts are thixotropic and have clays that dehydrate irreversibly (Soil Taxonomy, page 233), it is necessary to separate this subgroup from the typic subgroup. Thus it is suggested that the hydric subgroup be redefined as having a weighted average ratio of 15-bar water retention of undried sample of all horizons between 25 cm and 1 m or to a lithic or paralithic contact shallower than 1 m, to percent organic carbon in the upper 18 cm that is more than 10. The typic subgroup, therefore, will be those having a ratio of less than 10.

LISTING OF THE ANDISOLS OF HAWAII

Based on the preliminary classification of the 17 soil series, the remaining 46 series of Andepts were reclassified into the Andisols. The listing in Table 1 shows all of the Andisols of Hawaii: Five Vitrustands, 17 Haplustands, One Placotropands, 16 Hydrotropands, and 24 Haplotropands. The reclassification was made with available data or by correlating the latest taxonomic names of the Andepts (USDA, 1980) to those of the Andisols.

SUMMARY AND RECOMMENDATIONS

The Andepts of Hawaii were reclassified into the proposed soil order Andisols using available data of selected soils. With some modification in the proposed definitions and taxa, the Vitrandepts, Eutrandepts, Placandepts, Hydrandepts, and Dystrandepts were tentatively reclassified as Vitrustands, Haplustands, Placotropands, Hydrotropands, and Haplotropands, respectively.

Andisols have not only low bulk density and an exchange complex dominated by short range order materials but generally also a high water content. The short range order or similar materials are defined as having a pH of 9.4 or over, high phosphate retention of 90% or more, and a variable charge of over 0.8 of the cation exchange capacity at pH 8.2 (using $BaCl_2$).

For the soils of Hawaii, additional data must be collected to confirm the definition of the short range order materials as well as the classification. Further study is also necessary to test the validity of the variable charge as a criterion for short range order materials. The principle involved in its measurement seems doubtful because the procedure used to determine the variable charge is not capable of distinguishing the variable from the permanent charge.

Because of limited data for the Vitrandepts in Hawaii, there is a special need to characterize these soils and to develop the criteria to identify and classify them.

To accommodate the Eutrandepts of Hawaii, Item 4 of the definition for Andisols should be modified. Item 4 would read:

> Have a weighted average (by thickness of subhorizons) in the major part of the soil between a depth of 25 cm and 1 m or a duripan or paralithic or lithic contact shallower than 1 m, a water retention of undried fine earth at 15-bars pressure of 35% or more, an ustic moisture regime, and a bulk density of the fine earth fraction of less than 0.9; and in addition either a ratio of 15-bar water percentage (undried) to the meq of exchangeable bases is 1.5 or less, or the pH of 1 g of fine earth in 50 ml of 1N NaF is 9.4 or more after two minutes, or both.

Table 1. Placement of soil series of the Andepts of the State of Hawaii in the proposed soil order Andisols.

Suborder	Great Group	Subgroup	Family	Soil Series
USTANDS	Vitrustands	Typic Vitrustands	Cindery, isomesic	Uma
			Ashy over cindery, isomesic	Huikau
		Entic Vitrustands	Medial, isomesic	Apakuie
		Mollic Vitrustands	Ashy, isomesic	Kilohana
			Medial over sandy or sandy-skeletal, isohyperthermic	Alae
	Haplustands	Typic Haplustands	Medial, isothermic	Kamaoa Kikoni Kula Palapalai Waimea
			Medial-skeletal, isohyperthermic	Kainaliu
			Medial over cindery, isothermic	Io Ulupalakua
		Entic Haplustands	Medial, isohyperthermic	Naalehu Pakini
		Lithic Haplustands	Medial, isohyperthermic	Kalaupapa
			Medial-skeletal, isohyperthermic	Waiawa
		Calcic Haplustands	Medial, isohyperthermic	Koko Oanapuka

Table 1 (continued)

Suborder	Great Group	Subgroup	Family	Soil Series
			Medial, isothermic	Waikaloa
			Medial-skeletal, isohyperthermic	Kaalualua
			Medial-skeletal, isothermic	Puu Pa
TROPANDS	Placotropands	Typic Placotropands	Hydrous, isomesic	Kahua
	Hydrotropands	Typic Hydrotropands	Medial over hydrous, isomesic	Puaulu
			Hydrous, isohyperthermic	Hana
			Hydrous, isomesic	Piihonua
			Hydrous, isothermic	Alapai Honaunau Honokaa Honomanu Kailua Kaiwiki Kealakekua Ohia
			Hydrous over fragmental, isohyperthermic	Olaa
		Acric Hydrotropands	Hydrous, isohyperthermic	Hilo
			Hydrous, isomesic	Akaka
		Lithic Hydrotropands	Hydrous, isothermic	Hilea
			Hydrous-skeletal, isohyperthermic	Panaewa

Table 1 (continued)

Suborder	Great Group	Subgroup	Family	Soil Series
	Haplotropands	Typic Haplotropands	Medial, isomesic	Hanipoe Kaipoioi Laumaia
			Medial, isothermic	Kapapala Oli Paaiki Pane
			Medial over cindery, isothermic	Tantalus
		Acric Haplotropands	Hydrous, isohyperthermic	Paauhau
			Hydrous, isomesic	Maile
			Hydrous over fragmental, isothermic	Honuaulu
		Entic Haplotropands	Medial, isomesic	Umikoa
			Medial over loamy-skeletal, mixed, isomesic	Olinda
		Hydric Haplotropands	Medial, isothermic	Manu
			Hydrous, isohyperthermic	Ookala
			Hydrous, isomesic	Manahaa Punohu Puu Oo

Table 1 (continued)

Suborder	Great Group	Subgroup	Family	Soil Series
			Hydrous, isothermic	Kukaiau Moaula Niulii
		Hydric Lithic Haplo-tropands	Medial, isothermic	Puhimau
			Hydrous-skeletal, isomesic	Puukala
		Lithic Haplotropands	Medial, isothermic	Heake

Andepts are described as having an exchange complex dominated by amorphous materials. Because these materials have short range crystallographic order and other than amorphous, it is recommended that the term "short range order materials" be used to characterize these soils and the exchange complex.

In applying the proposed key to the soils of Hawaii, the following changes were made in the various taxa. These changes are therefore recommended:

1. Key to the subgroups of Vitrustands

Redefine the typic subgroup to have more than 70% fine to coarse sand (0.1 to 2 mm), or more than 35% in volume, greater than 2 mm in some subhorizon within 1 m of the surface. The psammic subgroup should be dropped and the mollic and umbric should be introduced to account for the Vitrustands having a mollic and umbric epipedon, respectively.

2. Key to the subgroups of Haplustands

Change the subgroup name ustollic to calcic, yet retain the definition of the former, so that calcic subgroups have a subhorizon within 1.5 m of the surface that contains soft, powdery secondary lime. Thus, the typic subgroup should be one with a mollic epipedon.

3. Key to the great groups of Tropands

Amend the definition of Tropands to read: "Other Tropands that have 15-bar water retention of undried samples of 100% or more and have a SiO_2/Al_2O_3 molar ratio of less than 0.85 on the weighted average of all horizons between 25 cm and 1 m or a lithic or paralithic contact shallower than 1 m."

4. Key to the subgroups of Hydrotropands

Eliminate the altic subgroups and introduce the acric subgroup for the Hydrotropands with a zero or positive delta-pH. Thus, the acric subgroups have a zero or positive delta-pH in any horizon between 25 cm and 1 m or to the lithic or paralithic contact that is shallower than 1 m. The typic subgroup, therefore, will be one that has a negative delta-pH.

5. Key to the subgroups of Haplotropands

Differentiate the hydric and typic subgroups by redefining the former as: Have a weighted average ratio of percent 15-bar water retention of undried soil between 25 cm and 1 m or to a lithic or paralithic contact

shallower than 1 m to percent organic carbon of the upper 18 cm that is over 10. The typic subgroup thus will have a ratio of less than 10.

Define acric subgroups so that they have a zero or positive delta-pH in some horizon between 25 cm and 1 m or to a lithic or paralithic contact that is shallower than 1 m. The hydric subgroups, therefore, will have a negative delta-pH.

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DISCUSSION

Q. V. Ndoreyaho: Normally the pH measured in KCl is at least one unit lower than that measured in H_2O. In the data shown the difference was between 0.1 and 0.2. How do you explain this?

A. G. Uehara: The pH in H_2O approaches that in 1N KCl as the weathering of the soil material increases. In Hawaii the small difference in pH occurs only in the most highly weathered soils with low SiO_2/Al_2O_3 ratios. Most of the Andepts (Tropands) of Rwanda are still very young and have high inherent fertility.

THE KANDIC HORIZON AS A DIAGNOSTIC SUBSURFACE HORIZON

F.R. Moormann and S.W. Buol

INTRODUCTION

Perhaps the most severe classification problem for soils in which low activity clays dominate is the placement in Soil Taxonomy of pedons with a subsurface horizon that fulfills the textural requirements for an argillic horizon (Soil Taxonomy, 1975, p. 19-27), but the main accessory property, i.e. clay skins in at least part of the argillic horizon, are so weakly expressed that consistent quantification by either field or laboratory procedures is doubtful.

This problem has permeated the discussions of ICOMLAC, as witnessed by most of the committee's circular letters, as well as by the summaries of discussions of the First and Second International Soil Classification Workshops. As a consequence of discussions in Malaysia and Thailand, a working hypothesis was introduced whereby a finer textured subsurface horizon (F.T.S.H.) with precisely defined limits is to be used as a diagnostic property for the purpose of distinction between low activity clay (LAC) Alfisols and Ultisols on the one hand, and Oxisols and LAC Inceptisols on the other. Subsequently the concept of the F.T.S.H. has been tested while refining the definition and proposing "kandic horizon" as its name.

It should be noted that the problem of recognizing an argillic horizon based on the presence of clay skins is not limited to the LAC taxa falling under the mandate of ICOMLAC and ICOMOX. Indeed, this problem is recurrent in the literature, as may be seen from a recent review and study by McKeague et al. (1981). Nevertheless, the difficulties of using the argillic horizon concept in classification are clearly multiplied in many of the LAC pedons that are in close spatial association with pedons that have oxic horizons. Difficulties are therefore particularly common in udic to perudic, isothermic or warmer isosoil temperature regions.

GENESIS

A kandic horizon is a subsurface horizon with a significantly finer texture than the overlying horizon or horizons. The higher clay content of the kandic horizon cannot, by current macro- and micromorphological diagnosis, be traced to the subsurface accumulation by illuviation of layer-lattice clays. By convention, the clay fraction of a kandic horizon is composed predominantly of 1:1 lattice layer silicates, mainly kaolinite, with varying amounts of oxyhydroxides of Fe and Al.

The textural differentiation in pedons with a kandic horizon may be the outcome of one or more processes acting simultaneously or sequentially, affecting the surface horizons, the subsurface horizons or both, of the mineral soil. These processes are not all clearly understood and agreed upon. Those that are considered most important can be summarized as follows:

Clay eluviation and illuviation. In soils with a kaolinitic and/or oxidic mineralogy of the clay fraction, evidences of illuviation of clay-sized particles are frequently absent. Specifically, clay skins which are considered concomittant to the illuviation process can be completely absent. Often they are present only at depths below or in quantities less than the limits considered diagnostic for an argillic horizon (Soil Taxonomy, p. 25 and 38).

The absence of diagnostic clay skins may be due to a lack of orientation of the clay-sized particles during the eluviation-illuviation process. This is particularly so where a considerable portion of the clay fraction consists of Fe Oxyhydroxides. More often, however, clay skins that may have formed as part of the early genesis of the kandic horizon may have disappeared under the environmental conditions in which kandic horizons are found. Biological activity of roots abundant in udic regimes may be one cause, but the main cause appears to be the activity of the soil fauna. Thorough mixing of the soils mass by termites and ants and, to a lesser extent, by earthworms, will cause the partial or total disappearance of clay skins over time and to a considerable depth, e.g. more than 150 cm in soils on permeable, well-drained formations.

Many soils with a kandic horizon are found on old surfaces, where the illuviation process may no longer be operative, or at least acting so slowly that mixing by soil organisms or deformation by dessication pressures easily overtakes the formation of clay skins. Characteristic for such conditions is the short-distance spatial variability in the occurrence of illuvial clay skins. As a result, they may be found in some pedons but not in other nearby pedons which otherwise have the same profile morphology. Even within the same horizon of a single pedon, some peds may have clay skins while others do not.

Clay destruction in the epipedon. The weathering of lattice-layered silicates is a process which may lead to the relative loss of clay-sized particles from the pedon. This loss is more from the upper horizon(s) where weathering processes are most intense. Under superficially hydromorphic conditions, this process can be relatively fast. Slow clay destruction with subsequent elimination of bases and some silica (ferrallitization) is a process particularly enhanced by high surface soil temperatures in well-drained soils. Because this process affects superficial horizons to a greater degree than horizons deeper in the pedon, a vertical textural differentiation will occur in time. The relatively coarser residual material at the surface can, due to biological action, be mixed with the underlying material, thus giving rise to a gradual increase in clay content from the surface down. Whereas this process is slow, its effects will be mainly noted on old to very old stable surfaces.[1]

Selective erosion. Rain drop plash and subsequent surface erosion cause colloidal humus and the finest soil particles to be moved further downslope than the coarser fractions. Eventually, part of the fine fraction may be eliminated from sloping polypedons, leaving a coarser surface material. Mixing by ploughing or biological activity may cause the whole surface horizon to become relatively coarser textured. The speed of this process depends on many factors, but in climates with highly erosive rains,

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[1]The process of elimination of clay-minerals from the surface, without concomittant accumulation in the B horizon, is known as "appauvrissement" in the French literature.

on soils with incomplete or absent plant cover it may be very rapid. Coarser surface soil textures can frequently be measured in runoff plots within a few years. The superficial oblique movement of clay downslope seems to be widespread and selective erosion probably is a major process leading to textural differentiation in older cultivated lands, even if cultivation is intermittent as under shifting cultivation.

The process certainly is not exclusive to LAC soils. However, areas dominated by LAC soils frequently coincide with areas that have erosion rains so that textural differentiation due to selective erosion is a common occurrence. In warm ustic moisture regimes with high intensity rainstorms at the onset of the rainy season, selective erosion on soils without a protective plant cover is widespread.

Sedimentation of coarser textured surface materials. In stratified parent materials, coarser materials may overlay finer textured strata. Most commonly such a textural suite may be found in floodplains or on the lower concave aspects of slopes. The young sedimentary nature of the coarser textured surface material is often identified by clear microstratification and the finer textured subsurface layers should not be equated with a kandic horizon. However, in other landscape positions, lithological discontinuities occur, which may consist of a coarser material without microstratification overlying a finer textured stratum. If the finer textured stratum fulfills the requirements of the kandic horizon, defined below, there is no known way to exclude it from the definition of this horizon. In fact, lithological discontinuities are now known to occur in many of the soils of the intertropical zone and in many cases the superficial material is coarser textured than the underlying stratum. In sloping land, for instance, surface soil material which has lost part of its clay due to one of the processes described above, may move downslope so that the coarser textured surface layers in a given pedon may not have formed in situ.[2]

Biological Activity

Reworking of soils by earthworms, termites and ants is often cited

[2]The definition in the French classification (Aubert and Segalen, 1966) of the "remaniement" (reworking) process recognizes this as one of several explanations for a lower clay content in the surface layers.

as a cause for the development of coarser textured surface soils. Detailed studies in this respect do not corroborate this contention and the material brought to the surface by these organisms is finer textured because of a relatively lower content of the coarser sand fractions and of a higher clay and fine silt content. In termite hills, for instance, the clay content is generally higher than that of the surrounding surface soils because the material is largely derived from the finer textured subsoil.

In summary, it can be stated that the kandic horizon is almost always polygenetic and at least due in part to its old age it is not possible to quantitatively determine the share of each of the processes contributing to its formation.

SIGNIFICANCE TO SOIL CLASSIFICATION

The kandic horizon plays, by definition, a role only in the classification of soils in which the clay fraction is formed predominantly by low activity clays. In these LAC taxa the use of the argillic horizon to distinguish Alfisols and Ultisols from Oxisols and Inceptisols loses much of its meaning. The main accessory properties of the argillic horizon are either partially or completely absent or they are so weakly or irregularly detectable that they cannot serve as appropriate quantitative differentiae. Yet, among these LAC soils many have a vertical textural differentiation which cannot be distinguished from others in which an argillic horizon has been recognized. Textural differentiation in LAC soils is, by itself, believed to be sufficiently important for the understanding of soil development and interpreting their management properties that it should be recognized at a high level of the classification. In clayey textured soils, the textural differentiation loses much of its genetic and practical importance. Genetically, the presence of kandic horizons indicates a high degree of weathering of the mineral soil material. This is mostly related to the common occurrence of soils with a kandic horizon on old surfaces where weathering has taken place under warm climatic conditions with moderate to high precipitation during the rainy season(s). However, not all soils with a kandic horizon are old in the present landscapes: part of

them have formed in sediments of various age containing few weatherable clay minerals.

The lack of weatherable minerals observed in the kandic horizon pertains to the clay fraction in which 1:1 lattice layers clay and/or oxyhydroxides of iron dominate, with or without gibbsite. The composition of the coarser fractions, more in particular the 20-2000 micron fraction does not necessarily always lack weatherable minerals. Whereas the content of silt and sand sized weatherable minerals in the kandic horizon is often low, this is not always the case, most notably in kandic horizons of soils developed on weathering products of crystalline rocks in landscapes which during the late Pleistocene period have undergone rejuvenation due to erosion.

In summary, the main significance of the kandic horizon is taxonomic, i.e. to distinguish in the field between soils with a distinct clay increase with depth (Alfisols and Ultisols) and soils with no or only a weak clay increase (Oxisols and LAC Inceptisols). However, certain genetic scenarios are indicated by its identification.

IDENTIFICATION

The kandic horizon, by definition, is a subsurface horizon, underlying one or more coarser textured horizons. The overlying horizons may normally by equated with an epipedon although occasionally the upper part of the kandic horizon may be the lowest part of an attenuated mollic, umbric or ochric epipedon. If a diagnostic lay content increase falls within such an epipedon it is the increase that is determinant, and not the other characteristics. The coarser overlying horizons should be of sufficient magnitude that they can be recognized as such, when mixing the superficial soil layers to a depth of 18 cm, as in ploughing.[3]

The upper boundary of the kandic horizon normally is clear or gradual. A computer analysis of 45 low activity clay soils with an increase of the clay content as required for a kandic horizon indicated that in 15 profiles

[3] In some pedons under continuous pasture or natural vegetation this requirement may be waived, provided the increase of clay content conforms to that of an abrupt textural change (Soil Taxonomy, p. 47) and takes place at a depth of not less than 5 cm.

the required clay content increase took place within 3.5-6.5 cm (clear boundary) while in 30 the increase occurred within 6.5-12 cm (gradual boundary). The distinctness of the clay content increase in isotropic parent materials is therefore a reasonable field characteristic to separate the kandic from the oxic or cambic horizon, where the clay content increase is commonly absent or diffuse.

In anisotropic parent materials, the transition to the kandic horizon is mostly clear or abrupt, and is frequently marked by the presence of a stoneline or a gravelly layer. The material overlying this gravelly layer may have been deposited or it may have been brought to the surface by biological activity (termites, ants, earthworms); it should, however, fulfill the requirement, that is contain less clay than the materials of the underlying kandic horizon.

The probability that the differentiation between overlying coarser material and a finer textured subsoil is an exclusive lithological phenomenon increases with the depth at which the transition to the kandic horizon takes place. Moreover, the influence of the kandic horizon on management properties of the soil also decreases with the depth of this transition. For this reason, the top[4] of the kandic horizon should be found at a reasonable depth which, by convention is defined as follows:

- If the clay content of the overlying, coarser textured horizon(s) is 20 percent or more, the upper boundary of the kandic horizon[4] should occur at less than 100 cm from the surface.
- If the clay content of the overlying, coarser textured horizon(s) is less than 20 percent, and the particle size class (of part of or all of the upper 100 cm) is finer than sandy or sandy skeletal, the upper boundary of the kandic horizon should occur at less than 125 cm from the surface.
- If the particle size class of the upper 100 cm is sandy or sandy skeletal (the texture is sand or loamy sand), the upper boundary of the kandic horizon should occur at less than 200 cm from the surface in the major part of the pedon.

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[4]The top or upper boundary of the kandic horizon is the depth at which the percentage of clay exceeds that of the overlying horizon by the appropriate amount after fitting a smooth curve or where applicable by comparing the 18 cm (mixed) % clay content to the 30 cm clay content.

Other field characteristics of kandic horizons are not normally diagnostic, since these horizons may have properties of the argillic, the cambic or the oxic horizons. Some resemble argillic horizons in having a well-developed subangular blocky texture, or the presence of bleached grains of sand and silt in the overlying coarser textured horizon(s). The ratio of fine clay (particles smaller than 0.2 μm) to total clay may be larger in the kandic horizon than in the overlying coarser horizon(s) but very few data are available.

Other kandic horizons have one or more properties of the oxic horizon and they would be called an oxic horizon but for the distinct clay content increase. For the same reason, in pedons dominated by low activity clays, but having weatherable minerals in the coarser fractions, we may find horizons which would have been called a cambic horizon but for the clay content increase.

The kandic horizon is parallel or nearly so to the surface of the polypedon. If this is not the case a recent deposit of the coarser surface material should be expected.

SUMMARY OF PROPERTIES

The kandic horizon is a subsurface horizon in which at 50 cm below the top of the horizon or immediately above a lithic, paralithic or petroferric contact, whichever is shallower, the fine earth fraction has an apparent CEC/NH_4OAc at pH 7 of 24 meq or less per 100 g clay or an apparent ECEC of 16 meq or less per 100 g clay[5]. It has the following properties that can be used for identification:

1. The presence of one or more coarser textured horizons overlying the kandic horizon is required. The minimum depth of the overlying horizons is 18 cm, after mixing as in ploughing or 5 cm if the transition to the kandic horizon is an abrupt textural change (Soil Taxonomy, p. 47) and the site has not been cultivated.
2. The kandic horizon contains more total clay than the overlying horizon as follows. The increase in clay content is reached within a vertical

[5] As determined by the sum of NH_4OAc exchangeable bases (Na, K, CA, Mg) plus KCl exchangeable Al on the fine earth fraction divided by percentage clay.

distance of 12 cm or less.[6]

a. If the horizon, overlying the kandic horizon has less than 20% total clay in the fine-earth fraction, the kandic horizon must contain at least 4% more clay.

b. If the horizon, overlying the kandic horizon has more than 20% total clay in the fine-earth fraction, the ratio of clay in the kandic horizon to that in the overlying horizon must be 1.2 or more, or the kandic horizon must contain at least 8% more clay.

3. A kandic horizon should be at least 30 cm thick as measured from its top in the absence of a lithic, paralithic or petroferric contact within 50 cm of the surface, or at least 15 cm thick if such a contact is present. Excluded from the definition of a kandic horizon are finer textured lamellae, irrespective of their cumulative thickness.

4. The layers or horizons overlying a kandic horizon should not show fine stratification, nor should they have an organic carbon content that decreases irregularly with increasing depth.

5. A kandic horizon may have clay skins but they should not be thick, and continuous in all parts, and the cross section should not have more than 5% oriented clay, to a depth of 125 cm below the surface of the soil or 75 cm below the top of the kandic horizon, whichever is deeper.

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[6]The top or upper boundary of the kandic horizon is the depth at which the percentage of clay exceeds that of the overlying horizon by the appropriate amount after fitting a smooth curve or where applicable by comparing the 18 cm (mixed) % clay content to the 30 cm clay content.

DISCUSSION

Q. C. Sys: How can we recognize the kandic horizon in soils that we suppose to be truncated?

A. F.R. Moormann: The definition of the kandic horizon implies that this cannot be done. If criteria and class limits are proposed which can solve this problem, they might be incorporated in the proposals.

Q. P. Mondjalis-Poto: 1. Let us suppose that the clay increase of 1.2 over a distance of 15 cm is not due to pedogenetic processes but to a lithologic discontinuity, would we have a kandic horizon in this case? 2. How do you distinguish, in the field, between a kandic horizon and a cambic horizon?

A. F.R. Moormann: 1. Yes; unless the coarser-textured overlying material is clearly a recent deposit. 2. If there is a clear increase in clay, it will be a kandic horizon; if not, it may be a cambic horizon. Of course, to qualify for the kandic horizon, the soil material will have to be dominated by low activity clay.

Q. V. Rutunga: Should we describe soil profiles in increments of 15 cm in order to facilitate the recognition of a kandic horizon?

A. F.R. Moormann: This is an excellent idea, but this practice should be limited to "benchmark" profiles, described to set the standards for the taxon or for a survey area.

Q. J. Bennema: Should we not pay more attention to the use of phases and consider that in our discussions?

A. F.R. Moormann: Yes, this seems to be a good idea. But even phases have to be defined, including the limits of the class.

Q. S.W. Buol: I agree that the laboratory data variation with respect to particle size was disturbing. But what would happen if we subjected bulk density and structural consistence measurements to the same testing? We may even be more disturbed.

A. F.R. Moormann: I have no comment except that you are so right.

LOW ACTIVITY CLAY SOILS OF THE UPPER PLATEAU OF SUDAN

Mohamed A. Ali

ABSTRACT

LAC soils occur in the Sudan in the upper plateau of the extreme south, an old surface of Paleozoic age. Soils are formed in parent materials derived from banded acid gneisses and schists.

The climate is wet monsoon. Rains of 1,400-1,700 mm fall in a bimodal pattern. The moisture regime is udic. Oxisols occur on plateau tops at elevations higher than 1200 m and with rainfall greater than 1,400 mm. Ultisols in these localities are limited to plateau edges.

LAC Ultisols occur on plateau tops in areas of perudic moisture regime at elevations between 1,000-1,200 m. Annual rainfall ranges between 1,200-1,400 mm.

Both kind of soils were formerly grouped as the "red loams." Recent field and laboratory investigations, guided by Soil Taxonomy, have helped to better characterize, differentiate and classify these soils.

The volume of available data is not enough to carry the classification beyond the great group level. The Oxisols are perhaps mostly Haplorthox while the LAC Ultisols are Paleudults.

INTRODUCTION

Sudan lies between latitudes 3 degrees 53' - 21 degrees 55' N and longitudes 21 degrees 54' - 38 degrees 30' E. It is a generally flat country with the Nile river traversing it from south to north. Most of the soils that have been investigated in reasonable detail occur in the arid and semi-arid zones of central and northern Sudan. No LAC soils were reported in these environments.

Information on soils of the most southerly areas is very scanty. The FAO/UNESCO Soil Map of the World shows Rhodic Ferralsols along the borders with Uganda and Zaire. In the local agricultural literature these soils are described as the "Red Loams." The area is known as "the Green Belt" (Green, 1948).

Field and laboratory examination of the soils across the Green Belt carried out to prepare the present contribution have shown that most of the "Red Loams" are LAC Oxisols and Jltisols. These upper plateaux are perhaps the main locality where LAC soils occur in Sudan.

The Environment

The uplands of southern Sudan constitute the northern limits of the central Africa plateau. Two main landscape units have been observed: (a) the northern, relatively lower, ironstone plateau flanking the Nile swamps, and (b) the upper plateau along the borders with Uganda and Zaire in the extreme south. These old surfaces were formed as a result of the peneplanation of metamorphic rocks of Paleozoic age.

Soils are formed at elevations of more than 1,000 in parent materials derived mainly from banded schists and gneisses. These areas enjoy annual precipitation that ranges between 1,400-1,700 mm. Rainfall occurs between March and November in a bimodal pattern with peaks in April and August. The soil moisture regime is udic.

Natural vegetation is rain forest which has given way to a system of shifting cultivation. Dominant trees are *Termanalia glaucescens*, *Albizia zygeo*, *Vitex domana*, *Acacia compylacantha* and *Anogeisus schimpero*. Undergrowth consists of the following grasses: *Impercatra cylindrica*, *Setaria sphacelata*, *Sporobolus pyramidalis*. *Hyperherria cymbaria* and *H. variables*, *Pennesetum Purpureum* is dominant in stream valleys. Food crops grown include the following: eleucine, cassava, maize, banana (plantain), pineapples, and sorghum varieties. A few pawpaw trees are grown in front of most of the isolated huts. Coffee (*Coffea Robusta*) is the main cash crop. It is confined to areas of higher precipitation up the plateau, mostly around Obbo, Iwatoka, and the Aloma plateau. In the Maridi district where rainfall is between 1,200-1,400 mm short staple cotton is grown to feed a local textile mill at Nzara.

Domestic animals are limited to a few goats because of heavy infesta-

tion by the tse tse fly.

LAC Soils

Extensive soil surveys have shown that soil formation is greatly influenced, under Sudan conditions, by climate and parent materials. Most of the soils in the northern arid and semi-arid zones are Entisols (mostly fixed sand dunes), Aridisols, and Vertisols associated with high activity clay Alfisols.

In areas of wet monsoon climate, where soil moisture regimes are udic, the dominant soils on the old stable surfaces are LAC Oxisols and Ultisols. Fig. 1 shows the approximate boundary of the LAC soils.

The Oxisols

These soils are characterized by a deep profile. A horizons are dark greyish brown to dark brown due to relatively high organic matter contents (2-2.5% O.C.). The B_2-oxic horizon is 100-120 cm thick. It has yellowish red to red colours. The subsoils consist of partly weathered rock.

Texture of the oxic horizon is clay; structure is weak, fine and medium subangular blocky. Moist consistence is very friable. Fine and medium tubular pores are many; fine roots grow throughout the thickness of the horizon. Table 1 shows the laboratory analysis of a Haplorthox in Lujulu coffee farm--Aloma plateau, Yei district.

The Oxisols are associated with LAC Ultisols, which occupy the sloping sides of the plateau edge.

The Ultisols

Towards the northern limits of the upper plateau, where annual precipitation is between 1,200-1,400 mm (Yambio district) the Oxisols give way to an association of LAC Ultisols, which occur on the more leached plateau tops, and high activity clay Alfisols which occur on the slopes.

LAC Ultisols have deep profiles comparable to those of the Oxisols. A horizons are dark reddish-brown. The B_2 t (argillic with no significant clay skins) (FTSH, ICOMLAC, 1980) is dark reddish-brown. The top of this horizon is relatively compact and has platy structure. B_2 t horizons have weak medium and fine subangular blocky structure. Consistence is slightly

Table 1a. Profile SD2, Haplorthox.

Horizon	Depth (cm)	pH Kcl	pH H_2O	Text (%) S	Text (%) Z	Text (%) C	CEC Meq/100 g soil	CEC Meq/100 g clay	NH_4OAC Ext Bases Ca	Mg	Na	K
A11	0-6	4.7	5.8	56.7	9.2	34.1	10.7	31.4	4.2	1.4	--	0.4
A12	6-13	4.4	5.5	53.8	9.3	36.9	9.5	25.7	3.1	0.9	--	0.1
A3	13-30	4.2	5.3	52.2	7.6	40.2	7.2	17.9	1.4	0.5	--	0.1
B21	30-56	4.1	5.0	46.6	7.7	45.7	5.7	12.5	0.4	0.2	--	TR
B22	56-70	4.1	5.0	46.0	7.4	46.6	4.7	10.0	0.2	0.1	--	TR
B23	70-110	4.3	4.9	36.7	6.3	57.0	4.2	7.4	0.2	0.1	--	TR
	110-155	4.6	5.4	32.4	8.7	58.9	3.5	5.9	TR	TR	--	TR
C	155-180	4.8	5.6	32.4	7.7	59.9	3.6	6.0	--	TR	--	TR

Horizon	B.S.% By sum	B.S.% By NH_4 AOC	water 15 bar	O.C. (%)	Dith Ext (%) Fe_2O_3	Dith Ext (%) AL	sum bases	acidity	Ext AL	CEC sum cat	CEC Bases + AL	AL sat%
A11	38	56	12.0	2.56	2.1	0.5	6.0	9.9		15.9		
A12	27	43	12.5	2.12	2.2	0.5	4.1	10.9	0.3	15.0	4.4	7
A3	16	28	12.7	1.42	2.4	0.6	2.0	10.4	1.1	12.4	3.1	35
B21	6	11	14.1	0.58	2.7	0.6	0.4	9.7	1.4	10.3	2.2	75
B22	4	6	14.1	0.75	2.6	0.6	0.3	7.9	1.5	8.2	1.8	83
B23	4	7	17.1	0.57	3.1	0.7	0.3	7.5	1.0	7.8	1.3	77
	--	1	18.8	0.38	3.2	0.7	TR	6.5	0.3	6.5	0.3	100
C	--	1	18.3	0.32	3.0	0.6	TR	5.9	--	5.9		

Table 1b. Total analysis and clay mineralogy.

Depth (cm)	---% clay--- K_2O	Fe	x-Ray Relative Amount			DTA (%)	
0 - 6	0.1	6.3	KK3[a]			KK68	G1
6 - 13							
13 - 30	0.1	6.5	KK4	G1-1		KK58	G11
30 - 56							
56 - 70	0.1	6.8	KK4	G1-1		KK64	G11
70 - 110							
110 - 155							
155 - 180	0.1	7.1	KK5	GE1	G1-1	KK63	GI2

[a]Kind of mineral: KK: Kaolinite, GI: Gibbsite, GE: Goethite. Relative amounts: 6-indeterminate, 5-dominant, 4-abundant, 3-moderate, 2-small, 1-trace.

friable when moist, slightly sticky and plastic when wet--few broken cutans are observed in the lower parts of the B_2t horizon.

Table 2 shows the laboratory data of a LAC Paleudult in Yambio district.

DISCUSSION

Soils reported as LAC Oxisols and Ultisols in this paper are described by local scientists as "red loams." On the FAO/UNESCO soil map these soils are shown as Rhodic Ferralsols.

Very little is known about the soils of southern Sudan. Field and laboratory work initiated by preparation for participation in the present Workshop have added new information that has helped to better characterize and classify these soils.

Tables 1 and 2 show the following main diagnostic characteristics (Isbell, 1979):

1. Abundance of kaolinite clay mineral by both x-Ray and DTA methods. Occurrence of a FTSH horizon in the Ultisol profile SD4.
2. The (1N NH_4OAC) CEC in the B_2 horizon of the Oxisol is 12 meq/100 g clay. In the Ultisol B_2t horizon the figure is 16 meq/100 g clay.
3. pH in KCl is less than 4.5 in both soils.
4. Al saturation in the oxic horizon is more than 70%, but in the argillic horizon of the Ultisol (Table 2) it is less than 50%.
5. Base saturation (NH_4OAC) ranges between 1-11 in the oxic horizon while in the argillic horizon of the Ultisol BS ranges between 30-37%.

The data conform to the defined characteristics of Oxisols and LAC Ultisols. But it is important to note that field differentiation of these soils needs more refinement. Rudimentary clay cutans or their absence in the argillic horizon of the Ultisols makes it very difficult to differentiate between a structural and textural B_2 horizon. Other morphological criteria have to be looked into to help field identification.

The area where these soils occur is relatively less developed agriculturally. The dominant practice is shifting cultivation. No proper mapping of soils has so far been carried out.

Table 2a. Profile SD4, Paleudult.

Horizon	Depth (cm)	pH Kcl	pH H_2O	Text (%) S	Text (%) Z	Text (%) C	CEC Meq/100 g soil	CEC Meq/100 g clay	NH_4OAC Ext Bases Ca	Mg	Na	K
A11	0-6	5.3	6.3	67.7	9.6	22.7	7.6	33.5	4.1	2.2	--	0.4
A12	6-19	4.5	5.6	64.2	8.6	27.2	7.0	25.7	3.0	1.3	--	0.1
B21t	19-40	4.0	5.1	47.5	6.9	45.6	6.1	14.5	1.2	0.6	--	TR
B22t	40-84	4.1	5.3	41.1	5.4	53.5	5.3	9.9	1.1	0.5	--	TR
B23	84-124	4.3	5.4	39.0	5.4	55.6	4.5	8.1	1.2	0.4	--	TR
	124-165	4.7	6.0	69.1	2.4	10.6	18.4	--	3.6	2.4	--	0.8

Horizon	B.S.% By sum	B.S.% By NH_4 AOC	water 15 bar	O.C. (%)	Dith Ext (%) Fe_2O_3	Dith Ext (%) AL	sum bases	acidity	Ext AL	CEC sum cat	CEC Bases + AL	AL sat%
A11	60	88	7.9	1.56	1.8	0.2	6.7	4.5		11.2		
A12	42	63	8.3	1.26	1.8	0.2	4.4	6.2		10.6		
B21t	17	30	13.3	0.72	2.5	0.4	1.8	8.9	1.4	10.7	3.2	44
B22t	19	30	15.1	0.46	2.6	0.4	1.6	6.9	1.0	8.5	2.4	38
B23	22	36	16.1	0.32	4.6	1.3	1.6	5.7	0.5	7.3	2.1	24
	21	37	18.4	2.14	7.9	0.6	6.8	26.1		32.9		

Table 2b. Total analysis and clay mineralogy.

Depth (cm)	---% clay--- K_2O	Fe	x-Ray Relative Amount	DTA (%)
0 - 6	0.2	5.9	KK5[a]	KK59
6 - 19				
19 - 40				
40 - 84	0.1	5.5	KK4	KK60
84 - 124				
124 - 164				

[a]Kind of mineral: KK: Kaolinite, Gl: Gibbsite, GE: Goethite. Relative amounts: 6-indeterminate, 5-dominant, 4-abundant, 3-moderate, 2-small, 1-trace.

Modern agricultural techniques like fertilization, improved seeds, and selection of the most suitable land use have not yet been introduced to the area to any recognizable level. The observed soil classification furnishes a scientific basis to apply technologies developed for similar soils in more advanced systems of agriculture.

Soil Taxonomy (Soil Survey Staff, 1975) is hoped to help technology transfer. At the Soil Survey Administration of Sudan the findings of the Benchmark Soils Project are closely followed through the quaternary journal. The information cannot be adopted at present in Southern Sudan because of the level of technical knowledge and stage of agricultural development. But as far as classification of the soils as a basis for common understanding of the properties, and potential behaviour of soils, the system has been of great help.

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LAC ALFISOLS AND ULTISOLS IN TANZANIA

J.K. Samki

A number of people undertook soil surveys in Tanzania at a reconnaissance level before 1960. In the latter part of the sixties FAO assisted in the compilation of the land resources map of Tanzania at 1:2,000,000. Since 1975, the National Soil Service (an FAO/UNDP assisted project) has carried out the survey of priority areas as selected by the government, while regional integrated projects have undertaken land resources surveys in a number of regions of Tanzania. Therefore to date the kinds of soils present in the country are in general well understood.

Low activity clay (LAC) soils are regarded by the author as those soils that have an argillic horizon with a CEC of less than 24 meq per 100 g clay. In the FAO/UNESCO system, which is the system of reference in Tanzania, Alfisols correlate with Entric Nitosols and Luvisols, while Ultisols correlate with Dystric Nitosols and Acrisols, depending on base status and clay distribution.

In Tanzania the LAC Ultisols are derived from a variety of parent materials, especially materials derived from gneiss, granites, schists and mudstone under a total rainfall of over 750 mm in the monomodal and 1,000 mm in the bimodal rainfall areas and temperatures that range from isothermic to isohyperthermic. On the other hand, LAC Alfisols are derived from the same parent materials as the Ultisols but under rainfall of below 1,000 mm in the bimodal rainfall areas.

In comparison with Inceptisols and Oxisols, these soils have been found to have higher available water-holding capacity (other things being equal) attributed to the presence of argillic horizons in the subsoils; also in comparison with Oxisols and Inceptisols, crops grown on these soils can stand drought longer, which is very important for rainfed agriculture under rainfall that is erratic. In Tanzania rainfall can be erratic, more so in the bimodal rainfall areas than in the monomodal rainfall areas.

Tanzania has established agro-ecological zones. In the second revision of the agro-ecological zones map of Tanzania, LAC Ultisols are represented in 4 of the 20 agro-ecological zones established (ecological zones number 2, 6, 8, and 10). LAC Alfisols are represented in 2 of the 20 ecological zones. The agro-ecological zones have been established on the basis of total annual rainfall, number of wet months during the main wet season, rainfall pattern and soil (with special emphasis on moisture retention).

Where cropping is being carried out, Alfisols and Ultisols are used for a variety of both shallow and deep-rooted crops. Depending on rainfall amount and distribution, these Alfisols and Ultisols are used for sweet potatoes, sisal, cassava, maize, sorghum and cotton in the low altitude areas; coffee, maize, beans and bananas in the high altitude areas.

Deficiency of nitrogen is widespread for most crops; and while response to phosphatic fertilizers is erratic for a number of crops, response to potassium fertilizers is imperfectly understood. Using maize as a test crop, recommended fertilizer rates for the Ultisols are as follows: ecological zone 2: 80 kg N, 40 kg P_2O_5; ecological zone 6: 40 kg N, 40 kg P_2O_5; ecological zone 8: 60 kg N, 40 kg P_2O_5. Subsoil acidity in the Ultisols is also thought to be affecting crop yields seriously through its deleterious effect on root development; it is below 6.0 and in some cases it can go as far down as 4.0. As for the LAC Alfisols, recommended fertilizer rates for maize are as follows: ecological zones 12: 40 kg N, 40 kg P_2O_5; and ecological zone 20: 80 kg N, 40 kg P_2O_5.

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DISCUSSION

Q. R. Frankart: 1. Is the distinction between Oxisols and LAC Alfisols and Ultisols based on texture, on clay skins, or on both properties? 2. Why is root development restricted to the upper 60 cm?

A. J.K. Samki: 1. The distinction between the mentioned soils is based on the presence or absence of an argillic horizon which in turn is based on both texture and the presence of cutans. 2. Root development can be seriously affected by low pH in the subsoil. Some Ultisols of Tanzania have pH values of well below 6 and in some cases as low as 4.0.

SOIL-LANDSCAPE RELATIONSHIPS IN ANGOLA

E.C. Sousa

ABSTRACT

This paper deals with general soil-landscape relationships in Angola with special reference to the nature, extent and distribution of Low Activity Clay Alfisols and Ultisols. An outline of the environmental condition as well as of the soil survey and soil classification background is first given.

LAC soils may occupy about 70% of the total area of Angola but precise estimates are difficult due to differences in classification and routine laboratory procedures. They are mostly restricted to units known as Oxypsammic Soils, Tropical Fersiallitic Soils, Paraferrallitic Soils and Ferrallitic Soils in the present soil classification of Angola. LAC Alfisols and Ultisols seem however to be limited in extent.

Oxypsammic Soils and Ferrallitic Soils have formed on deeply weathered, often reworked, material on old stable surfaces having a gently undulating to somewhat rolling topography. Tropical Fersiallitic Soils and Paraferrallitic Soils are typical of land subjected to rejuvenation where relief turns more rugged.

RESUME

Dans cette note on fait une synthèse sur les rélations entre les sols et le relief d'Angola. On attire l'attention spécialement sur les Alfisols et Ultisols. D'abord, on fait un mise au point sur les conditions du milieu et aussi sur la cartographie et la classification des sols dans ce territoire.

LAC sols peuvent occuper près de 70% de la surface du territoire d'Angola si bien qu'il soit très difficile d'obtenir des calculs précises à cause des classifications et des processus laboratoriaux diverses utilisés. Ces sols se situent en grande partie dans les unités de l'actuelle classification des sols d'Angola connus comme des Sols Oxypsammitiques, Sols Fersiallitiques Tropicaux, des Sols Paraferrallitiques et des Sols Ferrallitiques; cependant, il semble que LAC Alfisols et Ultisols occupent des aires très limitées.

Les Sols Oxypsammitiques et les Sols Ferrallitiques se sont formés sur des matériaux très meteorisés et frequement remaniés, sur des anciennes surfaces très stables depuis long temps, ayant un modulé très douce jusqu'à ondulé. Les Sols Fersiallitiques Tropicaux et les Sols Paraferrallitiques sont caractéristiques des reliefs rejeunis.

INTRODUCTION

Extensive soil survey work has led to a good knowledge of soil distribution in Angola. Many latter-day studies of soil genesis have provided a better understanding of their nature and evolution. This paper gives general soil-landscape relationships. Special reference is made to Low Activity Clay Soils and among them to Alfisols and Ultisols. Since the larger part of existing information about Angola has been published in Portuguese an outline is first given of the environmental conditions as well as of the soil survey and soil classification background.

PHYSICAL ENVIRONMENT

Location

The Popular Republic of Angloa lies on the west coast of Africa between approximately 4 degrees and 18 degrees S latitude and 12 degrees and 24 degrees E longitude. It has a total area of about 1,247,000 sq. km.

Geomorphology

Nearly 65% of the territory is at altitudes between 1000 and 1500 meters; about 10% is below 500 meters and about 8% is above 1500 meters with a negligible 0.1% above 1000 meters.

According to Marques (1977), seven main geomorphological units may be considered in Angola, showing different relations between pedogenesis and morphogenesis. The low altitude Coastal Belt of comparatively recent age maintains a balance between pedogenesis and morphogenesis. The Transitional Zone modeled from the mid-Tertiary surface is made up of several stages having different degrees of stabilization of the physical environment. In the Marginal Mountain Range relief is very rugged, attaining heights of 2600 m, and morphogenesis is consequently favoured. The Southern Border of the Congo Basin comprises three subunits, namely the Cassange Depression where morphogenesis is favoured, the Cuanza-Luando Depression more favourable to pedogenesis and the Cassai Depression where pedogenesis overrides morphogenesis. The Old Plateau is made up of an extensive surface that is a residuum of the upper Cretaceous planation, raised in the late Secondary or early Tertiary, where pedogenesis is favoured. The Northern Border of the Kalahari Basin contains three subunits, namely the Cuvelai-Lueque Depression showing a balance between pedogenesis and morphogenesis, the Cubango Basin where pedogenesis is favoured and the Cunene Depression where the relation between pedogenesis and morphogenesis is an intergrade between the other two. The Zambeze Basin, an area of comparatively recent stabilization, is draining to the Indian Ocean and is favourable to pedogenesis.

Geology

Three main geological divisions are considered in Angola (MPAM and CEPT, 1968):

The Old Massif is made up of two Precambrian formations--the Basement Complex and the Western Congo System--plus eruptive rocks. The Basement Complex comprises more or less metamorphosed eruptive and sedimentary formations containing gneissic granites, gneisses, slates, schists and quartzites. The Basement Complex is surmounted in unconformity by the Western

Congo System, which includes Upper Precambrian sedimentary formations consisting mostly of arkoses, graywackes, quartzites, slates, limestones and conglomerates. The eruptive rocks are both Precambrian and more recent and have a predominance of granites, granodiorites, quartzodiorites, porphyrites, andesites, gabbros and anorthosites, the latter two forming an important Precambrian intrusion in the south.

The Covering Formations comprise the Kalahari deposits, the Karroo and the Continental Cretaceous formations. They include mainly shales, sandstones, conglomerates and sands of eolian origin. Doleritic and kimberlitic intrusions, probably dating from the post Karroo, are frequently found in these areas.

The Coastal Zone contains various marine sedimentary basins that include Secondary, Tertiary, and Quaternary formations where conglomerates, sandstones, marls, clay and sand deposits are found.

Climate

Angola lies largely in the trade wind belt and has an alternate wet and dry climate. To the southwest, however, it suffers the influence of tropical calms leading to desert climate which is further enhanced by the Benguela cold stream.

According to Azevedo and Sousa (1973) the climate of Angola by the Thornthwaite system of classification is semi-arid along the coast turning arid in a narrow strip south of Luanda. Inland the climate is mostly humid. It is generally megathermal in the north and mesothermal in the centre and the south. Moist climates make up nearly 72% of the total area compared to about 28% dry climates. Megathermal climates occupy about 18% of the area against 82% mesothermal climates.

Data supplied by Azevedo et al. (1972) shows that mean annual temperatures vary roughly between 17 degrees C and 26 degrees C. Lower values are found at higher elevations and in the southwest, and higher values in the Zaire Basin.

Rainfall varies widely from less than 20 mm in the southwest to over 1600 mm in the north. In general rainfall tends to increase from the coast inland and northwards, highest values being reached in the mountainous re-

gions at the centre and in the northern part of the territory. As is normal in the tropical regions, rains fall in the warmer months; the colder months are mostly dry.

Vegetation

Barbosa (1970) has distinguished 32 types of vegetation grouped into 10 formations as follows: Thick Forests, Forest-Savanna Mosaic, Thicket-Savanna-Woodland Mosaic, Thicket-Savanna Mosaic, Edaphic Formations, Woodlands, Tree and/or Shrub Savanna, Steppes, Desert and Grasslands.

SOIL SURVEY AND SOIL CLASSIFICATION

Planned reconnaissance and cartography of the soils of Angola may be said to have started as early as 1946. But systematic soil survey work for a General Soil Map of Angola was begun only in 1954 by the "Missao de Pedologia de Angola" (MPA) later named "Missao de Pedologia de Angola e Moçambique" (MPAM). Province (formerly district) by province publication started in 1959. General soil maps at 1:500,000 or 1:1,000,000 of six provinces were already published before the extinction and integration of the MPAM in the "Centro de Estudos de Pedologia Tropical" (CEPT) in 1973. Those of two more provinces are in press. It is expected that field work carried out up to 1974 will enable the CEPT in Lisbon to cover most of the remaining part of the territory. Side by side with the work of the MPAM, many localized larger scale soil surveys were carried out, especially in the late sixties and early seventies.

MPAM's General Soil Maps follow a taxonomic classification where the highest level soil units correspond generally to orders and the lowest soil units defined are *groupings* corresponding on an average to a taxonomic level very close to the soil family. Normally associations of groupings are used as mapping units (MPA, 1959, 1961, 1963; MPAM, 1968; MPAM and CEPT, 1972).

The general scheme of soil classification followed in the provincial General Soil Maps shows a certain evolution of concepts although its main

outline has remained essentially the same. The highest taxonomic levels of the soil classification as given by MPAM and CEPT (1968) are as follows:

- Weakly Developed Soils--mainly Entisols, partly Inceptisols and possibly Aridisols;
- Calcareous Soils--mainly Aridisols, few Mollisols and Inceptisols;
- Heavy Clay Soils--mostly Vertisols;
- Tropical Arid Soils--mostly Aridisols;
- Calsiallitic Soils of Sub-humid and Humid Regions--mainly Inceptisols and Entisols;
- Podzolized Soils--Spodosols and Entisols;
- Paraferrallitic Soils--mostly Ultisols, Inceptisols and Entisols;
- Ferrallitic Soils--Entisols and Inceptisols but also Oxisols and Ultisols;
- Hydromorphic Soils--severally distributed Aquic suborders;
- Organic Soils--mostly Histosols.

The Soil Maps include in addition some Unspecified Soils, Soils with Laterite at Shallow Depth, Beach Sands, Desert Dunes and Rocky Land.

GENERAL SOIL CLIMATE GEOMORPHIC RELATIONSHIPS

Calcareous Soils, Heavy Clay Soils, Tropical Arid Soils and some Unspecified Soils are located mainly in the Coastal Belt and the southern part of the Kalahari Basin of Angola, in connection with a semi-arid or arid climate; they make up about 12% of the territory of Angola. Tropical Fersiallitic Soils and Paraferrallitic Soils appear mostly in the Transitional Zone and the Marginal Mountain Range, under subhumid and humid climate; they come up to about 8%. Ferrallitic Soils cover most of the Old Plateau and of the Southern Border of the Congo Basin, predominantly under humid climate; they are the dominant soils of Angola, occupying around 45% of the total area. Slightly Leached to Leached Soils are distributed in small patches through most of the subarid to humid regions; they come up to about 20%. Hydromorphic Soils, sometimes associated with Podzolized Soils, appear mostly in the Zambeze Basin and the Cassange Depression, generally under humid and sometimes subhumid climate; they come

up to roughly 4%. Weakly Developed Soils and Rocky Land are irregularly distributed and add up to around 9%.

Kaolinite is the most ubiquitous clay mineral and it is generally predominant at heights above 400 m and rainfall over 600 mm; its association with montmorillonite in drier climates may be a question of inheritance (Furtado and Herbillon, 1964). Micaceous minerals are also extensively found and may even predominate in small areas under 400 mm rainfall; their presence in regions of high rainfall is also assigned to inheritance (Furtado and Herbillon, 1964; Furtado, 1967, 1969; Furtado and Silva, 1968). Montmorillonite is generally found at low altitudes and may be the predominant mineral when rainfall is under 400 mm; its existence under higher rainfall is normally limited. Gibbsite is found in regions of high rainfall even in soils derived from granite (Furtado, 1973); it is practically nonexistent when rainfall is under 1200 mm but may predominate in the clay fraction when rainfall exceeds 1400 mm. Goethite is frequent, especially in humid climates.

LOW ACTIVITY CLAY ALFISOLS AND ULTISOLS

It is not easy at the moment to find the correct place of all the soils of Angola in the classification system of the Soil Conservation Service (Soil Survey Staff, 1975). While Portuguese soil scientists follow essentially the same field methods as the SCS there are some important departures in routine laboratory procedures. A difference that is pertinent for the present purpose is that cation exchange capacity (CEC) is generally obtained adding the sum of bases to the extractable acidity measured by Ba-triethanolamine at pH 8.1 (Mehlich, 1953). This makes it difficult to use the definition of low activity clay as "any clay having a CEC of less than 16 me/100 g by the buffered NH_4OAc method" (Uehara, 1979). It can of course be assumed that in soils with pH-dependent charges CEC measurements at pH 8.1 will be higher than those at pH 7. Available data obtained directly in the clay fraction by the buffered NH_4OAc method seems to support this assumption. Uncertainties will remain as regards some soils having a CEC just above 16 me/100 g by the Ba-triethanolamine method.

Six of the highest level taxa given above may contain Alfisols and Ultisols but not all of them are LAC soils. Discussion is therefore restricted to Slightly Leached to Leached Soils, Tropical Fersiallitic Soils, Paraferrallitic Soils and Ferrallitic Soils within which should be found most if not all LAC Alfisols and Ultisols.

Slightly Leached to Leached Soils

For the present purpose only the subdivision called Oxypsammic Soils is of interest. These are coarse-textured soils generally having less than 15 and often less than 10% clay at any depth, formed from essentially quartziferous materials of good permeability; they have a more or less clear A1 and a textural B that in some cases does not qualify as an argillic horizon. Reaction is weakly to strongly acid and base saturation is lower than 60 and often lower than 30%. Kaolinite is always the dominant clay mineral but very small amounts of goethite, micaceous minerals and at times even gibbsite may be found. Available micromorphological data (Sousa, 1981) shows that significant illuvial clay is not a consistent feature; the type of skeleton grains indicate eolian transport; presence of "runiquartz" and iron oxide crystallites suggest polycyclism.

Oxypsammic Soils make up about 19% of the country (Azevedo et al., 1972) but it is not easy to estimate the area of Alfisols and Ultisols within them. Oxypsammic Soils have a wide distribution (MPAM and CEPT, 1968; Diniz, 1973) and are mostly found on gentle slopes in regions where annual rainfall is over 700 mm, often associated with sandy Ferrallitic Soils. Clay illuviation within the pedons is favoured by enough rainfall and good permeability but their frequent occurrence on mid to lower parts of slopes may imply also some lateral movement of clay.

Tropical Fersiallitic Soils

These are mineral soils having a fair amount of weatherable minerals. They may or may not have a cambic or argillic horizon. Base saturation is generally above 50%. Kaolinite is the dominant mineral; iron oxides are present in fair amounts together with small quantities of micaceous minerals. Micromorphological data is so far very scarce (Condado, 1969);

it shows illuvial clay accumulation at shallow depth indicating strong erosion.

Tropical Fersiallitic Soils come up to about 4% of the territory of Angola (Azevedo et al., 1972). Many are Alfisols but according to the data given by Franco (1964), only a few of them will have low activity clay. They are characteristic of rugged relief and appear mainly in the Transitional Zone and the Marginal Mountain Range.

Paraferrallitic Soils

These soils are akin to but less developed than the Ferrallitic Soils and differ from the latter as regards certain physico-chemical and mineralogical characteristics. They are normally medium- to fine-textured and less often coarse-textured soils that generally have a cambic or argillic horizon and may sometimes have a lithic contact at less than 1 m depth. Amounts of weatherable minerals are low but in general higher than those found in Ferrallitic Soils. Base saturation seldom exceeds 50%. Kaolinite is always the dominant mineral in the clay fraction; goethite appears in varying proportions; micaceous minerals are often present in very small amounts; gibbsite and even quartz may be occasionally present in minute quantities. Micromorphological data on these soils is limited (Condado, 1969; Réfega, 1972); it seems to lead to both *in situ* formation with or without concentration of illuvial clay and formation on transported material without illuvial clay concentration.

Paraferrallitic Soils occupy about 4% of the surface of Angola (Azevedo et al., 1972). Many of them fulfill requirements of Ultisols but it is not possible to estimate the area that can be assigned to the latter. Paraferrallitic Soils occur mostly on rolling land subjected to rejuvenation; they are well represented in the Transitional Zone, the Marginal Mountain Range and in parts of the Old Plateau in regions where annual rainfall is usually above 1000 mm.

Ferrallitic Soils

These are mineral soils resulting from very intense weathering in which the original rock structure may be found only at considerable depth; a textural B may or may not be present but a residual horizon called fer-

allitic B is a permanent feature; horizon boundaries are diffuse or gradual. Silt content is usually low, silt/clay ratio is less than 0.25, content of weatherable minerals is low or nonexistent; CEC is less than 15 and generally less than 10 me/100 g and base saturation is under 50%.

This concept of Ferrallitic Soils is wider in scope than that of Oxisols. They are LAC soils varying from Slightly Ferrallitic Soils, some of which are Ultisols, through Typical Ferrallitic Soils that are Oxisols, to Psammo-ferrallitic Soils that may be Entisols and Inceptisols. Kaolinite is always the dominant clay mineral; iron oxides in varying degrees of crystallization (but often as goethite) appear in small to fair amounts; micaceous and interstratified minerals may be present in minute quantities and gibbsite may show in minute to small amounts especially in regions of high rainfall. The "oxic syndrome" of Buol and Eswaran (1978) is not a general feature among them. Existing micromorphological data refers especially to the central part of Angola; granic NRDP has been found in Psammo-ferrallitic Soils (Condado, 1969) and fairly well expressed plasmic fabrics as well as ferri-argillans with strong continuous orientation have been reported in Slightly Ferrallitic Soils (Réfega, 1972; Benayas and Ricardo, 1973; Sousa, 1976). On the other hand presence of phytoliths; "runiquartz;" subrounded, rounded and fractured quartz grains; as well as inherited pedorelics up to considerable depths; suggest widespread transport and reworking of material.

More than half of the surface occupied by Ferrallitic Soils in Angola belongs to Psammo-ferrallitic Soils and only about 20% of the total area falls under Slightly Ferrallitic Soils (Azevedo et al., 1972). The latter contain Red Slightly Ferrallitic Soils that are often but not always Oxisols, and Brownish and Yellow Slightly Ferrallitic Soils that more often than not are Ultisols; they add up to about 12%. An exact estimate of Ultisols is, however, difficult.

As elsewhere in Africa, Ferrallitic Soils are mostly associated with stable surfaces made up of gently undulating to somewhat rolling land where rainfall is generally above 1000 mm. Stone lines made of reworked petroplinthite are common at depths from a few centimeters to several meters; when exposed at "free surfaces" cementation of material follows in the form

of wedges driving inwards. Transport and reworking are also evident in the rather homogeneous materials that cover the stone lines and form present-day soil; a 10,000 to 20,000 years old prehistoric artifact found at a depth of about 4 m was recently reported (Ricardo et al., 1980). Impoverishment of clay in the upper horizons is normal, it being deeper the older the soil (Sousa, 1976). In such a landscape colour toposequences are frequent; they have red members on the well-drained upper parts of interfluves followed downslope by yellowish-red, reddish-yellow, yellow, brownish and grayish members; one or more members may however be absent in any sequence. From the upper to the lower members there is in general a decrease of clay and free iron. Formation of argillic horizons in lower end members may be an effect of both vertical and oblique clay translocation.

CONCLUSION

LAC soils are widely found in Angola and may cover around 70% of the total area. They are mostly confined to 4 units of the present soil classification on Angola. Oxypsammic Soils and Ferrallitic Soils are found on gentle reliefs whereas Tropical Fersiallitic Soils and Paraferrallitic Soils are associated with rugged reliefs. LAC Alfisols and Ultisols seem to be limited in extent. Estimates of area are not possible.

Although a large mass of information exists regarding the soils of Angola, classification according to Soil Taxonomy (Soil Survey Staff, 1975) is not easy due to differences in classification systems and routine laboratory procedures. Establishment of correlations as well as some additional information may be helpful in this respect.

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DISCUSSION

Q. R. Frankart: 1. What is the concept and definition of the textural B2 horizon? 2. In which classes is it used as a differentiating criterion?

A. E.C. Sousa: 1. A textural B2 horizon is one that shows a more or less clear clay accumulation. No rigid limits for clay increase have been set up and not all of the B2 horizons correspond to the argillic hori-

zon as defined in Soil Taxonomy. 2. A textural B2 horizon characterizes the Slightly Leached to Leached Soils ("Solos Fracamente Lavados a Lavados"), but its presence is also permitted in some other soils with specific sets of characteristics.

STATUS OF ICOMMORT

A. Van Wambeke

The International Committee on Moisture Regimes in the Tropics, ICOMMORT, has issued three circular letters in which the concerns about the use in Soil Taxonomy of soil moisture regimes was summarized.

There has not been a major change in perspectives since the last International Soil Classification Workshop in Damascus. The major points of discussion in ICOMMORT correspondence related to the following topics:

(1) A reminder of the purposes of introducing soil moisture regimes in Soil Taxonomy indicates that the taxa are based on properties which are either the result of genesis or are important for genesis. Moisture regimes as such are considered a soil property important for genesis. The section in the profile in which the climatic properties are recognized in the soil is the moisture control section which is only a part of the hydrological profile from which plant roots extract water. For this reason one cannot expect moisture regimes to answer all questions related to land use.

(2) It is obvious that more precise definitions of moisture regimes necessitate more accurate measurements. Many discussions dealt with the conditions under which soil temperature and moisture should be measured in order to determine the regime of a pedon. It has been found that kinds of uses can drastically modify the climatic conditions in the soil which would result in a change in classification at the suborder level. In order to arrive at a reproducible identification of a soil, some kind of standardized methodology for measuring climatic soil properties should be devised.

(3) In the third ICOMMORT newsletter the views of members were reported in which climatic properties of soils were regarded as creating geographical segments in which individual soil scientists would become isolated, thus reducing the flow of technical information between climatic zones. The letter also included another contribution from the U.S. domes-

tic front: the Soil Conservation Service is developing an information sheet on each soil series giving data on actual moisture contents during one year under specific conditions. This water-supplying capacity of the soil is a valuable information base to determine the proper classification of a soil.

(4) There are still some difficulties in the computation of temperature regimes, especially the "iso" property. Some countries do not calculate summer and winter temperatures according to the methodology proposed in Soil Taxonomy. It is of course essential that the same method of calculation be used to achieve comparable classifications.

(5) At present several groups are working on subdivisions of soil climatic regimes. Some generalized schemes have been developed, mostly considering mathematical models or water balances as a basis for comparison on a worldwide scale. A scheme for subdividing temperature regimes in tropical areas was also proposed.

(6) It is the intent in the next circular letters to report on the use of moisture regimes in the order of Aridisols and Alfisols.

DISCUSSION

Q. W.G. Sombroek: At what level are the proposed subdivisions of the ustic soil moisture regime to be used in Soil Taxonomy?

A. A. Van Wambeke: We are thinking of subdivisions at the subgroup level to subdivide great groups, but there is no general agreement on this matter at this time.

Q. C. Sys: I should prefer not to proceed to more detailed subdivisions of the present soil moisture regimes. If soil differences occur due to variation within the moisture regimes as now defined, they should be expressed by using soil properties. This can be illustrated by two examples:

1. The soils occurring in the dryer part of the udic moisture regime under tropical forest have a high base saturation (BS) in the topsoil as compared with the soils occupying the more humid parts which are desaturated throughout the profile.
2. In the dryer and central part of the ustic areas, Ultisols develop

a highly saturated topsoil before grading into Alfisols. BS should therefore indicate some differences in the soil moisture regime as follows:

ustic-udic: low BS throughout the profile, Ultisols

typic-ustic: high BS in topsoil, low BS in subsoil, Ultisols

ustic-aridic: high BS throughout the profile, Alfisols.

A. A. Van Wambeke: There is no doubt that if chemical, physical or morphological soil features were available that reflect differences in the soil moisture regime, we would prefer to use them instead of moisture or temperature regimes as such.

SOIL TEMPERATURE REGIME STUDIES IN VENEZUELA

J.A. Comerma and J.M. Sánchez

INTRODUCTION

Soil Taxonomy (Soil Survey Staff, 1975) uses soil temperature as a classification criterion at different categorical levels. For its use Soil Taxonomy defines soil temperature regimes, based on annual average values above or below certain soil temperatures, measured at 50 cm depth, and considering the degree of variation between summer and winter values.

As a classification criterion, one would expect from soil temperature implications on soil genesis as well as on the use and management of the soils with different crops.

We understand that for the establishment of the different soil temperature regimes, very few data on intertropical regions were used, as there were few available, consequently the limits were based on soil features and crops that are of importance in high latitude areas.

As Venezuela exhibits a wide range of altitude and climatic conditions, we have been interested in ascertaining the validity of the criteria for our conditions. In two previous papers (Comerma et al., 1978; Comerma and Sanchez, 1980), summarized here, and some additional data, we have tried to answer the following questions:

(1) Is 50 cm a good depth to measure soil temperature independent of daily fluctuations? What is its relation to air temperature? How do we measure it?

(2) What kind of fluctuations in soil temperature with time do we have? Which are the coldest and warmest months and the degrees of difference between them? Are they related to the rainy and dry period?

(3) Do the limits established to separate the 9 soil temperature regimes represent significant limits to other soil properties and for use and management for different crops? Will it be necessary to propose modification of these limits or to create new ones?

MATERIALS AND METHODS

At the beginning of this study we had available records of air and soil temperatures, coming from airports and a few agricultural experiment stations, for 27 locations throughout the country, complete only for the period 1971-1975. The records included measurements of air temperature at 1.5-2 m height, and soil temperature at 5, 10, 20, 50 and 100 cm depth. Both temperature measurements were at fixed hours of 8 a.m. and 2 p.m.; as they corresponded closely to maximum and minimum values, those two were selected. Air and soil thermometers had a precision reading of 0.2 degrees C; the former were under the meteorological cover while the soil thermometers were in bare soil as is conventional.

All air temperature measurements were averaged first daily and then monthly for each year. Soil temperature measurements for 8 a.m. and 2 p.m. were separately averaged by months for the period of 5 years, for each depth and location. By computer we also got the following information:

(a) Monthly average values of air temperature for each year, 5-year period and each location; the same for soil temperature for each hour, for the two hours averaged, for each depth, month, year and 5-year period.

(b) Coefficient of variation of soil temperature for each depth, hour, year, 5-year period and location, as well as the same coefficient for the average of 27 locations for the 5-year period, for each depth and for both the 8 a.m. and 2 p.m. soil temperatures.

(c) Average difference between the temperatures at 8 a.m. and 2 p.m. for the 5-year period, for each depth and for the 27 locations.

With the above data we could attempt to answer the first two sets of questions asked at the beginning, but due to the fact that the great majority of the locations were below 1000 m above sea level, we had to increase the number of measurements above that altitude. With that purpose, in the station Maracay-CENIAP which is under our control, we tried to ascertain the question, How do we measure soil temperature in the open field? To answer it we opened, next to the installed geothermometers, several holes with an auger down to 50 cm and inserted calibrated thermometers at the same time, then waited for intervals of 5 minutes and read

the different thermometers until reaching the equilibrated temperature of the installed geothermometer at 50 cm. This turned out to be 15 minutes. With that information we proceeded to measure soil temperature at that depth in 49 new locations, with bare or as bare as possible and not shaded surfaces, specially between altitudes of 1000 and 4000 m. Several observations on soil properties of the auger holes, road cuts, time of the observations and type of crops, changes in natural vegetation, etc., were taken during the traverses by road.

RESULTS AND DISCUSSION

In Table 1 we can observe the characteristics of the meteorological stations used in this study. From it we can deduce that there is a rather good coverage of our physiographic areas below 1000 m altitude and the subhumid and dry areas of Northern Venezuela. From the study of the bioclimatic zones of Venezuela (Ewel, 1968), using the Holdridge Classification, we can also infer that there are several bioclimatic levels in the mountainous areas (Andes, Northern coastal range, etc.) which are not well covered.

Soil Temperature Differences with Depth

In Table 2 are presented for the different soil depths, the absolute differences in Celsius degrees between the soil temperature values taken at 8 a.m. and 2 p.m. for the 27 stations during the period 1971-1975. Also in that table we included the coefficient of variation for these values at each soil depth.

In order to judge the significance of the daily fluctuation, taken as the difference between the 8 a.m. and 2 p.m. readings we considered that the precision in the readings could only be equal to or larger than 0.2, as this is their scale of division. An error in measurement would occur during removal of the thermometers from the soil and raising them up to the reader. As a whole we estimated that both errors in measurement were less than 0.5 degrees C. As a consequence differences in soil temperature readings of 0.5 degrees C or less were considered as practically the same

TABLE 1 = SOME CHARACTERISTICS OF THE METEOROLOGICAL STATIONS

Location	Latitude	Longitude	Altitude m.o.s.e.	Rainfall, mm. $\bar{x}$ 1971-1975
Cumaná	10°27 N	64°11' W	02	306.8
Barcelona	10°07' N	64°41' W	07	525.4
Ocumare de la Costa	10°28' N	67°46' W	15	744.0
Coro	11°25' N	69°41' W	20	371.4
Mene Grande	09°49' N	70°55' W	27	1,442.4
Maiquetía	10°36' N	66°59' W	43	394.4
San Fernando	07°54' N	67°25' W	47	1,210.2
Maracaibo	10°34' N	71°44 W	66	574.0
Maturín	09°45' N	63°11' W	70	1,403.0
Puerto Ayacucho	05°36' N	67°30' W	74	2,140.4
Calabozo	08°45' N	67°32' W	100	740.2
Guasdualito	07°14' N	70°48' W	130	1,514.2
Tumeremo	07°18' N	61°27' W	180	1,356.6
Guanare	09°01' N	69°44' W	185	1,444.8
Acarigua	09°33' N	60°14' W	225	1,379.8
Yaritagua	10°04' N	69°07' W	375	911.6
San Antonio	07°51' N	72°27' W	377	793.6
Maracay (FAV)	10°15' N	67°39' W	442	730.8
Maracay (CENIAP)	10°17' N	67°37' W	455	869.4
Valencia	10°15' N	68°01 W	490	774.0
El Cují	10°10' N	69°19' W	600	604.4
Barquisimeto	10°04' N	69°19' W	613	489.0
Santa Elena	04°36' N	61°07' W	907	1,704.4
Caracas	10°30' N	66°56' W	1035	799.0
Bramón	07°39' N	72°24' W	1105	1,270.4
Mérida	08°36' N	71°11' W	1480	1,788.8
Mucuchíes	08°46' N	70°54' W	2980	582.2

TABLE 2 = AVERAGE DIFFERENCES IN SOIL TEMPERATURE AT DIFFERENT DEPTHS, BETWEEN MONTHLY AVERAGE VALUES AT 8 am AND 2 pm IN THE 27 STATIONS DURING 5 YEARS

Soil depth, cm	Absolute difference in °C	CV %
5	9.27	18.23
10	5.82	12.65
20	1.84	6.06
50	0.13	4.35
100	0.10	3.60

as they would be included in the error of measurement. According to the above criteria and observing Table 2 we can see that down to 20 cm the readings at 8 a.m. and 2 p.m. have differences due to daily fluctuations about 3 times as large as the possible errors in measurement, but at 50 cm or deeper the reading does not vary with time and consequently is independent of the daily fluctuation. The other measure of variability is the coefficient of variation, which in this case includes the measurements at 8 a.m. and 2 p.m. From it we can infer that the largest variations are at 5 and 10 cm; at 20 the variation decreases greatly and continues decreasing at 50 and 100 cm. The last two values are almost the same. All the above facts corroborate the validity of the measurement of soil temperature at 50 cm for our conditions, as an independent value of the daily fluctuations as established in Soil Taxonomy (Soil Survey Staff, 1978) and in other previous papers (Smith, 1964) for other areas.

Estimating Annual Average Soil Temperatures

Table 3 shows for the 27 locations: the average air temperature, the soil temperature at 50 cm depth and the difference. We can observe that in all cases the soil temperature is higher than the air temperature; the difference between the averages for all locations is 3.9 degrees C. The annual average at 50 cm depth and the annual average of the soil, considering all depths down to 1 m, are practically the same. The average for all depths is approximately 0.4 degrees C higher than at 50 cm. For all the above reasons we have generalized that to estimate the annual average temperatures at 50 cm depth in the soil, we have to add 4 degrees C to the external annual average, and not 1 degree C as it is suggested in Soil Taxonomy for other latitudes.

Coldest and Warmest Quarters

In relation to fluctuations during the year we selected the three consecutive coldest and warmest months for the two values (Table 4). It appears that the coldest quarter in air temperature is December, January and February. In the soil, in slightly over two-thirds of the cases, that is also the coldest quarter. The warmest quarter for air temperatures appears to be March, April and May. The warmest quarter for soil temperatures is

TABLE 3 = AVERAGE OF AIR AND 50 cm SOIL DEPTH TEMPERATURE DURING 5 YEARS AND ITS DIFFERENCES

Location	Annual air T°C $\bar{x}$ 5 years	50 cm soil depth T°C $\bar{x}$ 5 years	Difference between air and 50 cm soil T°C
Cumaná	26.4	31.8	5.4
Barcelona	27.1	30.7	3.6
Ocumare de la Costa	25.4	30.1	4.7
Coro	27.6	32.5	4.9
Mene Grande	27.2	31.2	4.0
Maiquetía	25.5	30.6	5.1
San Fernando	26.9	31.0	4.1
Maracaibo	27.3	30.3	3.0
Maturín	25.7	29.7	4.0
Puerto Ayacucho	26.6	29.9	3.3
Calabozo	26.0	29.8	3.8
Guasdualito	25.4	28.7	3.3
Tumeremo	24.5	28.2	3.7
Guanare	25.6	29.9	4.3
Acarigua	25.6	29.4	3.8
Yaritagua	25.9	27.4	1.5
San Antonio	25.6	28.9	3.3
Maracay (FAV)	24.4	28.7	4.3
Maracay (CENIAP)	24.7	28.7	4.0
Valencia	25.5	28.0	2.5
El Cují	23.8	27.9	4.1
Barquisimeto	23.5	29.5	6.2
Santa Elena	20.8	25.3	4.5
Caracas	20.6	25.6	5.0
Bramón	20.2	22.7	2.5
Mérida	18.6	24.2	5.6
Mucuchíes	11.0	14.2	3.2

TABLE 4. DIFFERENCES BETWEEN SOIL AND AIR TEMPERATURE DURING THE THREE CONSECUTIVE COLDEST AND WARMEST MONTHS IN VENEZUELA

STATION	COLDEST TRIMESTER				WARMEST TRIMESTER			
	Air		Soil		Air		Soil	
	Months	$\overline{X}$°C	Months	$\overline{X}$°C	Months	$\overline{X}$°C	Months	$\overline{X}$°C
CUMANA	12-1-2	25.6	12-1-2	30.7	5-6-7	26.9	8-9-10	32.5
BARCELONA	12-1-2	26.3.	12-1-2	30.3	3-4-5	28.0	3-4-5	31.7
OCUMARE DE LA COSTA	12-1-2	24.3	11-12-1	28.6	5-6-7	26.0	3-4-5	31.5
CORO	12-1-2	26.3	12-1-2	31.2	8-9-10	28.5	8-9-10	33.6
MENE GRANDE	11-12-1	26.5	11-12-1	30.3	5-6-7	27.7	6-7-8	31.9
MAIQUETIA	12-1-2	24.2	12-1-2	28.5	8-9-10	26.7	6-7-8	32.1
SAN FERNANDO	7-8-9	26-3	7-8-9	29.8	2-3-4	28.0	2-3-4	32.8
MARACAIBO	11-12-1	26.3	10-11-12	29.5	5-6-7	28.3	5-6-7	31.5
MATURIN	12-1-2	24.8	12-1-2	28.8	4-5-6	26.3	3-4-5	30.7
PUERTO AYACUCHO	6-7-8	25.4	7-8-9	28.1	1-2-3	28.0	1-2-3	32.3
CALABOZO	7-8-9	25.2	7-8-9	28.9	3-4-5	26.8	2-3-4	32.0
GUASDUALITO	6-7-8	24.7	6-7-8	27.9	2-3-4	26.5	2-3-4	30.0
TUMEREMO	12-1-2	23.6	12-1-2	27.0	8-9-10	25.1	8-9-10	29.2
GUANARE	6-7-8	24.7	6-7-8	29.1	2-3-4	26.8	2-3-4	31.2
ACARIGUA	7-8-9	24.7	7-8-9	28.5	2-3-4	26.7	2-3-4	31.3
YARITAGUA	12-1-2	25.4	11-12-1	26.9	3-4-5	26.6	2-3-4	2[illegible]
SAN ANTONIO	12-1-2	24.1	12-1-2	27.6	6-7-8	26.9	8-9-10	30.2
MARACAY FAV	12-1-2	23.3	12-1-2	27.4	4-5-6	25.5	4-5-6	29.8
MARACAY CENIAP	12-1-2	23.5	12-1-2	27.2	4-5-6	26.0	4-5-6	30.8
VALENCIA	12-1-2	24.5	11-12-1	27.1	4-5-6	26.5	4-5-6	28.9
EL CUJI	12-1-2	23.0	11-12-1	27.3	3-4-5	24.3	2-3-4	28.9
BARQUISIMETO	12-1-2	22.7	11-12-1	28.9	3-4-5	23.9	2-3-4	30.9
SANTA ELENA	7-8-9	20.1	6-7-8	24.9	3-4-5	21.6	3-4-5	25.6
CARACAS	12-1-2	19.1	12-1-2	23.9	5-6-7	21.7	4-5-6	26.7
BRAMON	12-1-2	19.4	12-1-2	21.9	3-4-5	20.9	8-9-10	23.4
MERIDA	12-1-2	17.7	10-11-12	23.6	4-5-6	19.1	2-3-4	24.8
MUCUCHIES	12-1-2	10.8	7-8-9	12.7	3-4-5	11.5	2-3-4	16.3

February, March and April. In general there is coincidence between the coldest and warmest air and soil temperature values, but warmer soil temperatures occur slightly before.

The difference between the coldest and warmest quarter in the soil, as an average for the 27 locations, is 2.3 degrees C; the range of variation is 0.7 to 4.2 degrees C. As we see all locations fall into the denomination of "iso" according to Soil Taxonomy.

Rainy and Dry Seasons

Table 5 shows the variation of temperature with the rainy and dry period. In it we can observe that the rainiest quarter is July, August and September, while the driest is January, February and March. In general, the dry period tends to be warmer in the air as well as in the soil. The average difference between the driest, and rainiest quarter in soil temperature is about 1 degree C with a range variation of 0.1 to 3 degrees C.

As a general conclusion we can say that the main variations in soil temperature occur one immediately after the other and all during the dry period. Between December and April occur the extreme annual variations in soil temperature, February being the transitional month between the coldest and warmest quarter. This would suggest that the best time for instantaneous soil temperature measurements is the period of May to November in order to avoid the extreme variations.

Relationship Between Altitude and Temperature

Table 6 shows the data that help to establish the relation between the altitude of the observations and the soil temperature at 50 cm. It includes most meteorological stations plus the additional 49 observations registered by us, in total 68 sets of data. Fig. 1 shows how good this relation is, resulting in a coefficient of correlation of $r = -0.97$. The equation of regression indicates that for every 100 m increase in altitude there is 0.5 degrees C decrease in soil temperature.

In Fig. 1 by interpolation we have established the relationship between limits on the soil temperature regimes and the altitude. From it

TABLE 5. VARIATIONS IN AIR AND SOIL TEMPERATURE WITH THE RAINY AND DRY SEASON IN VENEZUELA

STATION	RAINIEST TRIMESTER			DRIEST TRIMESTER		
	T $\overline{X}$°C			T $\overline{X}$°C		
	Months	Air	Soil	Months	Air	Soil
CUMANA	8-9-10	26.8	32.5	1-2-3	25.7	30.9
BARCELONA	7-8-9	26.8	30.5	2-3-4	27.5	31.4
OCUMARE DE LA COSTA	7-8-9	25.8	29.9	1-2-3	24.6	30.2
CORO	10-11-12	27.3	32.3	2-3-4	27.0	32.2
MENE GRANDE	9-10-11	26.7	30.8	1-2-3	27.1	31.3
MAIQUETIA	10-11-12	25.8	29.8	2-3-4	24.5	30.4
SAN FERNANDO DE APURE	7-8-9	26.3	29.8	1-2-3	27.4	31.9
MARACAIBO	7-8-9	27.6	30.5	12-1-2	26.7	29.8
MATURIN	7-8-9	25.9	29.6	2-3-4	25.6	30.3
PUERTO AYACUCHO	5-6-7	25.6	28.5	12-1-2	27.5	31.5
CALABOZO	6-7-8	25.5	29.1	1-2-3	25.8	31.5
GUASDUALITO	7-8-9	24.7	27.9	12-1-2	25.3	28.9
TUMEREMO	6-7-8	24.3	28.2	2-3-4	24.3	28.1
GUANARE	5-6-7	25.0	29.2	12-1-2	25.4	30.0
ACARIGUA	6-7-8	24.9	28.7	12-1-2	25.8	29.7
YARITAGUA	6-7-8	25.7	27.2	1-2-3	25.9	27.5
SAN ANTONIO	10-11-12	25.0	28.7	6-7-8	26.9	29.8
MARACAY FAV	8-9-10	24.2	28.5	1-2-3	23.9	28.1
MARACAY CENIAP	8-9-10	24.6	28.1	1-2-3	24.0	28.3
VALENCIA	7-8-9	25.6	28.0	1-2-3	24.9	27.8
EL CUJI	6-7-8	23.7	27.1	1-2-3	23.5	28.3
BARQUISIMETO	5-6-7	23.6	28.5	12-1-2	22.7	29.3
SANTA ELENA	6-7-8	20.2	24.9	1-2-3	20.9	25.4
CARACAS	8-9-10	21.3	25.9	1-2-3	19.5	24.7
BRAMON	9-10-11	20.5	23.4	1-2-3	20.0	21.9
MERIDA	9-10-11	18.9	23.8	1-2-3	18.1	24.5
MUCUCHIES	7-8-9	10.8	12.7	12-1-2	10.8	15.4

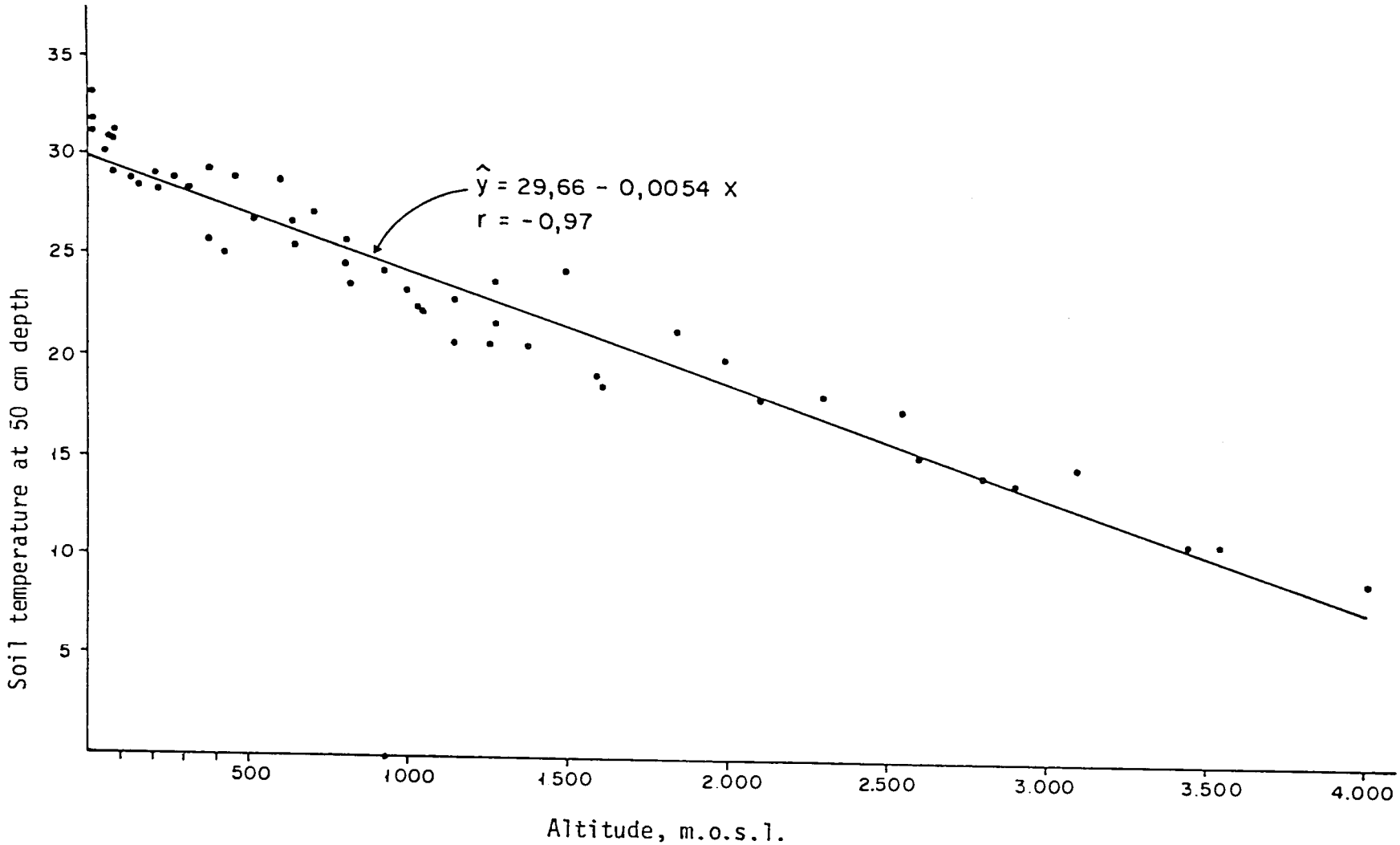


Fig. 1. RELATIONSHIP BETWEEN ALTITUDE OVER SEA LEVEL, AND SOIL TEMPERATURE AT 50 cm DEPTH IN VENEZUELA

TABLE 6 = SOIL TEMPERATURES AND ITS CORRESPONDING ALTITUDES AT VARIOUS LOCATIONS IN VENEZUELA

Location	Altitude (m)	Soil temperature at 50 cm (°C)
Cumaná	10	30.8
Barcelona	12	33.0
Ocumare de la Costa	15	30.4
Coro	15	31.4
Maiquetía	43	32.6
Ciudad Bolívar	45	34.0
San Fernando	48	29.9
Maracaibo	65	30.6
Maturín	70	30.4
Banco de San Pedro - Calabozo	75	29.0
Estación Biológica - Calabozo	85	30.0
Jusepín	135	28.6
Guanare	150	28.2
Tumeremo	160	29.4
Turén - Centro Administrativo	215	28.8
Acarigua - Araure	220	28.0
Guanipa	275	28.6
Yaritagua - El Rodeo	320	28.2
San Antonio (Táchira)	375	29.2
Estado Aragua (vía Ocumare)	380	25.5
Estado Sucre	430	25.0
Maracay - CENIAP	455	28.7
Valencia	480	27.1
Estado Aragua (vía Choroní)	520	26.6
El Cují (Estado Lara)	600	28.4
Barquisimeto	610	31.4
Estado Aragua (vía Ocumare	610	25.4
Estado Aragua (vía Choroní)	630	26.4
Estado Monagas	650	25.2
Valera	700	27.0
Estado Aragua	805	25.5
Estado Aragua (vía Ocumare)	820	23.6
Estado Barinas	800	24.6
Estado Bolívar	810	26.1
Estado Monagas	920	24.1
Santa Elena (Estado Bolívar)	860	25.3
Estado Aragua (vía Ocumare)	900	23.6
Estado Aragua (El Mirador)	1000	23.2
Estado Aragua (vía Choroní)	1030	22.4
Caracas	1035	22.0
Estado Aragua (vía Choroní)	1050	22.2
Estado Bolívar	1130	23.0
Estado Aragua	1140	20.8
Bramón	1140	22.8
Estado Monagas	1260	20.4
Estado Trujillo	1280	23.8
Estado Aragua (vía Choroní	1285	21.4
Valle Lindo (Estado Lara)	1300	21.0

./..

Table 6 (cont.)

Estado Aragua (vía Choroní)	1380	20.5
Estado Bolívar	1430	22.0
Mérida	1495	24.2
Sanare	1500	18.0
Estado Mérida	1600	19.2
Estado Aragua (vía Choroní)	1610	18.6
Cubiro (Estado Lara)	1750	21.0
Estado Trujillo	1840	21.2
Estado Mérida	2000	20.0
Santo Domingo	2100	18.0
Estado Trujillo	2300	18.2
Estado Mérida	2550	17.4
Estado Mérida	2600	15.2
Estado Mérida	1800	14.2
Estado Mérida	2900	13.8
Mucuchíes (Estación Experimental)	3100	14.8
Estado Mérida	3460	10.8
Estado Mérida	3550	11.0
El Aguila	4060	9.0

we concluded that 22 degrees C corresponds to about 1400 m, 15 degrees C to 2600 m and 8 degrees C to 3900 m.

To judge the suitability of these limits, we have searched for relations between these altitudes, their corresponding temperatures, and changes in other ecological criteria (like natural vegetation) as well as the adaptability of our main crops and other characteristics which may affect soil interpretation. Starting with the limit of the isohyperthermic at 22 degrees C, we have seen this corresponds in Fig. 1 to about 1400 m above sea level. In practice we did observe that this altitude may vary between 1100 m and 1400 m depending on factors such as eastern or western exposure to the sun. In relation to the question: Does this altitude represent an important limit in relation to an ecological zone that may affect crop adaptability and other soil interpretations? The answer, in our conditions, is: Yes, we think it is of importance because it marks the upper altitude of optimum conditions for many cultivars of crops like sugar cane and citrus, affecting not only their yields but also the quality of the produce. But, we also think that to consider all soils below that altitude as uniform in respect to crop adaptability and other soil interpretations is too general. It is possible to have another division for tropical crops at lower altitudes which may be somewhere around 400 to 600 m. Below this altitude there are crops like cotton, cocoa, mangoe, bananas, etc., which are commonly planted, and above it and up to 1100 to 1400m, there are other common crops like sugarcane, citrus, etc., which are better adapted. That altitudinal limit corresponds to about 28 degrees C at 50 cm depth in the soil or around 24 degrees C average external temperature. This temperature has also been used in the Holdridge (Ewel, 1968) system of classification of bioclimatic zones, to separate the tropical from the premontane zone. If we want to maintain the isohyperthermic for the regime with soil temperatures equal to or higher than 22 degrees C, then it could be applied to the range 22 degrees C to 28 degrees C, and above it we could name it "isomegathermic" or "isosuperthermic." The possible importance of this limit in areas different from the tropics, that is in areas that are "non-iso" or just megathermic, would have to be considered as well.

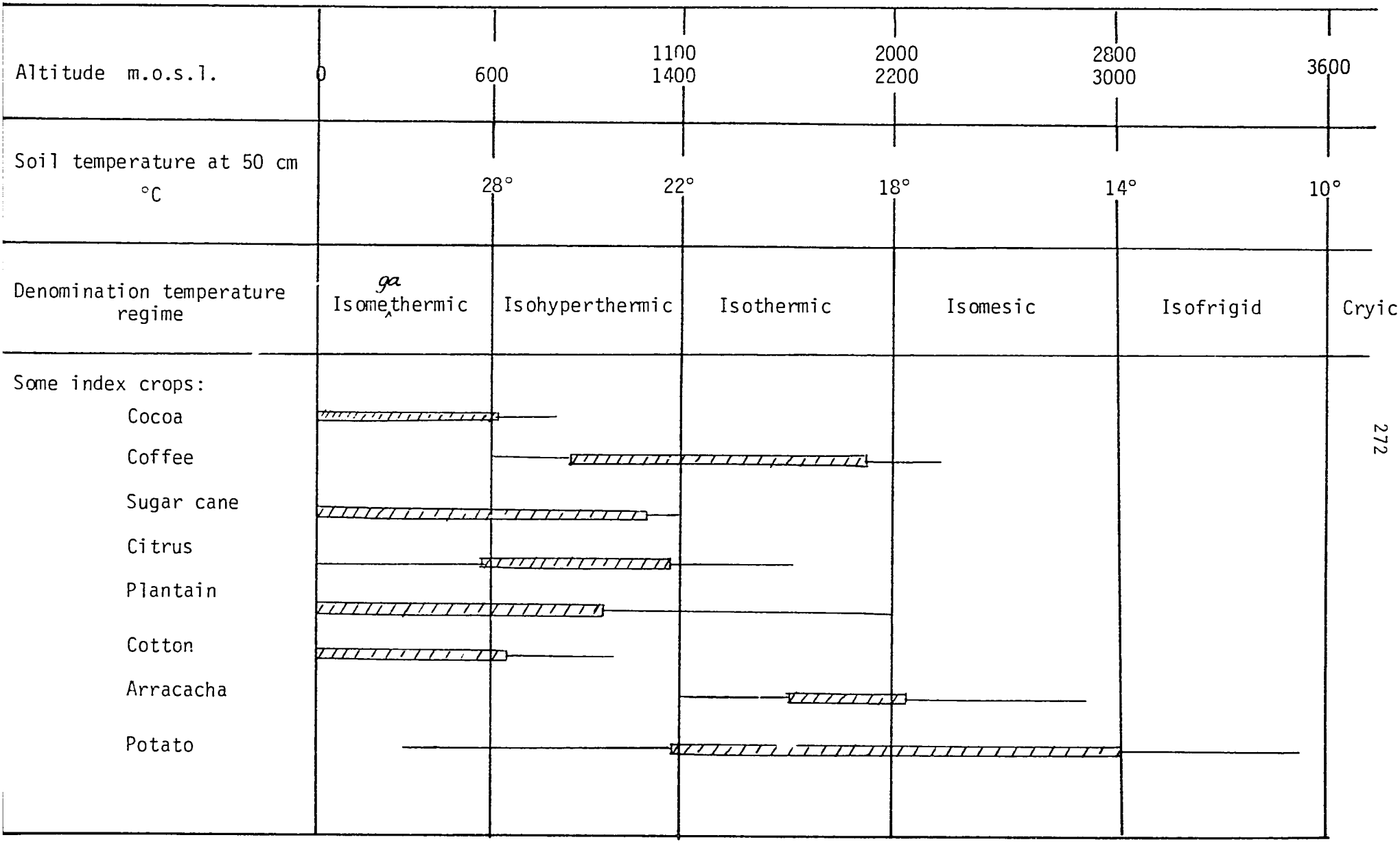
The next limit would correspond to the soil temperatures between 22 degrees C and 15 degrees C for the isothermic, or around 1100-1400 m and 2600 m. Our first consideration is that around 2000 to 2300 m there is

a very important upper limit, for many of the countries around this latitude, which is for coffee under shade. That altitude corresponds to 18 degrees C at 50 cm depth, and if tested and accepted by others, could constitute the lower limit for the isothermic.

The next consideration is in relation to the 15 degree C limit. The equivalent altitude, or 2600 m, in our conditions does not seem to be related to important ecological changes or to crop responses; but somewhat higher, at 2800 to 3000 m, there is a very important limit: "the paramo." This limit represents an important change in natural vegetation, going from forest to a shrub type of vegetation, the accumulation of organic matter in the soil seems to be higher and more contrasted with the subsoil, there are occasional frost nights and the type of crops also changes. This altitude, 2800 to 3000 m, was checked in several places, and the corresponding soil temperature is 14 degrees C. We understand that in other latitudes, even within the tropics, the limit may vary slightly and be around 15 degrees C, as it is already in use; consequently we think the difference is not that critical. Between 2000 or 3000 m altitude there are not many extensive agricultural areas in Venezuela; nevertheless this zone is almost restricted to some fruits like strawberries and certain cultivars of peaches, besides crops like lettuce, carrots, onions, artichoke, etc., which are grown there because of the excellent phytosanitary conditions. The name for this possible zone, that is between 14 degrees C and 18 degrees C or 3000 m to 2000 m altitude, and if we follow the sequence of names for temperature regimes, would be "isomesic."

The next limit is 8 degrees C which was established to separate the mesic from the frigid or the cryic. It has already been suggested by Smith (1976) that this limit for tropical areas should be raised to 10 degrees C. We do agree with that suggestion based on the fact that the upper limit of cultivation in Venezuela was observed in this study at about 3600 m. This altitude corresponded in the soil with 10 degrees C and not 8 degrees C. In the zone between 14 degrees C and 10 degrees C there are an increasing number of nights with frost, and the crops like potato, carrots and certain types of onions are limited to few areas. If we follow the sequence of names for temperature regimes, we could call this isofrigid or cryic. Considering that even though both have the same limits in their

TABLE 7 = PROPOSED SOIL TEMPERATURE ALTITUDE AND MORE COMMON CROPS IN VENEZUELA



Optimum

Suboptimum

TABLE 8 = RELATIONSHIP AMONG THE TEMPERATURE REGIMES OF SOIL TAXONOMY, THE BIOCLIMATIC ZONES OF HOLDRIDGE AND OUR PROPOSAL, FOR TROPICAL AREAS

SOIL TAXONOMY		BLIOCLIMATIC ZONES OF HOLDRIDGE		OUR PROPOSAL	
Denomination	Limits in soil temperature at 50 cm depth °C	Denomination	Air temperature	Denomination	Limits in soil temperature at 50 cm depth °C
Isohyperthermic	> 22	Tropical	> 24	Iso megathermic	> 28
		Premontano	18-24	Iso hyperthermic	< 28 > 22
Isothermic	< 22 > 15	Montano bajo	12-18	Isothermic	< 22 > 18
Isomesic	< 15 > 8	Montano	6-12	Isomesic	< 18 > 14
Cryic or Isofrigid	< 8 > 0	Sub alpine	3-6	Isofrigid	< 14 > 10
				Cryic	< 10

definition, the isofrigid may reach higher temperatures in certain periods of the year. Consequently it seems more logical to propose isofrigid for this area, and leave the cryic for the region with temperatures below 10 degrees C throughout the year, and occurring in our conditions, at altitudes above 3600 m.

We do not have data on soil temperature for the pergelic regime, but we know that the altitude with permanent ice is around 4600 m. This could possibly then represent the limit of division between the cryic and the pergelic, but some measurements should be made before considering it.

CONCLUSION

In Table 7, we summarize the proposed changes with their altitudinal limits, soil temperatures and some index crops as examples. In Table 8 we show the relationship between the present limits of the soil temperature regimes, the criteria of air temperature used in the bioclimatic zones of Holdridge, and our proposed limits. In this table we can observe that by adding 4 degrees C to the air temperature of the limits of Holdridge, we find a rather good correspondence, specially for the isomegathermic, isohyperthermic, and again quite good for the isomesic and isofrigid.

We hope that these proposed changes in soil temperature regimes will raise enough curiosity to increase the number of measurements in other tropical areas, relate these data with other soil characteristics and with the type of crops and farming used in those areas, so that we can improve the taxonomy of soils and the possibility of making better interpretations.

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DISCUSSION

Q. A. Van Wambeke: Don't you think that the limits which you propose are strongly dependent on the conditions under which the soil temperatures are measured?

A. J.A. Comerma: Yes, the temperatures vary depending on whether they are measured under bare, slightly shaded, or completely shaded surfaces. Data from the Amazon forest show that there may be differences of up to 5 degrees C at 50 cm depth between bare and forested soils, and surface temperatures may differ by as much as 10 to 15 degrees C. I believe it is convenient to use bare surfaces because of easy standardization. Also, the World Meteorological Organization uses bare soil as a standard for soil temperature measurements and we could thus use their data directly without introducing factors relative to the degree of shading. Finally, bare soil is the most common state of the soil when the seed is germinating and the plant is emerging and it is this state when soil temperature may be critical in many tropical areas.

Q. J.M. Spain: A comment about the upper elevation limit of cropping. This varies depending on latitude. As you move away from the equator to higher latitudes, cropping is carried out to much higher elevations. In the case of Peru, potatoes, barley, rye, and other common crops are grown up to about 4,500 m. The explanation may be the greater seasonality at higher latitudes and thus longer days during the growing season, more energy available to growing crop, etc.

A. J.A. Comerma: We have to make measurements at other latitudes in tropical areas. In Venezuela we could only study latitudes from 4 to 11 degrees N. We expect some variation not only with altitude at different latitude, but also variation in the type of crops. At the same time, there are differences between the east and west slopes of the Andes of about 300 to 400 m with respect to the upper limit of cultivation; the east slopes being colder than the west slopes. This means that the same temperature limit for the cultivation of specific crops are 300 to 400 m higher on the west slopes than they are on the east slopes of the Andes.

Q. C. Sys: I believe we should leave the soil temperature regimes as they are now. For management we need more detailed information on air temperature with fluctuating optima according to the development stage of the crop. For wheat, for example, we should consider the following temperatures:

- mean temperature, vegetative stage
- mean temperature, flowering stage
- mean temperature, ripening stage
- average minimum temperature of coldest month combined with average daily maximum temperatures for coldest month.

Soil temperature regime cannot provide this information. I agree that the present temperature regimes are useful, but I think we should not go any further.

A. J.A. Comerma: The intent of our paper is not to give precise data on agroclimatological requirements of different crops, but to use some important ones as indicators of ecological changes that may be related to other soil properties and can improve the interpretations for different taxa. The present temperature regimes have been conceived on the basis of crop belts in temperate regions. What we suggest here are changes according to crop belts important in the tropical region based on the knowledge we gained through our work in Venezuela.

THE SOIL MOISTURE REGIME MAP OF THAILAND

Lek Moncharoen

ABSTRACT

The preliminary soil moisture regime map was established for soil surveying and classification in Thailand. The daily soil moisture records from 17 sites of eight selected areas were used in estimating soil moisture regime. The method consisted of classifying the soil moisture regime according to Soil Taxonomy, and identifying the influencing factors for each site. The soil moisture regime map was compiled from the interpretation of influencing factors from climatological data, a land use map, an isohyetal map, and a topographic map. Information from field observation for the areas in which data was not available was also referred to. From the study, five soil moisture regimes were recognized in Thailand: namely the aquic, ustic, udic, perudic and peraquic moisture regimes. The distribution of each soil moisture regime is shown in the map.

The soil moisture-prediction method of the U.S. Army Waterways Experiment Station was used to test for its accuracy and applicability to Thailand. The comparison of predicted and measured values gave fairly good results for the well-drained sites. The prediction method is likely to be useful for Thailand, at least where the accretion of soil moisture is related to rainfall and depletion of soil moisture is related to evaporation, transpiration and drainage. However, more average predictions should be developed from soil properties and other factors at other sites.

INTRODUCTION

Soil classification in Thailand initially followed the Great Soil Group system as formulated by the Soil Conservation Service of the United

States Department of Agriculture. This system was modified for tropical conditions by Dudal and Moormann in 1964. In recent years, the application of a new classification system (7th Approximation and Soil Taxonomy) has been introduced to soil survey and classification in Thailand. Early work concerned soils already mapped at the great group level and individual profiles at the family level. At present, all of the series used as basic mapping units in our soil survey efforts have been revised to fit the new classification. Since the soil moisture regime is a very significant criteria for the new classification system, it is necessary to have soil moisture regimes mapped for soil survey and soil correlation works, especially now when the detailed-reconnaissance soil survey of the whole country is nearly completed. Unfortunately little work has been done on this subject in Thailand. The moisture-strength of soil samples has been studied in 1964 to 1965 to predict soil trafficability. The Soil Survey Division began working on soil temperature and moisture regimes in 1978; the data from which is the process of computation. An attempt has been made to estimate soil moisture regimes from presently available data. The primary purposes of this report are to: (a) present the preliminary soil moisture regime map of Thailand which we intend to use in soil classification and mapping, (b) show some quantitative changes in moisture conditions with the passage of time among soils under different environments and (c) use the soil moisture prediction to follow the WES (U.S Army Waterways Experiment Station) method for testing the applicability for Thailand.

SOIL MOISTURE MEASUREMENT AND MAPPING

Daily soil moisture records at various depths from the Moisture-Strength Project in 1964 to 1965 were used in estimating soil moisture regimes. The sites are shown in Fig. 1, which consists of 17 sites from eight selected areas in Thailand. The method of soil moisture measurement involved the use of electrical resistance units which consist of two Monel metal screen electrodes separated and surrounded by layers of a fiberglass cloth in a perforated Monel metal case. The time of record was from 380 to 485 days. Measurements were taken early each morning at the site to

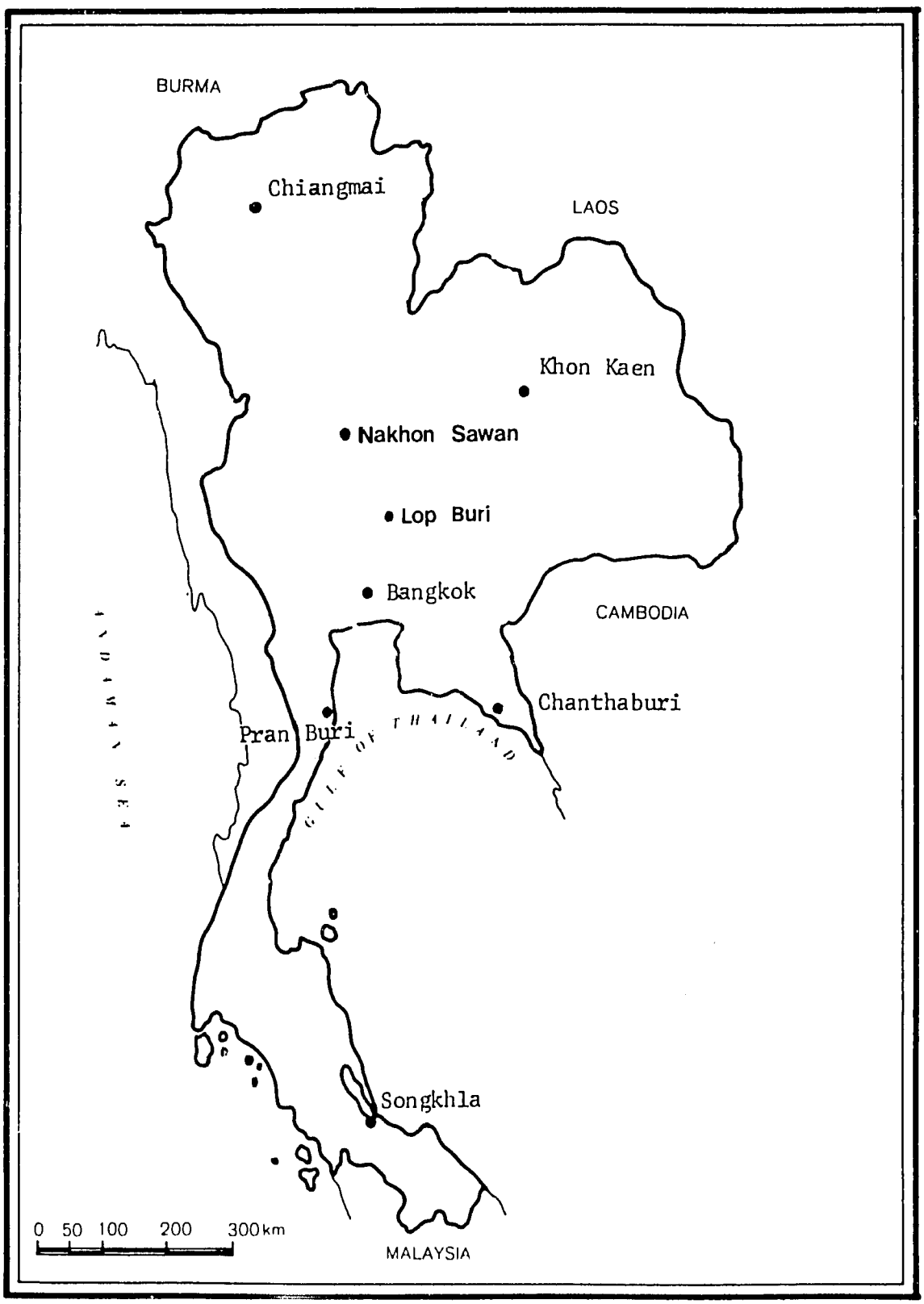
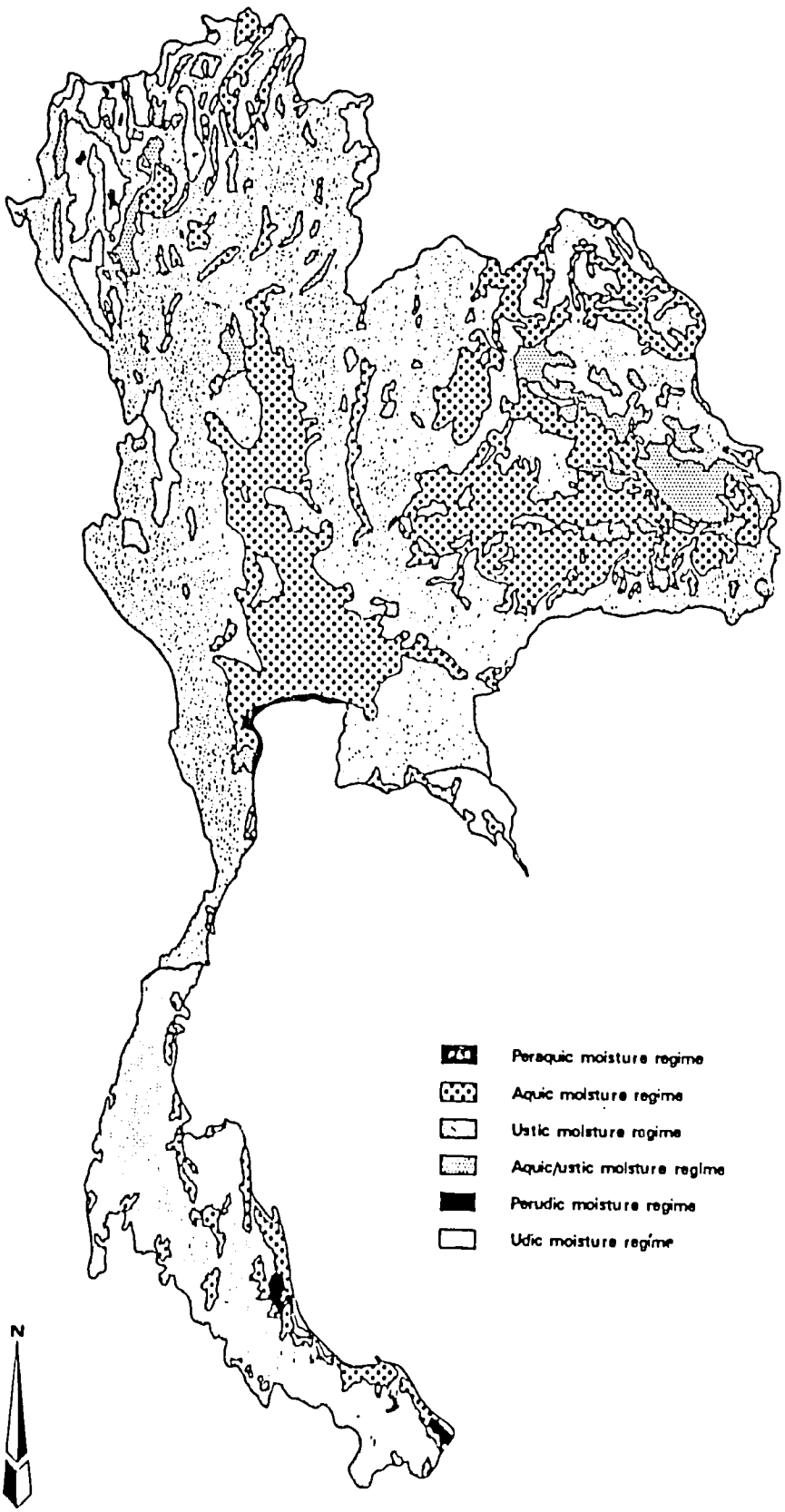


Fig. 1 Locations of da[illegible]asurement sites of the soil moisture content.

Map Showing Soil Moisture Regime of Thailand



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L. MONCHAROEN

obtain a consistent 24-hr. time interval. Included in each site measurement were rainfall amount, air temperature and depth to ground water. The soil classifications, some soil properties, and important site descriptions are summarized in Tables 1 and 2.

The daily records of soil moisture from each site in terms of percentage by weight and millimeters of water per 10 cm of soil thickness were plotted against the time of measurement as shown in Figs. 2 to 4. The soil moisture conditions of each site were classified according to Soil Taxonomy. The periods of dryness and water saturation of the soils under different climatic conditions, vegetation and land use, and other relevant conditions are summarized in Table 2.

From the study, three types of soil moisture regimes can be classified from 17 sites, namely the ustic, udic and aquic moisture regime. Factors that influence the moisture regime can be identified as the amount of rainfall, number of rainy days, vegetation and land use, elevation, and depth of ground water level.

The soil moisture regime map was established by the interpretation of influencing factors from climatological data, a land use map, an isohyetal map, and a topographic map. This also necessitated information from field observations especially for the areas in which data was not available. The final results were obtained from combining and estimating the available data. The aquic moisture regime dominantly occurs in rice paddies which cover lowlying lands throughout the country. The peraquic moisture regime occupies the tidal flat and swamp areas dominantly along the Gulf of Thailand. The udic moisture regime dominates the Southern Peninsula where the total number of rainy days exceeds 150 and the total amount of rainfall exceeds 2,000 mm per year. In the North and West Continental Highlands where there are hills covered with evergreen vegetation and the elevation ranges between 1,000 and 1,600 m above sea level lies the udic moisture regime. From field observation, areas above 1,600 m are expected to be of the perudic moisture regime. The rest of the areas are classified under the ustic moisture regime.

Table 1 Classification and some soil properties at test sites.

Location	Site No.	Classification	Moisture retention at 15 atm (%)	Bulk density (gm/cc)	Organic matter (%)	Total Pore Sat'n (%)
Chiang Mai	PD 241	Loamy, Paleaquults	a) 8.3 b) 7.8	a) 1.28 b) 1.46	a) 2.87 b) 0.95	a) 39.7 b) 31.0
	PD 242	Loamy, Paleustults	a) 2.7 b) 2.5	a) 1.40 b) 1.48	a) 0.78 b) 0.55	a) 33.7 b) 29.8
	T. 3	Clayey, Palehumults	a) 26.0 b) 23.3	a) 0.8 b) 0.95	a) 5.74 b) 3.27	a) 85.4 b) 66.7
	PD 243	Loamy, Paleaquults	a) 5.5 b) 5.5	a) 1.53 b) 1.69	a) 1.55 b) 0.62	a) 26.9 b) 21.7
Khon Kaen	PD 246	Loamy, Paleustults	a) 2.5 b) 3.0	a) 1.61 b) 1.63	a) 0.95 b) 0.62	a) 24.3 b) 23.6
	PD 247	Loamy, Paleaquults	a) 4.7 b) 4.8	a) 1.51 b) 1.54	a) 1.05 b) 0.95	a) 27.9 b) 26.6
	PD 248	Loamy, Paleaquults	a) 3.2 b) 2.8	a) 1.44 b) 1.50	a) 0.78 b) 0.76	a) 31.7 b) 28.9
	PD 249	Loamy, Natraquults	a) 6.5 b) 6.9	a) 1.44 b) 1.45	a) 0.78 b) 0.46	a) 31.2 b) 31.1
Nakhon Sawan	PD 251	Clayey, Paleustults	a) 16.0 b) 16.6	a) 1.30 b) 1.43	a) 2.87 b) 2.83	a) 39.8 b) 32.7
Lop Buri	PD 252	Clayey, Paleaquults	a) 35.2 b) 34.8	a) 1.01 b) 1.07	a) 3.27 b) 3.0	a) 61.8 b) 56.3
	PD 253	Clayey, Tropaquents	a) 24.8 b) 24.8	a) 1.10 b) 1.13	a) 2.27 b) 2.75	a) 53.4 b) 50.9
	PD 254	Clayey, Paleustults	a) 20.5 b) 22.6	a) 0.99 b) 1.10	a) 2.87 b) 2.08	a) 63.8 b) 53.7
	PD 255	Clayey, Paleustults	a) 12.6 b) 13.6	a) 1.25 b) 1.43	a) 1.65 b) 1.77	a) 42.0 b) 31.9
	PD 256	Clayey, Tropaquents	a) 18.1 b) 19.1	a) 1.34 b) 1.38	a) 2.23 b) 1.77	a) 37.7 b) 35.6
Bangkok	PD 244	Clayey, Tropaquepts	a) 25.7 b) 24.3	a) 1.15 b) 1.30	a) 1.98 b) 1.55	a) 49.7 b) 39.6
	PD 245	Clayey, Tropaquepts	a) 26.5 b) 25.8	a) 1.29 b) 1.34	a) 3.00 b) 1.65	a) 40.2 b) 37.3
Pran Buri	PD 257	Quartzipsamments	a) 3.0 b) 2.9	a) 1.39 b) 1.47	a) 0.70 b) 0.55	a) 34.2 b) 30.3
Chantha-buri	PD 258	Clayey, Paleustults	a) 20.6 b) 20.9	a) 1.34 b) 1.30	a) 3.27 b) 1.98	a) 37.2 b) 39.5
	PD 259	Clayey, Paleudults	a) 26.7 b) 29.1	a) 0.87 b) 0.92	a) 3.00 b) 2.75	a) 80.2 b) 74.0
Songkhla	PD 260	Loamy, Paleudults	a) 5.2 b) 5.7	a) 1.35 b) 1.60	a) 1.45 b) 0.78	a) 36.2 b) 24.6

a. Depth between 0 and 15 cm.
b. Depth between 15 and 30 cm.

Table 2 Moisture condition between Aug 64 - Jul 65 and some major site descriptions.

Location	Site No.	Soil moisture condition No. of dry (days) Depth (cm) 7.5-15	15-25.5	25.5-30	30-37.5	Moisture regime after Soil Taxonomy	Land use	Elevation (m)	Total annual rainfall (mm) Long term avg.	Year of record	Difference for year of record (%)	No of rain long term avg.
Chiang Mai	PD 241	Saturated				Aquic	Paddy	349	1,219	820	-33	122.4
	PD 242	91	77	89	22	Ustic	Dipterocarp	318				
	TS 3 √1		69	69	80	Udic	Evergreen	1,087				
	PD 243	Saturated				Aquic	Paddy	340				
Khon Kaen	PD 246	140	167	164	184	Ustic	Upland crops	165	1,257	980	-22	106.8
	PD 247	Saturated				Aquic	Paddy	179				
	PD 248	Saturated						158				
	PD 249	Saturated						163				
Nakhon Sawan	PD251	239	202	190	45	Ustic	Upland crops	3.3	1,112	1,298	+17	
Lop Buri	PD252	Saturated				Aquic	Paddy	62	1,239	1,331	+ 7	127.4
	PD253 √2	37	7	0	20	Udic	Upland crops	62				
	PD254	101	97	83	5	Ustic	Upland crops	83				
	PD255	Saturated				Aquic	Paddy	44				
	PD256	128	128	114	122	Ustic	Upland crops	47				
Bangkok	PD244	Saturated				Aquic	Paddy	1.7	1,404	1,257	-10	
	PD245	Saturated						1.7				
Pran Buri	PD257	204	206	228	327	Ustic	Lawn	8	1,031	713	-31	
Chanthaburi	PD258	151	157	97	99	Ustic	Lawn	11	2,801	2,600	- 7	172.4
	PD259	82	56	0	0	Udic	Trees	23				
Song Khla	PD260	10	0	0	0	Udic	Rubber	16	2,092	1,476	-30	160.6

√1 monthly measurement , √2 high in watertable level

PREDICTION METHOD OF SOIL MOISTURE CONDITIONS

The WES soil moisture prediction method was tested for accuracy and applicability. The soil prediction method is a system that accounts for soil moisture accretion and depletion in soil layers on a daily basis. The method is based on studies that show that accretion of soil moisture is related to rainfall and depletion of soil moisture is related to evaporation, transpiration and drainage. Daily moisture content is predicted by accreting soil moisture for each rainstorm (according to a certain pattern). The factors needed to make a prediction of soil moisture are initial moisture content, field-maximum moisture content, field-minimum moisture content, minimum-size storm, depletion relation and transition dates. The method is described in detail in USAE-WES, 1954 and 1957.

Initial Moisture Content

The measurements at the sites were used as the initial moisture contents. The starting dates of record for predictions and the measured moisture contents are summarized in Table 3.

Field-Maximum and Field-Minimum Moisture Contents

The field-maximum and field-minimum moisture contents obtained from examining the soil moisture records for the sites were summarized in Table 3.

Minimum-Size Storm

A minimum-size storm is one from which no moisture accretion or depletion in soil occurs. Its size depends principally upon the type and amount of vegetation cover. Data of minimum-size storms for the sites are tabulated in Table 3.

Accretion Relations

The amount of water taken up by a soil depends primarily upon the amount of rainfall and the amount of space in the soil available for stor-

Table 3 Summarization of initial measured moisture content, field maximum, field minimum and minimum-size storm.

PD site	Initial measured moisture content mm/10 cm			Moisture content mm/ 10 cm				Minimum-size storm (mm)
	Date of record	0-15 (cm)	15-30 (cm)	Field max. 0-15	Field max. 15-30	Field min. 0-15	Field min. 15-30	
241	4 May 64	32.8	26.5	39.7	34.2	10.3	10.2	3.8
242	16 May 64	14.3	9.8	25.8	21.2	3.0	3.2	2.5
243	4 May 64	34.7	30.2	37.6	32.8	6.7	6.8	3.8
244	1 Aug.64	51.5	50.2	51.5	50.2	23.5	27.7	3.8
246	6 May 64	22.6	18.2	23.8	23.9	2.8	3.8	3.8
247	6 May 64	17.0	23.7	27.8	20.3	5.2	8.0	2.5
248	6 May 64	24.2	23.2	35.0	30.8	4.0	2.7	3.8
251	1 Aug.64	28.0	30.8	32.7	35.0	10.0	17.0	3.8
252	1 Aug.64	32.5	40.7	44.2	48.0	21.2	33.2	3.8
253	25 Aug.64	25.0	32.0	45.0	42.7	20.5	27.8	3.8
254	1 Aug.64	26.7	30.5	33.3	36.3	13.3	21.7	2.5
255	6 June 64	30.2	31.0	37.0	37.7	12.5	14.5	3.8
256	6 June 64	42.2	38.2	43.7	33.2	16.7	21.8	3.8
257	1 May 64	7.7	5.0	20.4	19.7	1.2	2.3	2.5
258	22 July 64	46.0	42.0	47.5	43.4	23.0	24.0	5.1
259	1 Aug. 64	41.5	41.2	42.0	43.2	20.3	25.2	5.1
260	14 Aug. 64	17.0	13.2	21.8	24.3	6.7	9.0	2.5

ing the water. Accretion is divided into two classes: I and II, depending on whether rainfall is less or more, respectively, than the available storage in Fig. 5 as an example. The accretion relations derived for the 17 sites are shown in Table 4.

Depletion Relations and Transition Dates

Depletion is a moisture loss from a given soil layer for a period of no accretion. From the record of daily soil moisture contents, specific depletion curves were developed for 0-15 cm and 15-30 cm soil layers at each site. The depletion curves were constructed according to procedures outlined in USAE-WES, 1954 and 1957. Average depletion curves were developed from a family of such curves traced from the record of depletion of soil moisture versus days for periods between rains. Depletion rates were different among seasons (transition dates) and layers, requiring separate curves. Fig. 6 shows the average depletion of PD 254 and Table 5 summarizes the depletion of soil moisture within 10 and 20 days.

Comparison of Predicted and Measured Values

The specific site factors were used to predict moisture content for 17 sites. Fig. 7 shows graphically the day-by-day comparison between the predicted and actual moisture contents of PD 254 for the 15-30 cm soil layer only. Also shown on the graphs are the rainfall data. Predictions were continuous from the starting date to the termination of data collection.

The average deviations of prediction from measured moisture contents are shown in Table 6. Prediction accuracy is considered good when the average algebraic deviations approach zero and the average absolute deviations are 1.7 mm of water per 10 cm (0.1 in/6 in) soil layer or less. The average absolute and algebraic deviations are much larger than the above-stated limits due to including sites with water table. The average deviations of the well-drained site had 1.8 mm of water per 10 cm soil layer.

Table 4 Soil Moisture Accretion Relations

Site	Soil layer cm	Accretion Regression Equations	
		Class I	Class II
241	0-15	Y = 1.00 X	Y = 0.51 Z
	15-30	Y = 0.12 X	Y = 0.47 Z
242	0-15	Y = 0.22 X	Y = 0.42 Z
	15-30	Y = 0.03 X	Y = 0.57 Z
243	0-15	Y = 0.38 X	Y = 0.57 Z
	15-30	Y = 0.17 X	Y = 0.32 Z
244	0-15	Y = 0.23 X	Y = 1.00 Z
	15-30	Y = 0.21 X	Y = 0.52 Z
246	0-15	Y = 0.41 X	Y = 0.96 Z
	15-30	Y = 0.30 X	Y = 0.73 Z
247	0-15	Y = 0.34 X	Y = 0.65 Z
	15-30	Y = 0.24 X	Y - 0.78 Z
248	0-15	Y = 0.22 X	Y = 0.96 Z
	15-30	Y = 0.20 X	Y = 0.30 Z
251	0-15	Y = 0.40 X	Y = 0.86 Z
	15-30	Y = 0.13 X	Y = 0.79 Z
252	0-15	Y = 0.36 X	Y = 0.85 Z
	15-30	Y = 0.08 X	Y = 0.70 Z
253	0-15	Y = 0.30 X	Y = 0.89 Z
	15-30	Y = 0.09 X	Y = 0.48 Z
254	0-15	Y = 0.46 X	Y = 1.01 Z
	15-30	Y = 0.20 X	Y = 0.96 Z
255	0-15	Y = 0.30 X	Y = 0.84 Z
	15-30	Y = 0.20 X	Y = 0.61 Z
256	0-15	Y = 0.31 X	Y = 0.78 Z
	15-30	Y = 0.24 X	Y = 0.54 Z
257	0-15	Y = 0.24 X	Y = 0.44 Z
	15-30	Y = 0.23 X	Y = 0.73 Z
258	0-15	Y = 0.37 X	Y = 0.83 Z
	15-30	Y + 0.12 X	Y = 0.64 Z

Y = estimated accretion, mm of water per 10 cm soil layer.
X = rainfall, mm.
Z = available storage at start of storm; mm per 10 cm soil layer.

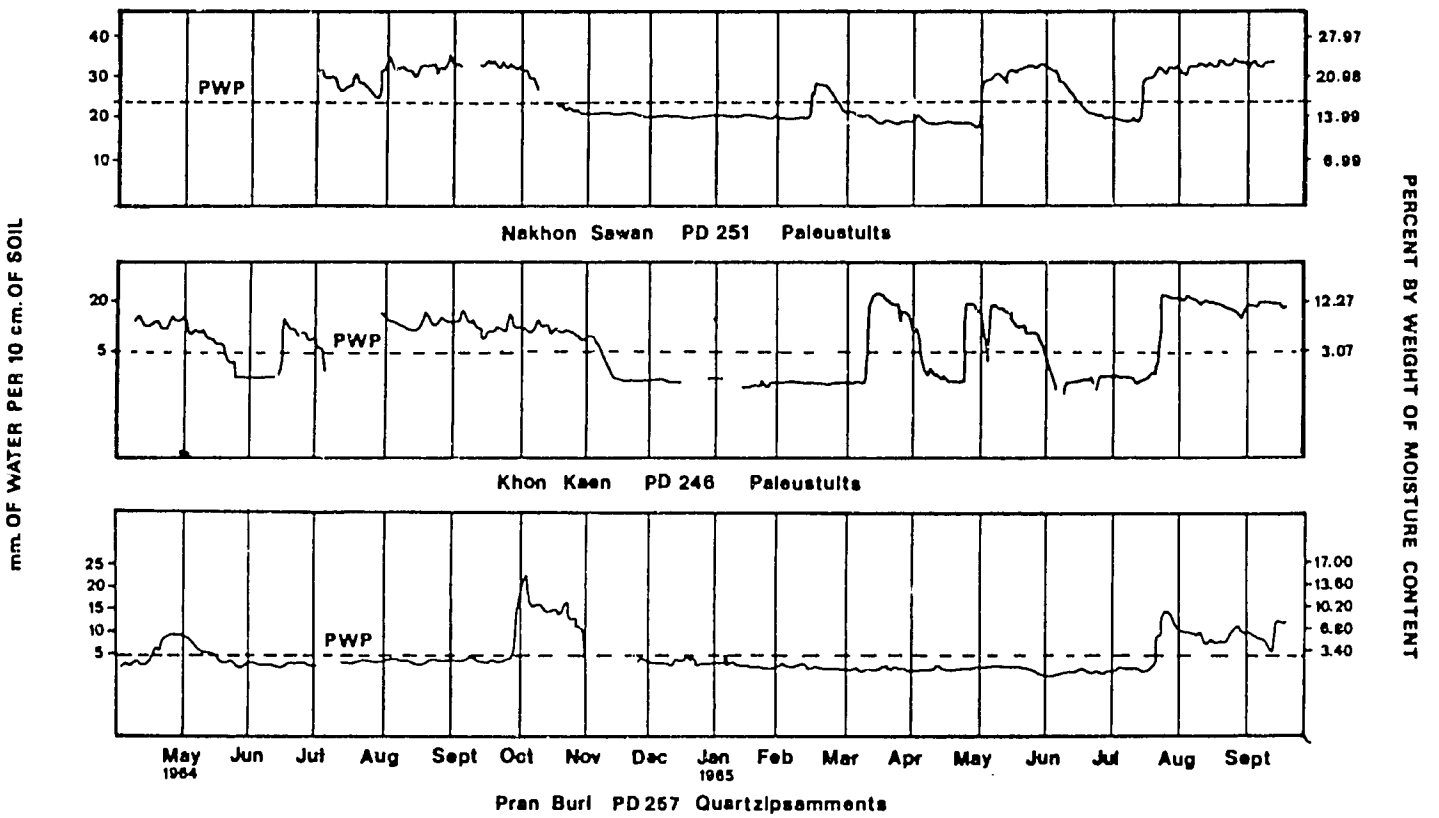
Table . 5.. Soil moisture depletion loss within 10 and 20 days (moisture content in mm/10-cm soil layer)

PD site	Summer				Winter			
	Depletion loss 10-day		Depletion loss 20-day		Depletion loss 10-day		Depletion loss 20-day	
	0-15	15-30	0-15	15-30	0-15	15-30	0-15	15-30
241	8.7	8.0	26.3	17.7	7.2	7.2	17.7	15.3
242	10.0	2.3	20.0	3.7	7.7	2.4	15.2	3.7
243	16.5	9.8	25.8	17.0	8.2	6.0	13.0	10.7
244	18.2	8.2	25.7	21.0	12.3	6.0	20.0	11.2
246	15.3	10.2	19.8	19.2	7.7	6.0	17.3	11.3
247	3.5	8.16	17.7	15.0	3.5	2.0	10.3	7.2
248	5.7	4.8	8.3	9.7	5.7	3.3	9.7	7.2
251	11.8	8.0	18.7	14.3	9.8	8.0	14.7	13.2
252	12.2	8.2	18.8	12.8	7.7	7.5	13.2	10.0
253	15.0	4.3	18.8	12.8	7.3	3.7	10.8	5.2
254	10.5	6.3	19.2	9.3	6.3	3.0	11.5	7.8
255	8.5	4.2	14.7	11.7	6.0	3.0	12.3	5.7
256	13.5	4.8	18.5	8.5	7.7	3.8	13.2	7.7
257	12.7	5.2	18.3	12.0	9.0	4.8	17.2	10.2
258	22.7	11.2	24.0	16.2	20.7	8.5	23.5	13.2
259	12.5	6.3	20.8	11.2	10.7	5.8	15.5	10.3
260	5.2	3.3	13.5	6.0	5.0	2.3	10.7	4.7

Table 6. Soil moisture deviations (mm/10 cm layer).

Site No.	No. of Measurements	0-15 cm Layer		15-30 cm Layer	
		Absolute	Algebraic	Absolute	Algebraic
241	485	4.50	-0.50	7.00	-7.00
242	474	4.17	-3.50	3.67	-3.50
243	491	8.00	-7.50	5.83	-5.83
244	392	10.50	-10.17	11.00	-11.00
246	491	2.83	-1.33	2.67	-2.00
247	491	4.00	-0.50	4.50	-4.33
248	489	5.33	-1.67	4.00	-2.83
251	424	1.50	-0.33	1.00	+0.17
252	441	1.33	-0.17	1.33	+0.17
253	415	1.67	-0.50	1.17	+0.17
254	419	1.50	+0.50	1.17	-0.17
255	496	1.83	-0.33	1.83	-1.33
256	495	2.50	-0.67	1.17	-0.50
257	497	1.67	-0.83	1.00	+0.17
258	429	3.00	-2.17	2.00	-1.17
259	416	2.00	-1.17	0.83	-0.50
260	380	3.00	-1.33	2.33	-1.67
	Average	3.50	-1.83	3.17	-2.50

FIGURE 2 DISTRIBUTION OF MOISTURE CONTENTS AT DEPTH 30-37.5 cm. OF USTIC MOISTURE REGIME



PWP = Permanent Wilting Point

FIGURE 3 DISTRIBUTION OF MOISTURE CONTENTS OF SOME PADDY SOILS. (30–37.5 cm)

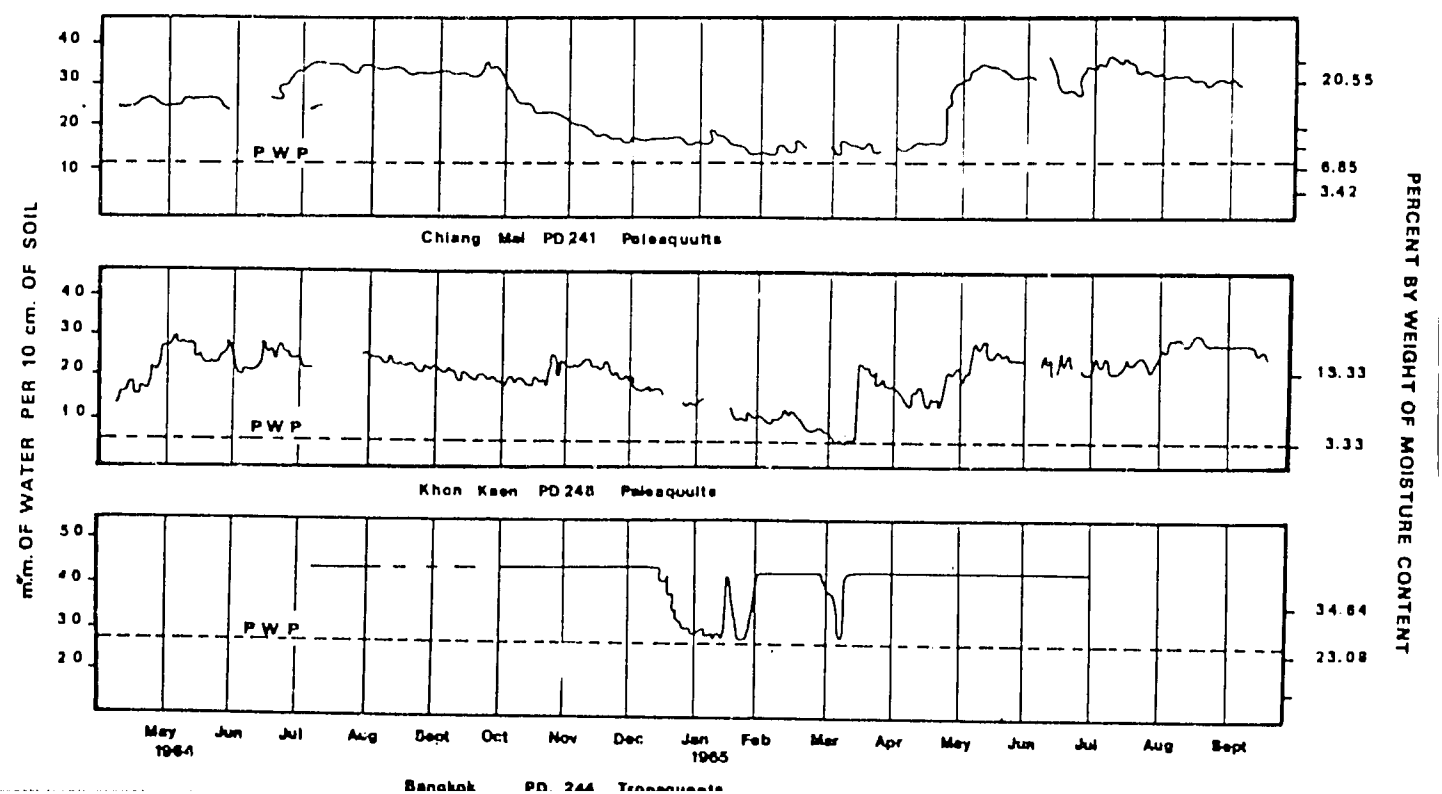


FIGURE 4 DISTRIBUTION OF MOISTURE CONTENTS AT DEPTH 15-22.5 AND 22.5-30 cm OF UDIC MOISTURE REGIME

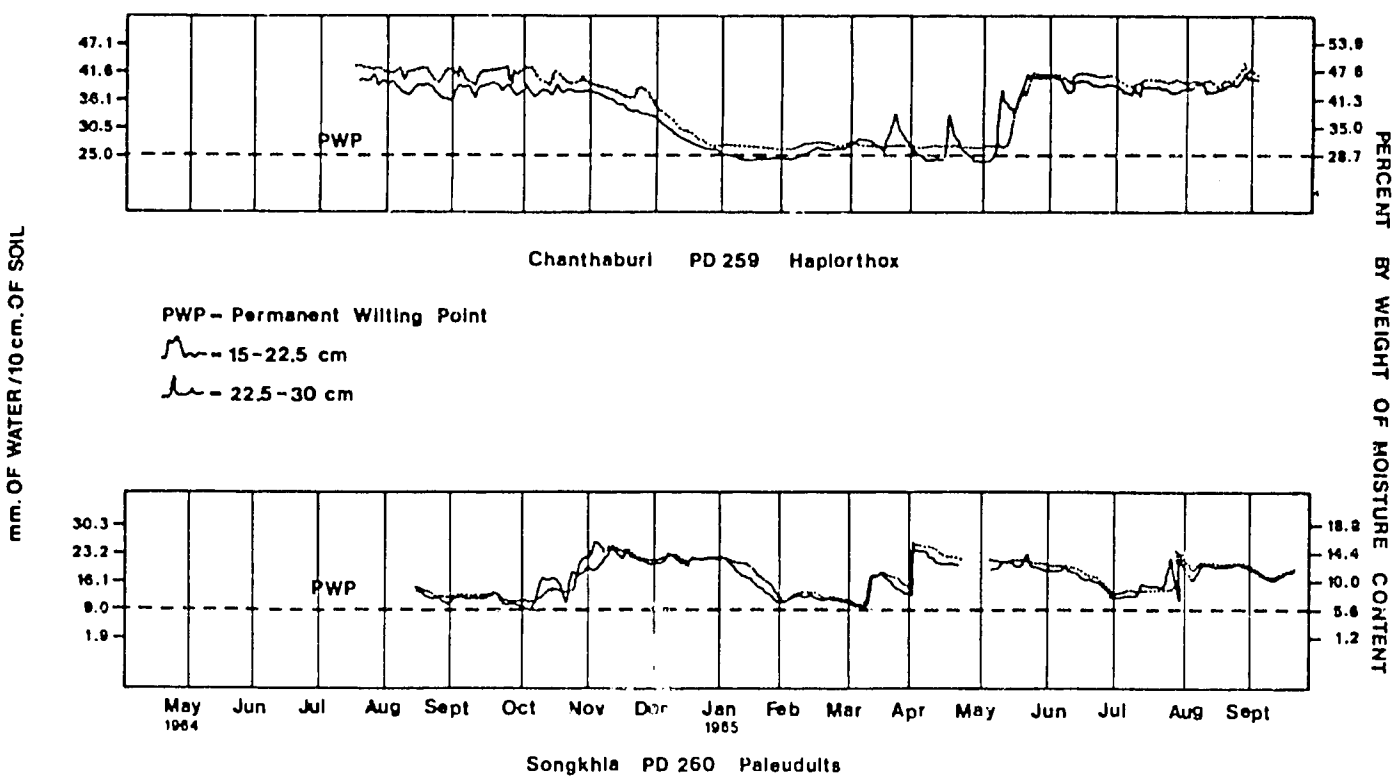
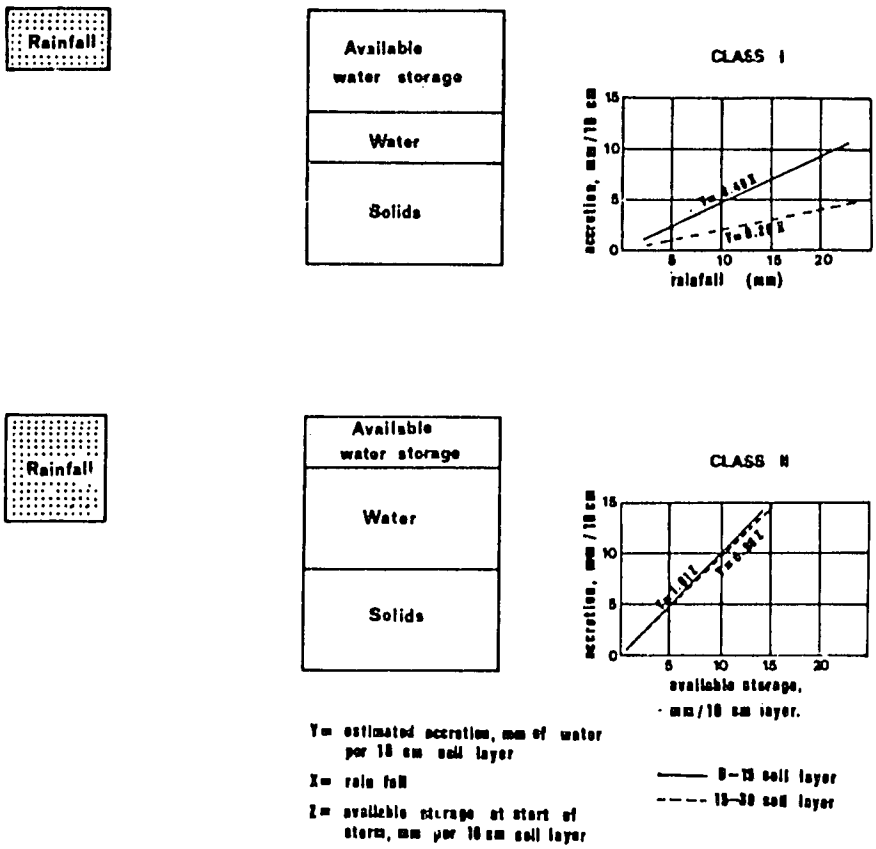


Figure 5 Accretion Relation of PD 254



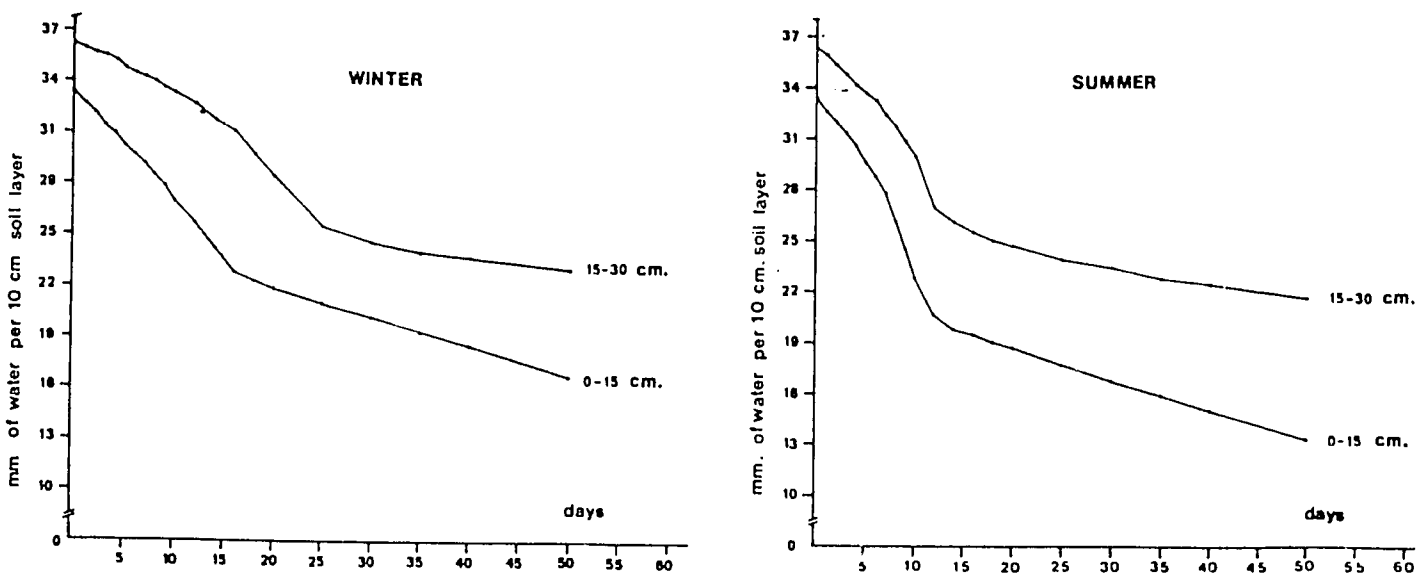


FIG. 6 : SOIL MOISTURE DEPLETION CURVES OF PD 254

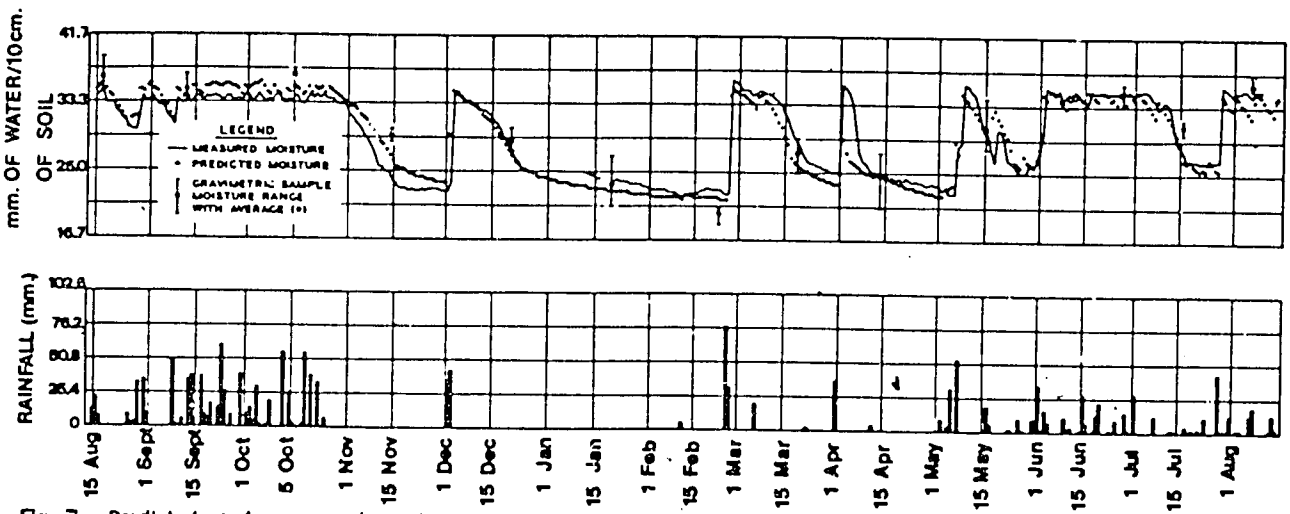


Fig. 7 Predicted and measured soil moisture conditions of PD 254, Lop Buri, Clayer, Paleustults

CONCLUSION

Based on the daily records of soil moisture regimes from 17 sites of eight selected areas in Thailand, and other relevant data that was compiled in this report, the following conclusions can be made:

a. Five soil moisture regimes are recognized in Thailand: namely aquic, ustic, udic, perudic, and peraquic moisture regimes. The distribution of each moisture regime is shown in the map.

b. Specific soil moisture-prediction relations were derived for 17 Thailand sites and tested for accuracy and applicability by predicting and measuring moisture contents for the periods of record. The average deviation between predicted and measured values in the depths 0-15 and 15-30 cm of well-drained sites give fairly good results.

The prediction method is thus likely to apply for Thailand. However, more average prediction relations should be developed from many sets of specific relations derived from correlations between soil properties and other site factors. The average prediction values from 17 sites are considered to be used in the improvement of the soil moisture regime map and the agroclimatic program of Thailand.

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DISCUSSION

Q. F.R. Moormann: Do you have soils with a peraquic soil moisture regime?

A. L. Moncharoen: Yes, this moisture regime occurs in the mangrove areas along the central coastal plain and in the boggy areas in the south of Thailand.

SOIL CLIMATE REGIMES IN CAMEROON AND THEIR RELATION TO AIR CLIMATE

J. Embrechts

ABSTRACT

The soil temperature regimes in Cameroon were determined by means of the relationship between the mean annual air temperature (MAAT) and the mean annual soil temperature (MAST) and their seasonal fluctuations. In the normal range of MAAT in Cameroon (20-30 degrees C) it was found that the MAST is 2.3 to 2.6 degrees C higher than the MAAT.

The difference between mean summer soil temperature (MSST) and mean winter soil temperature (MWST) being always less than 5 degrees C, only isotemperature regimes occur in Cameroon. The MAST decreases by 0.46 degrees C per 100 m increase in altitude. Isohyperthermic temperature regimes are predominant in Cameroon. Isothermic regimes occur above 1,600 m altitude, and isomesic regimes are present probably above 3,120 m altitude in the Cameroon mountains.

A map with the soil temperature regimes of Cameroon has been drawn.

The soil moisture regime of 200 meteorological stations in Cameroon has been calculated by means of Newhall's method. In certain climatological conditions the calculated soil moisture regime does not correspond to what can be deduced from natural vegetation. This may be attributed partly to the use of the evapotranspiration calculated according to Thornthwaite. In areas around 700 m in the southern part of the country the Newhall method gives results in agreement with the natural vegetation. Moreover in this area the values of the calculated Thornthwaite and the calculated Penman evapotranspirations practically coincide. On lower altitudes the evapotranspiration according to Thornthwaite is higher than the Penman evapotranspiration; on higher elevation Penman gives higher values. For this reason the evapotranspiration according to Thornthwaite has been adap-

ted as a function of the elevation. The limit between udic and ustic soil moisture regimes, obtained this way, broadly coincides with the present limit between the forest and the post-forest savannah.

A map with the soil moisture regimes of Cameroon has been drawn, taking into account the corrections that are to be made in the soil moisture regimes calculated with Newhall's mathematical model and also taking into account the presence of aquic and peraquic regimes.

RESUME

Les régimes de température du sol au Cameroun ont été déterminés à partir de relations entre la température moyenne annuelle de l'air (MAAT) et la température moyenne annuelle du sol (MAST) et leurs fluctuations saisonnières. On a trouvé que dans l'interval des MAAT au Cameroun (20-30 degrees C) la MAST est de 2.3 à 2.6 degrees C plus élevés que la MAAT. La différence entre les températures moyennes du sol en été (MSST) et en hiver (MWST) étant partout inférieure à 5 degrees seul les iso-régimes de température existent au Cameroun.

La MAST diminue en joyenne avec 0.46 degrees C par 100 m d'altitude. Le régime de température isohyperthermique est prédominant au Cameroun. Le régime isothermique apparaît à partir de 1,600 m d'altitude, tandis que le régime isomésique est vraisemblablement présent sur le Mont Cameroun au delà de 3,120 m.

Le calcul du régime hydrique du sol de 200 stations météorologiques au Cameroun a été effectué. Dans certaines conditions climatiques le régime hydrique calculé ne correspond guère avec la végétation naturelle. Ceci peut être attribué entre autres à l'utilisation de l'évapotranspiration d'après Thornthwaite. Dans les régions autour de 700 m d'altitude dans le sud du pays la méthode de Newhall donne des résultats qui correspondent avec la végétation naturelle. D'ailleurs à cette altitude les valeurs des évapotranspirations calculées d'après Thornthwaite et d'après Penman coïncident pratiquement. A moindre altitude l'évapotranspiration calculée d après Thornthwaite est plus élevée que l'évapotranspiration cal-

culée d'après Penman, à des altitudes supérieures à 700 m, la méthode Penman donne des valeurs plus élevées. Pour cette raison l'évapotranspiration selon Thornthwaite a été adaptée en fonction de l'altitude. La limite entre les régimes hydriques udiques et ustiques, obtenue de cette manière correspond en grande partie avec la limite actuelle entre la forêt et la savanne post-forestière.

La carte (Fig. 5) donne les régimes hydriques des sols au Cameroun, déterminés en tenant compte des évapotranspirations corrigées en fonction de l'altitude, et completée avec l'extension des régimes aquiques et peraquiques.

INTRODUCTION

In Cameroon long-term measurements of soil temperature and soil moisture are few. For this reason it is necessary to relate soil temperature and soil moisture to meteorological records. A model of soil moisture accretion and depletion has been developed by F. Newhall; for this model only the mean monthly air temperature and the mean monthly precipitation are required. A program in Fortran IV has been developed by Tavernier and Van Wambeke (1976) to calculate the soil moisture regimes using the Newhall model.

SOIL TEMPERATURE REGIMES

Relationships Between Air and Soil Temperatures

In Cameroon mean monthly soil temperatures (MMST) at 50 cm depth together with mean monthly air temperature (MMAT) have been registered for the years 1976, 1977 and 1978 for 15 meteorological stations (Ministry of Transports and Telecommunications, 1976, 1977 and 1978). Table 1 gives the location of those stations, the MAAT and the MAST, the difference MAST-MAAT, the mean summer air temperature (MSAT), the mean winter air temperature (MWAT), the difference MSAT-MWAT, the mean summer soil temperature (MSST), the mean winter soil temperature (MWST) and the difference MSST-MWST.

Table 1. Location, mean annual air and soil temperature and their difference, seasonal fluctuations of air and soil temperature, the differences between mean summer and mean winter air temperature and between mean summer and mean winter soil temperature (degrees C), for the years 1976, 1977, & 1978.

Station	Geographic location			Mean air and soil temperature			Seasonal air temperature			Seasonal soil temperature		
	Lat. N	Long. E	Alt. (m)	MAAT	MAST	MAST-MAAT	MSAT	MWAT	MSAT-MWAT	MSST	MWST	MSST-MWST
Ambam	2°23'	11°17'	602	24.0	26.8	2.8	23.1	24.5	-1.4	26.3	26.9	-0.6
Yaounde	3°52'	11°32'	753	23.8	26.5	2.7	22.7	24.4	-1.7	25.7	26.5	-0.8
Douala	4°01'	9°44'	5	26.6	28.6	2.0	25.2	27.5	-2.3	26.9	29.7	-2.8
Batouri	4°25'	14°24'	650	24.2	26.5	2.3	23.3	24.1	-0.8	25.7	26.1	-0.4
Yabassi	4°28'	9°59'	40	26.7	29.0	2.3	25.1	27.8	-2.7	27.3	30.4	-3.1
Yoko	5°33'	12°22'	1027	22.8	25.2	2.4	21.2	24.2	-3.0	24.0	25.9	-1.9
Betare-Oya	5°36'	14°04'	815	23.8	26.9	3.1	22.5	24.6	-2.1	25.9	27.3	-1.4
Koundja	5°37'	10°45'	1208	21.6	23.0	1.4	20.5	22.1	-1.6	23.3	22.0	+1.3
Mamfé	5°43'	9°17'	126	26.3	28.2	1.9	25.5	26.1	-0.6	27.4	28.3	-0.9
Bamenda	5°58'	10°09'	1608	19.5	21.5	2.0	18.4	20.2	-1.8	21.3	21.4	-0.1
Meiganga	6°32'	14°22'	1027	23.0	25.7	2.7	22.0	23.1	-1.1	24.8	25.6	-0.8
Banyo	6°47'	11°49'	1110	22.9	26.3	3.4	21.9	23.3	-1.4	25.1	26.6	-1.5
Ngaoundéré	7°17'	13°19'	1115	21.9	24.3	2.4	21.6	20.7	+0.9	23.6	23.6	0.0
Garoua	9°20'	13°23'	241	28.3	32.4	4.1	27.4	27.0	+0.4	31.7	30.6	+1.1
Maroua	10°28'	14°16'	423	27.8	28.8	1.0	26.6	25.8	+0.8	29.0	26.6	+2.4

The following relationship between the MAST and the MAAT has been calculated (Fig. 1).

$$MAST = 1.02355\ MAAT + 1.86783 \quad (1)$$

$r = 0.95723 \qquad n = 15$

The relationship is significant at the 0.1% probability level. By means of this relationship it is possible to calculate the MAST of stations where only the MAAT is known.

The MAAT in Cameroon, except for high mountain areas, varies between 20 and 30 degrees C (Table 1). For this range in air temperature the difference MAST-MAAT varies from 2.3 degrees to 2.6 degrees C as may be calculated from the previous equation.

In Cameroon the MWAT is usually higher than the MSAT, the winter being the season with less rainfall. Soil temperature regimes with a MSST-MWST of less than 5 degrees C are indicated by the prefix "iso-". All stations in Cameroon have a MSST-MWST of less than 5 degrees C, as may be seen in Table 1.

Mean monthly and annual air temperatures over long periods are known for 41 meteorological stations in Cameroon. For those stations the altitude and the corresponding MAAT is given in Table 2. The relationship between the MAAT and the altitude may be calculated. Data from some stations have been excluded from the regression because their air temperature is substantially below or above the general trend. For some stations the reason for this difference apparently is their topographic position immediately below an escarpment (Bali, Bambui) or at the foot of a slope (Ekona). Three other stations show geographic and climatic similarities: Maroua-Salak, Kaélé and Garoua; those are the only ones situated North of 9 degrees N in Soudanean and Soudano-Sahalean climates. The following relationship has been calculated (Fig. 2):

$$MAAT = -0.00450\ Alt. + 26.84674 \quad (2)$$

$r = -0.97169 \qquad n = 35$

The relationship is significant at the 0.1% probability level. This means that there is a negative gradient of the MAAT of 0.45 degrees C per 100 m increase in altitude. For meteorological stations where only precipitation has been recorded over a long period, air temperature data have been adapted from the nearest climatological station, taking into account

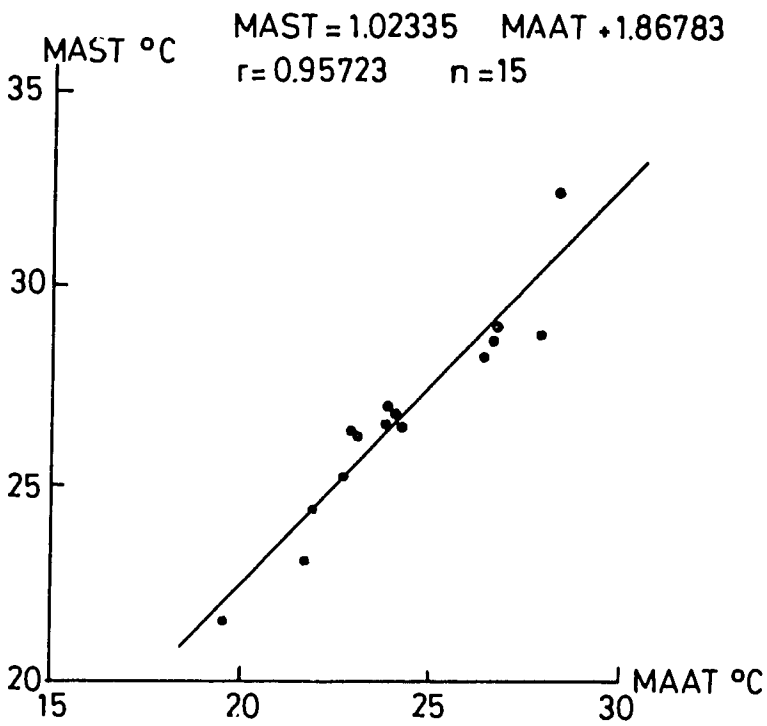

Fig. 1_ Relation between MAAT and MAST

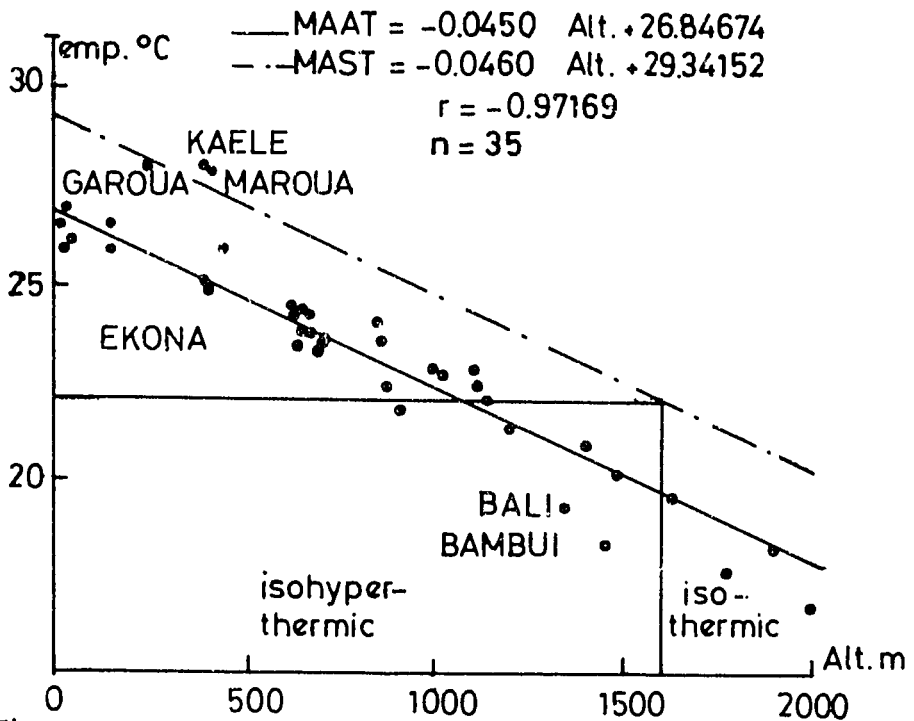

Fig. 2 - Relation between MAAT and altitude and between MAST and altitude.

Limit between isohyperthermic and isothermic temperature regimes.

the temperature lapse rate of 0.45 degrees C per 100 m increase with height given by equation (2).

In the aggregate the MAAT of 200 stations has been calculated, based on the temperature records of the 41 stations given in Table 2. The geographical location, mean annual rainfall and estimated MAAT of the 200 meteorological stations concerned are listed by Embrechts and Tavernier (1981).

Relationship Between MAST and Altitude

From equations (1) and (2) we may easily calculate the equation giving MAST as a function of altitude (Fig. 2):

$$MAST = -0.00460\ Alt = 29.34152 \qquad (3)$$

This equation sets the limit between the isohyperthermic and the isothermic regimes (22 degrees C) at an altitude of 1,600 m.

Assuming the same relation between MAST and altitude, the isomesic regime fixed at a MAST of 15 degrees C would be at 3,120 m.

The Soil Temperature Regime Map

Fig. 3 shows the distribution of soil temperature regimes in Cameroon. Isohyperthermic regimes are largely predominant. Isothermic regimes occur on the slopes and high plateaus in the western part of the country. An isomesic soil temperature is likely to occur on the Cameroon mountain above 3,120 m.

SOIL MOISTURE REGIMES

The Calculation of the Soil Moisture Regimes

For Cameroon the soil moisture regimes of 200 major and minor meteorological stations has been calculated. The MAAT of stations where only precipitation data are available has been obtained using relationship (2) between the MAAT and the altitude. The same procedure has been followed for the calculation of the MMAT but only if the pluviometric regimes of the stations were comparable.

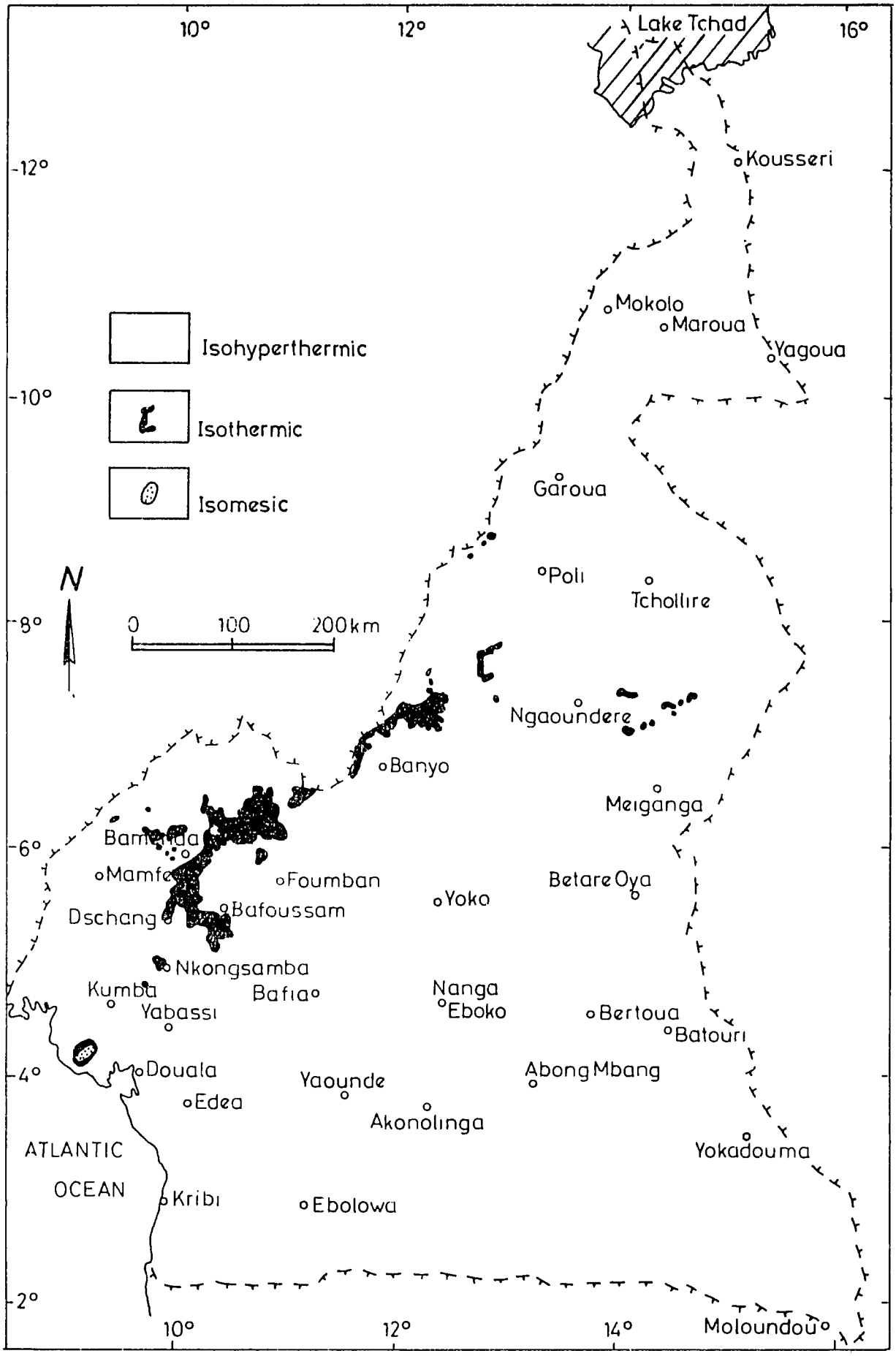

Fig. 3

Soil temperature regimes of Cameroon

Table 2. Altitude and MAAT for 41 stations in Cameroon[a]

Station	Alt (m)	MAAT (°C)	Station	Alt (m)	MAAT (°C)
Douala	13	26.4	Sangmelima	704	23.5
Kribi	19	25.8	Yaounde	760	23.4
Edea	32	26.9	Betare-Oya	804	23.5
Tiko	45	26.1	Ngambe	850	23.9
Barombi-Nkang	146	25.8	Tibati	867	23.5
Mamfé	152	26.5	Nkongsamba	877	22.3
Garoua	249	28.0	Ntem	914	21.7
Kaélé	387	27.9	Meiganga	1000	22.8
Bafia	398	25.1	Yoko	1031	22.7
Eseka	399	25.0	Banyo	1110	22.7
Maroua-Salak	404	27.8	Ngaoundéré	1119	22.3
Ekona	420	23.6	Babungo	1152	21.8
Poli	436	25.8	Koundja	1217	21.3
Nanga-Eboko	624	24.3	Bali	1341	19.2
Ebolowa	628	24.1	Dschang	1398	20.8
Yokadouma	640	24.2	Bafoussam	1450	20.1
Lomie	644	23.4	Bambui	1463	18.3
Batouri	655	23.8	Bamenda	1618	19.5
Akonolinga	670	24.1	Jakiri	1767	17.5
Bertoua	671	23.7	Santa	1890	18.2
Abong-Mbang	689	23.3			

[a]Slight differences in geographical situation and/or altitude for the same station in this table and in the previous one are due to divergent data given in different publications.

Suchel (1972) worked out a classification of pluviometric regimes in Cameroon based on rainfall distribution and total annual rainfall. Stations situated in the same pluviometric regime according to Suchel have approximately the same yearly distribution of sunshine and rainfall and thus similar patterns of MMAT.

Three soil moisture regimes have been recognized: perudic, udic and ustic. In addition aquic and peraquic regimes occur in valleys, floodplains and alluvial basins. The latter are defined by fluctuations of the groundwater table and are not calculated by means of the Newhall model.

Discussion of the Calculated Soil Moisture Regimes

Table 3 gives for the main stations the calculated soil moisture regime and the type of natural vegetation.

When the calculated soil moisture regimes for 200 meteorological stations are plotted on a map it becomes clear that the limit between udic and ustic soil moisture regimes corresponds fairly well with the actual boundary between dense forest and savannah in the zone of medium altitude (700 m) (Letouzey, 1959) However in the East (Table 3: Batouri, Bertoua) the udic-ustic limit is situated somewhat more to the north than the forest-savannah boundary. This may be explained by the large surfaces in that area covered by lateritic gravel or continuous ironstone. Those create poor physical conditions in the soil that prevent the return of a forest vegetation.

Other discrepancies are found in the coastal region and in the West and Northwest Provinces.

In the low altitude zone near the coast, characterised by a monsoon climate with high to extremely high rainfall, a constantly high air humidity and a relatively short dry season, ustic moisture regimes have been obtained for stations situated between 3°46' and 4°22' latitude N, and between 9°13' and 10°04' longitude E (Table 3: Edea, Tiko). The natural vegetation is an evergreen rainforest.

On the high plateaus in the western part of the country between 5°30' and 7° latitude the reverse is happening. The climate is still of a monsoon type but with a longer dry season. The present vegetation is anthropic mountain grassland. In this region udic regimes have been calculated

Table 3. Calculated soil moisture regimes for the principal meteorological stations in Cameroon arranged according to natural vegetation.[a]

Vegetation	Station	Geographic location Lat. N	Long. E	Alt (m)	Calculated soil moisture regime
Mangrove and evergreen rainforest	Douala	4°01'	9°44'	5	udic
Evergreen rainforest	Kribi	2°57'	9°54'	10	udic
	Eseka	3°37'	10°44'	398	udic
	Edea	3°46'	10°04'	31	ustic
	Tiko	4°05'	9°22'	58	ustic
	Ngambe	4°16'	10°36'	610	udic
	Nkongsamba	4°57'	9°56'	816	udic
Transition evergreen rainforest and semi-deciduous forest	Ambam	2°23'	11°17'	602	udic
	Ebolowa	2°51'	11°11'	628	udic
	Sangmelima	2°56'	11°57'	712	udic
	Mamfé	5°43'	9°17'	126	udic
Semi-deciduous forest	Lomié	3°09'	13°37'	624	udic
	Yokadouma	3°31'	15°06'	634	udic
	Nanga-Eboko	4°39'	12°24'	622	udic
	Akonolinga	3°46'	12°14'	671	udic
	Yaoundé	3°52'	11°32'	753	udic
	Abong-Mbang	3°58	13°12'	693	udic
Soudano-guinean postforest zone	Batouri	4°25'	14°24'	650	udic
	Bertoua	4°36'	13°44'	668	udic
	Bafia	4°44'	11°15'	500	ustic
	Betare-Oya	5°36'	14°04'	815	ustic
	Tibati	6°29'	12°36'	873	ustic
Soudano-guinean savanna	Yoko	5°33'	12°22'	1027	ustic
	Meiganga	6°32'	14°22'	1027	ustic
	Banyo	6°47'	11°49'	1110	ustic
	Ngaoundere	7°17'	13°15'	1115	ustic
	Poli	8°29'	13°15'	436	ustic

Table 3 (cont'd)

Vegetation	Station	Geographic location Lat. N	Long. E	Alt (m)	Calculated soil moisture regime
Soudanean savannah	Garoua	9°20'	13°23'	241	ustic
Sahelean steppes	Kaélé	10°85'	14°27'	389	ustic
	Maroua	10°28'	14°16'	423	ustic
Mountain groupings	Dschang	5°20'	10°03'	1407	udic
	Koundja	5°37'	10°05'	1200	udic
	Bamenda	5°58'	10°09'	1608	udic

[a]See footnote Table 2.

(Table 3: Bamenda, Koundja, Dschang).

It is assumed that these differences are due to the use of the potential evapotranspiration calculated according to Thornthwaite.

The Penman method is generally considered to be more accurate. The problem with that method, is that more climatic parameters need to be known. In places where sufficient information was available both methods were compared. A good relationship between altitude and the ratio of annual Thornthwaite and Penman evapotranspiration has been found (Table 4 and Fig. 4).

The general relationship is not valid for Kaélé and Maroua (Soudano-Sahelean climates). This is probably due to the very long dry season, the high maximum temperatures, and the importance of the Harmattan winds which cause high saturation deficits of the air during long periods.

The regression is:

$$Alt = 3,229 - 2,528 \frac{Th}{Pe} \qquad (4)$$

$r = -0.96802 \qquad n = 19$

This relationship is significant at the 0.1% probability level.

The annual evapotranspirations according to Thornthwaite and Penman are equal at an altitude of about 700 m, as can be calculated from equation (4).

From regression (4) annual Penman evapotranspiration may be calculated as a function of Thornthwaite evapotranspiration and of altitude in the

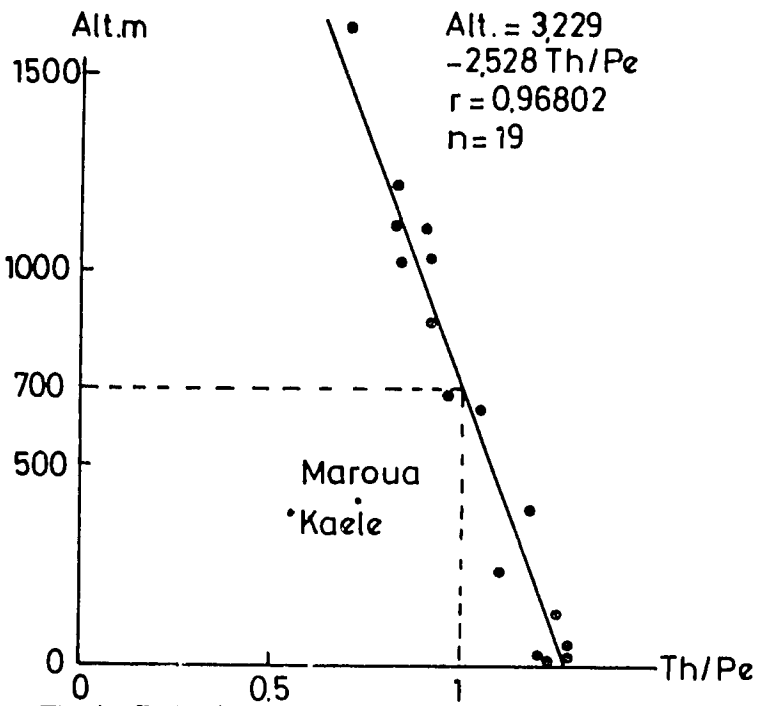

Fig.4 - Relation between altitude and the ratio of Thornthwaite (Th) to Penman (Pe) evapotranspiration

Table 4. Altitude, geographical location, annual evapotranspiration according to Thornthwaite (Th) and to Penman (Pe), Th/Pe and $\frac{(Th/Pe)w}{Th/Pe}$ for 21 stations in Cameroon during 1977.[a]

Station	Alt. (m)	Lat. N	Long. E	Th (mm)	Pe (mm)	Th/Pe	$\frac{(Th/Pe)w}{Th/Pe}$
Douala	13	4°01'	9°44'	1607	1302	1.23	1
Kribi	19	2°57'	9°54'	1740	1441	1.21	1.05
Edéa	32	3°48'	10°04'	1666	1302	1.28	0.96
Tiko	50	4°05'	9°22'	1621	1266	1.28	0.94
Mamfé	126	5°43'	9°17'	1612	1289	1.25	0.94
Garoua	241	9°10'	13°23'	1797	1618	1.11	1.03
Kaélé	389	10°05'	14°27'	1794	2984	0.60	0.75
Eséka	399	3°37'	10°44'	1598	1350	1.18	0.98
Maroua	423	10°28'	14°16'	1717	2141	0.80	0.71
Bafia	498	4°44'	11°15'	1419	1250	1.14	0.90
Ngambé	650	4°16'	10°36'	1293	1240	1.04	0.96
Bertoua	691	4°36'	13°44'	1253	1294	0.97	0.92
Yaoundé	753	3°52'	11°32'	1242	1271	0.98	1.04
Betare-Oya	815	5°36'	14°04'	1261	1460	0.86	0.94
Tibati	873	6°29'	12°36'	1260	1385	0.91	0.84
Yoko	1027	5°33	12°22'	1147	1389	0.83	0.83
Meiganga	1027	6°32'	14°22'	1187	1302	0.91	0.87
Banyo	1110	6°47'	11°49'	1164	1309	0.89	0.84
Ngaoundéré	1115	7°17'	13°19'	1044	1280	0.82	0.79
Koundja	1217	5°37'	10°05'	1055	1281	0.82	0.93
Bamenda	1618	5°58'	10°09'	884	1268	0.70	0.93

[a]See footnote Table 2.

range of 0 to 1,600 m above sea level. The transformed equation is:

$$\text{Adapted Thornthwaite (Ad.Th.)} = \frac{2,528}{3,229-\text{Alt}} \times \text{Th} \qquad (5)$$

Depending on the season, and on the type of climate, the ratios between the monthly Thornthwaite and Penman evapotranspiration are higher or lower than the annual average. This is shown by the last column of Table 4 where the ratio of Th/Pe for the winter months December, January and February (dry season) to annual Th/Pe is calculated.

From Tables 4 and 5, it becomes also evident that:

- the ratio of monthly evapotranspirations are lower than the annual average during the dry season, except for the coastal monsoon climate where the minimum ratio occurs somewhat later.
- the length of the period during which the monthly Th/Pe values are below the annual average, as well as the importance of the seasonal fluctuations, are negligible in the South (Bertoua), but tend to become more important towards the North (Ngaoundéré).

In Cameroon the regions at about 700 m altitude are situated in the southern part of the country, where not only is the annual Th/Pe ratio approximately 1, but also the monthly differences between the evapotranspiration calculated according to Thornthwaite and to Penman are negligible (Table 5: Bertoua).

In the monsoon climates at low altitude (Douala, Tiko, Edéa) located in the proximity of the ocean, the average humidity of the air is high even during the dry season; moreover the difference between daily maximum and minimum temperature is small. The calculated Thornthwaite evapotranspiration is higher than the Penman evapotranspiration (Fig. 4). Consequently the length of the dry period in these places is overestimated in applying Thornthwaite.

Since the fluctuation of the monthly Th/Pe ratio is low with regard to the yearly Th/Pe ratio (Table 5: Douala) the estimated Penman evapotranspiration from the calculated Thornthwaite evapotranspiration by formula (5) is likely to be reliable. By using the estimated Penman evapotranspiration (called adapted Thornthwaite evapotranspiration) in the Newhall method, the calculated soil moisture regime of the monsoon climate at low altitudes becomes dominantly udic except for seven stations situated at the lower eastern footslopes of Mount Cameroon.

In monsoon climates at altitudes above 1,200 m (Bamenda, Koundja, Bafoussam, Dschang), where the difference between the daily maximum and minimum temperatures is much greater than in the coastal plain (low altitude monsoon climate), the annual Thornthwaite evapotranspiration is less than the annual Penman evapotranspiration (Fig. 4). The period during which the monthly Th/Pe ratio is lower than the annual average is longer, but the divergences are not very important (Table 5: Bamenda). Therefore

Table 5. Monthly Thornthwaite (Th) and Penman (Pe) evapotranspiration, ratio Th/Pe, adapted Thornthwaite (Ad.Th) and rainfall (R) of some typical stations in various climates, for the year 1977.

1. Monsoon climates of the coastal regions

Douala: 4°04'N 9°41'E 13 m[a]

	J	F	M	A	M	J	J	A	S	O	N	D	Annual
Th	143.6	132.8	135.5	141.6	127.6	103.6	108.3	126.4	126.4	137.1	147.4	156.1	1606.9
Pe	108.8	116.8	132.4	119.1	117.8	95.1	79.4	87.7	96.0	112.2	110.7	125.6	1301.6
Th/Pe	1.32	1.14	1.17	1.19	1.08	1.09	1.36	1.44	1.32	1.22	1.33	1.24	1.23
Ad.Th	112.9	104.4	122.2	111.3	100.3	81.4	85.1	99.3	99.7	107.7	115.9	122.7	1262.9
R	10.9	13.2	147.0	280.3	329.7	380.0	872.9	784.9	461.7	196.3	45.8	32.2	3554.9

2. Monsoon climates of the western mountains

Bamenda: 5°56'N 10°09'E 1618 m[a]

	J	F	M	A	M	J	J	A	S	O	N	D	Annual
Th	72.8	75.2	91.8	82.4	80.6	67.4	64.8	63.5	66.1	67.4	74.5	77.5	884.0
Pe	113.8	132.4	151.0	114.9	108.5	88.5	78.7	84.9	82.5	100.8	113.1	113.4	1282.5
Th/Pe	0.64	0.57	0.61	0.72	0.74	0.76	0.72	0.75	0.80	0.67	0.66	0.68	0.69
Ad.Th	114.1	117.8	143.9	129.1	126.3	105.6	101.6	99.5	103.6	105.6	116.8	121.5	1385.4
R	9.7	1.8	17.9	206.2	243.7	241.5	571.2	338.6	437.2	142.0	0	0	2209.8

3. Subequatorial continental climate

Bertoua: 4°36'N 13°44'E 691 m[a]

	J	F	M	A	M	J	J	A	S	O	N	D	Annual
Th	90.1	105.5	134.4	128.6	120.0	99.5	77.6	98.9	102.6	106.0	101.9	87.8	1252.9
Pe	107.0	112.3	136.1	124.8	120.0	99.0	93.5	99.5	93.0	104.8	103.8	98.9	1293.7
Th/Pe	0.84	0.94	0.91	1.03	1.00	1.01	0.83	0.99	1.10	1.01	0.98	0.89	0.97
Ad.Th	89.7	105.1	133.9	128.1	119.5	99.1	77.3	98.5	102.2	105.6	101.5	87.5	1218.0
R	15.8	1.4	87.2	137.3	191.1	103.9	97.4	115.4	286.5	220.5	111.9	40.5	1389.3

4. Soudanian mountain climate

Ngaoundéré: 7°17'N 13°19'E 1115 m[a]

	J	F	M	A	M	J	J	A	S	O	N	D	Annual
Th	70.1	72.0	104.1	122.6	105.9	91.1	87.7	84.9	87.6	87.5	66.3	64.4	1044.2
Pe	103.9	112.8	137.0	119.4	116.6	109.8	85.9	91.8	93.9	101.7	104.7	102.3	1279.8
Th/Pe	0.67	0.64	0.76	0.94	0.91	0.83	1.02	0.92	0.93	0.36	0.63	0.63	0.79
Ad.Th	83.8	86.1	124.5	142.8	126.6	108.9	104.9	101.5	104.8	104.6	79.3	77.0	1244.8
R	0	0	0	31.5	145.9	288.2	340.5	260.7	210.1	80.2	0	0	1357.2

[a]See footnote Table 2.

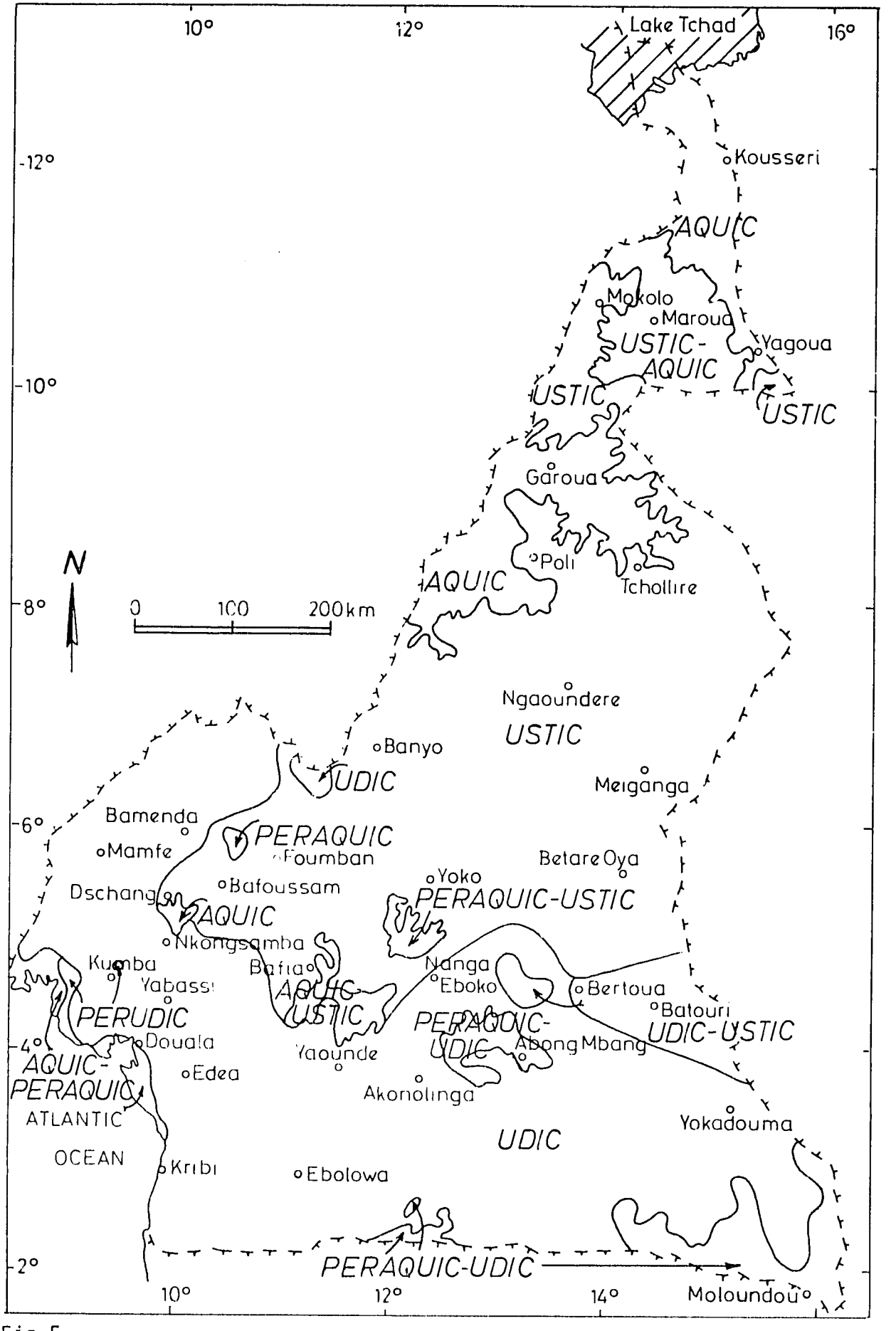

Fig.5

Soil moisture regimes of Cameroon

the length of the period during which the soil is dry or partially dry is underestimated when Thornthwaite evapotranspiration is used. Recalculation of the soil moisture regimes using the Adapted Thornthwaite evapotranspiration derived from formula (5), shows that the major part of the high plateaus in the Northwest Province (Bamenda) remains udic, but that the Western Province (Bafoussam, Dschang, Foumban) becomes mainly ustic.

In the center and the northern part of the country, at least at higher elevations, the Thornthwaite evapotranspiration is underestimated versus the Penman evapotranspiration, but this difference does not affect the classification of the calculated soil moisture regime, which is ustic due to the rather long dry season.

The Soil Moisture Regime Map

The map showing the distribution of the soil moisture regimes of Cameroon is represented by Fig. 5. The map has been drawn taking into account the corrections discussed in this paper and indicating aquic and peraquic regimes following the delineations of the soil map of Cameroon (Martin and Segalen, 1966).

ACKNOWLEDGEMENTS

The author is endebted to the Direction of the "Ecole Nationale Supérieure Agronomique, Cameroon" and to the "Algemeen Bestuur van de Ontwikkelingssamenwerking, Belgium" for providing the research facilities.

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SPATIAL VARIABILITY IN SELECTED PROPERTIES OF RWANDA SOILS

P. Vander Zaag, R.L. Fox, R.S. Yost, B. Trangmar, K. Hayashi, G. Uehara

ABSTRACT

Variograms of soil pH, exchangeable Ca, ECEC, Si in the saturation extract, and extractable NH_4 show long range spatial dependence of these properties in soils of Rwanda. The distance of spatial dependence (range) varies from 37.5 km for soil pH to more than 60 km for extractable NH_4. The results suggest that similar variance structures can occur in contrasting soils.

The structural information contained in the variogram was used to krige (estimate) the above soil properties in a grid over the entire country. Contour (isarithm) maps produced from the kriged points clearly display spatial variability of each property over the country. Maps of estimation variance constructed in a similar manner can be used to increase sampling efficiency to produce better maps.

INTRODUCTION

Soil properties vary spatially and temporally. Both kinds of variability can be categorized as being either systematic or random (see Fig. 1). Seasonal changes in soil temperature and soil moisture are examples of systematic temporal variability. These changes correspond to soil climate and can be classified and mapped. In contrast, random temporal variability associated with weather is unpredictable and therefore unmappable.

A similar situation exists with soil spatial variability. Soil properties that change systematically over the landscape are mappable, but random variability is not. Even within relatively pure map units, spatial variability causes plants to grow unevenly, soil test results to differ,

and septic tanks to perform unequally. Soil spatial and temporal variability remains a troublesome factor in soil interpretation and prevents us from making accurate predictions of soil performance at any particular point in the landscape.

Regionalized Variables

The theory of regionalized variables has been used by mining engineers to cope with spatial variability in ore deposits. A regionalized variable is a continuously distributed variable having a geographic variation too complex to be represented by a workable mathematical function (Campbell, 1978). The high cost of mapping spatial distribution of mineral concentration in ore deposits has spurred geostatisticians to develop accurate methods to assess ore quality at any point from as little data as possible. Excellent examples of use of regionalized variable theory in soil science are two sets of companion papers by Burgess and Webster (1980a, 1980b), and Yost et al. (1981a, 1981b).

The theory of regionalized variables hinges on the fact that the difference between the values of a property measured on a pair of samples increases as the sample distance increases. In other words, the covariance diminishes as the distance between pairs of points increases. The distance at which covariance between pairs of measurements disappears is called the range. In soils the range can be less than a centimeter or extend to several kilometers. Within the range, we say that the soil property in question is spatially dependent.

Autocorrelation and Semivariance

Spatial dependence of a soil property can be determined from autocorrelation or the semivariance. In both cases it is necessary to know the value of the property and the sample location. From these the nature and range of spatial dependence of the soil property can be determined.

In autocorrelation the value at each point is correlated first with itself, second with its nearest neighbor, third with its next nearest neighbor, and so forth. A plot of the correlation coefficient versus distance between neighbors is the correlogram. In general the correlation

coefficient decreases with increasing distance between neighbors.

The semivariance

$$\gamma(h) = \tfrac{1}{2} E[z(x) - z(x+h)]^2$$

is defined as one-half the expected value of the squared difference between the value (z) at locations (x) and (x+h), where h is the distance between sampling points. A plot of semivariance versus distance (h) results in a semivariogram or simply the variogram. The variogram is computed from the formula

$$\gamma(h) = \frac{1}{2N(h)} \sum_{i=1}^{N(h)} [z(x) - z(x+h)]^2$$

where N(h) is the number of sample pairs separated by distance h.

Variograms

Fig. 2 shows an idealized variogram. A detailed discussion of various possible types of variograms is found in a text by Journel and Huijbregts (1978). In most cases, the curve will not pass through the origin but will intersect the vertical axis at some point (nugget variance) between zero and the upper horizontal line called the sill. The nugget variance is caused by both measurement errors and microvariability of the parameter which cannot be detected at the scale of sampling. The sill consists of the nugget variance and a component that represents the range of variance due to spatial dependence in the data. When a variogram, like the one shown in Fig. 2, is obtained, we say that there is structure in the variance. An empirical equation can be fitted to the data points so that the curve is analogous to covariance with respect to distance. If the sampling distance is greater than the range over which there is spatial dependence among the data (i.e. no structure in the variance), the curve is identical to the sill and is called pure nugget effect. The variogram is not an end itself, but is the basis to do kriging or conditional simulation.

When the variability of a particular soil property is identical in all directions of two-dimensional space, the semivariance (h) is dependent only on the distance (h) between measured pairs and the variogram model

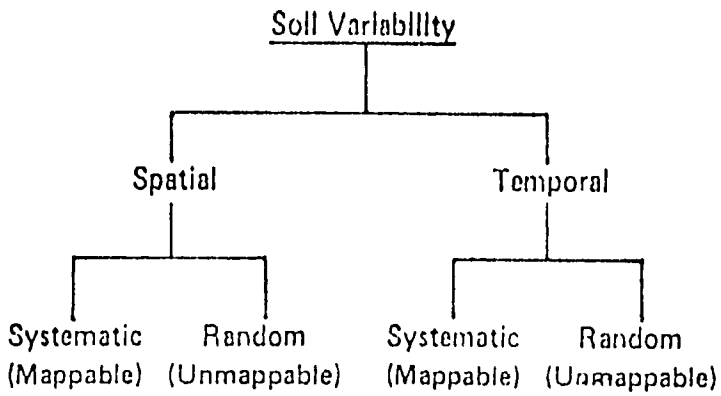

FIG. 1. Classification of soil variability.

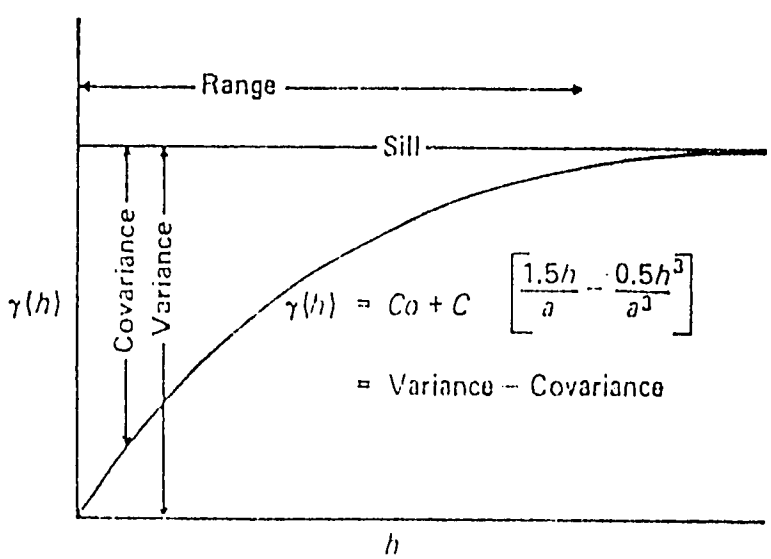

FIG. 2. Idealized variogram showing the semivariance γ(h) as the difference between the variance and the covariance. The range is the distance over which pairs of observations are spatially related.

is isotropic. The variogram model is anisotropic when its variability is not the same in every direction.

Kriging

Kriging is a technique to estimate the value of a soil property at an unsampled location from measured neighboring values. Because kriging uses the structural information condensed in the variogram, it offers more precise estimates of the variable at unsampled locations than averages of sampled points or regression estimates based on them. The best, linear, unbiased estimates (BLUE) are achieved by the Lagrange optimization procedure and the minimization of estimation variance. A sample calculation for kriging, prepared by D.R. Nielsen of the University of California at Davis, is attached to this paper. By necessity a trivial example is used, but it is clear that construction of a variogram and kriging requires high speed, machine computation.

The purpose of this paper is to report preliminary results of a geostatistical analysis of soil chemical data from Rwanda.

PROCEDURE

Fig. 3 shows the nine transects along which the sampling sites were located. A total of 119 locations were sampled, and at each location, samples from the 0-15 and 30-45 cm depths were collected. Each sample was analyzed for pH, exchangeable Ca, Mg, K and Na, KCl-extractable Al, percent Al-saturation, effective CEC, µg P-sorbed at an equilibrium P concentration of 0.02 and 0.2 ppm, extractable P by the Bray 1 and Olsen method, P and Si in the saturation extract, total N, NO_3, NH_4, and extractable S. Each sample site was identified by x, y coordinates. With the exception of one pair, all sample pairs were separated by distances greater than 3.75 km. There were 37 pairs separated by a distance of 5.0 ± 1.25 km. All higher separations had a larger number of pairs.

Estimates of Si and NH_4 were calculated using data transformed into natural logarithms. Journel and Huijbregts (1978) referred to this as lognormal kriging. This technique is employed whenever an improvement in the

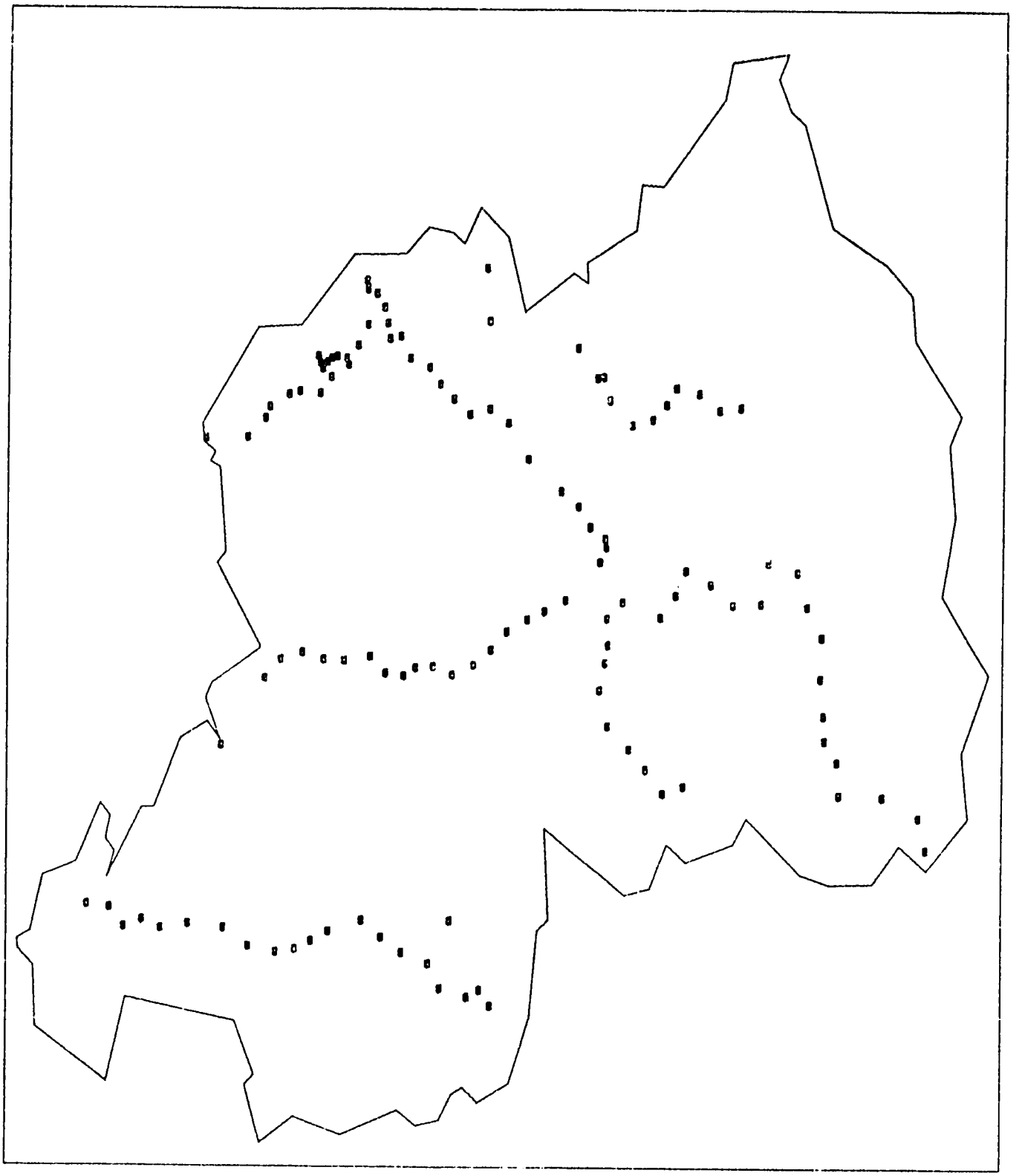

FIG. 3. Location of sampling sites.

structure in the variance is achieved over the normal method. The resulting kriged values and estimation variance were difficult to interpret in logarithm form and thus were re-expressed in terms of the original data. The re-expression was accomplished using the following equations from Journel and Huijbregts (1978): $Z_k = \exp[Y_k + (\sigma_k/2)]$ for the kriged values, and $EY_k = m^2[\exp(\sigma y^2)][1-\exp(-\sigma_k^2)]$ for the estimation variance where:

Z_k = kriged value converted to the original data

Y_k = logarithmic kriged value calculated by kriging

σ_k^2 = logarithmic estimation variance calculated by kriging

EY_k = estimation variance converted to the original data

m = mean of the original data

σ_y^2 = variance of the transformed data.

Variograms for each variable were constructed in the zero, 45, 90 and 135 degree directions to test for anisotropy.

RESULTS AND DISCUSSION

The variograms for pH, Ca, effective CEC (ECEC), log Si and log NH_4 are displayed in Figs. 4 to 8. These variables were selected primarily because they showed little anisotropy and could be displayed by a single isotropic variogram. The main features of the variograms are summarized in Table 1.

The most striking feature of the variograms is that the structure in the semivariance extends to more than 50 km. These large ranges indicate that certain soil properties are spatially related over long distances. At these large distances one would expect to find a large intercept (nugget effect) or even a pure nugget effect. This expectation arises from ranges of less than 10 m for a soil pH reported by Campbell (1978). It may very well be that for a particular variable, different forms of spatial relations emerge with increasing sample spacing in a "telescoping" effect. What would the variogram be like for soil pH collected on a one-meter grid over a 100 M^2 area? An equally interesting problem would be to compare variograms of different kinds of soil.

The large distances covered by the variogram indicate that the same type of spatial dependence of a particular property can occur in a number

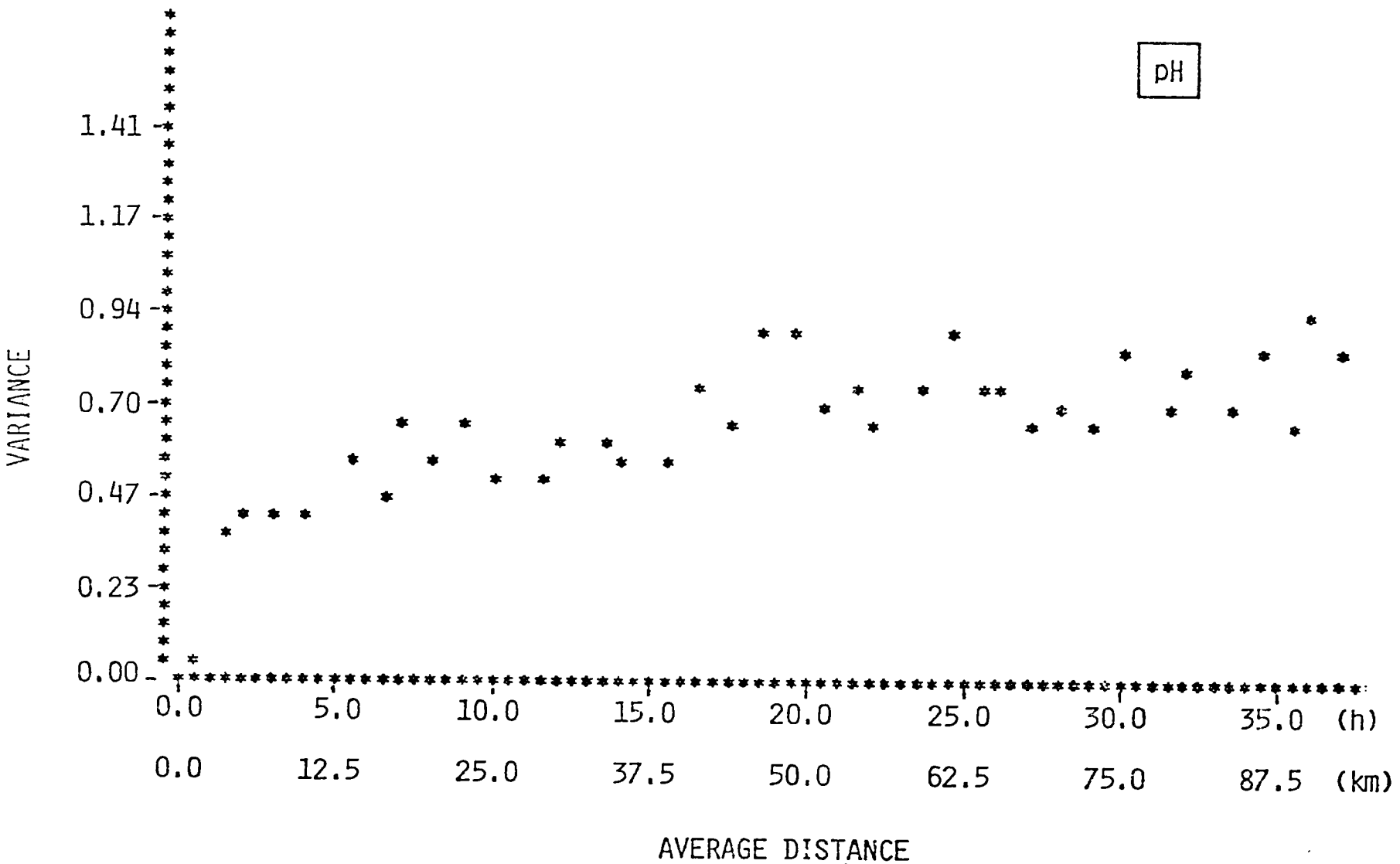

FIG. 4. Isotropic variogram of soil pH.

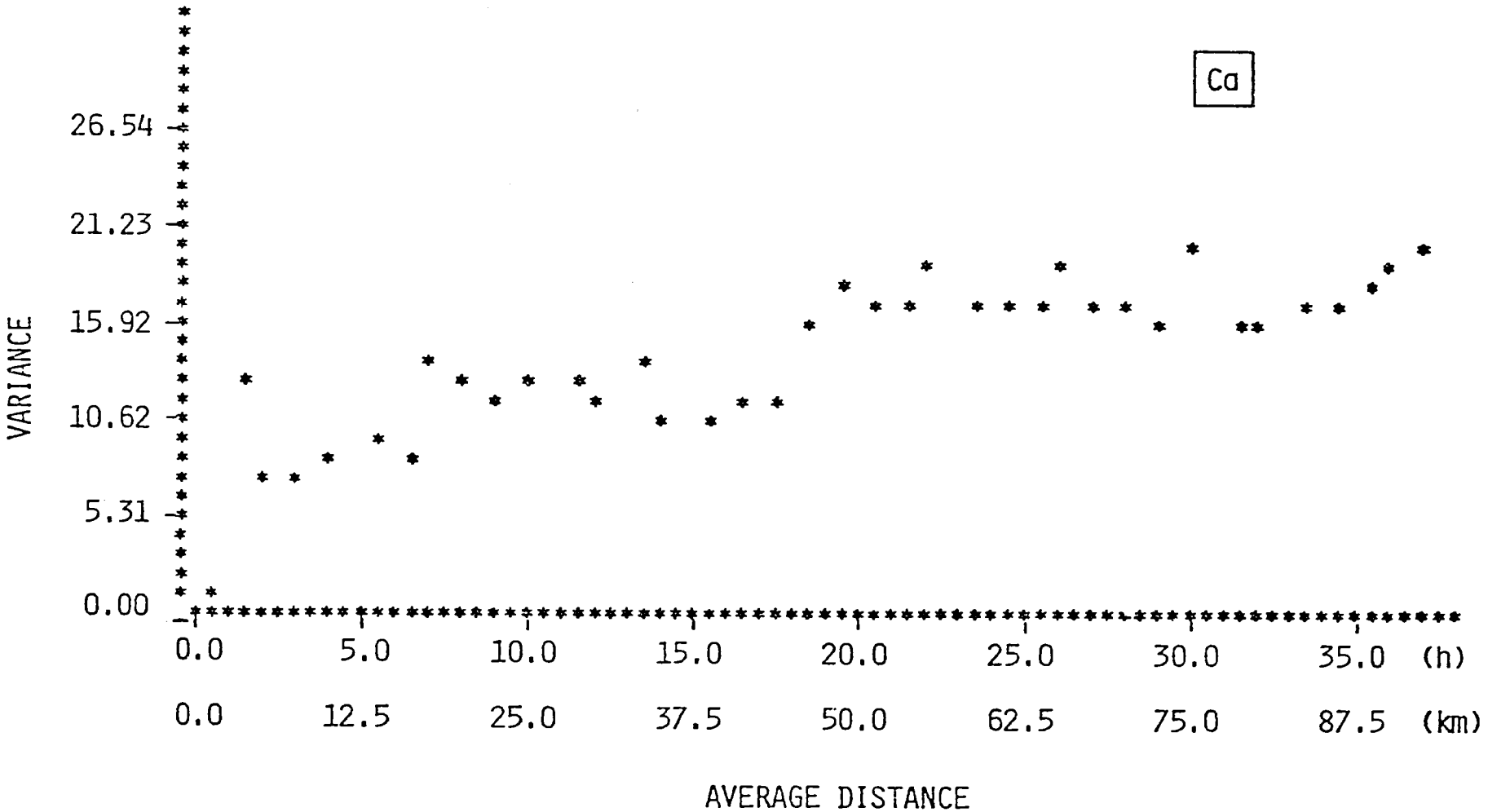

FIG. 5. Isotropic variogram for exchangeable Ca.

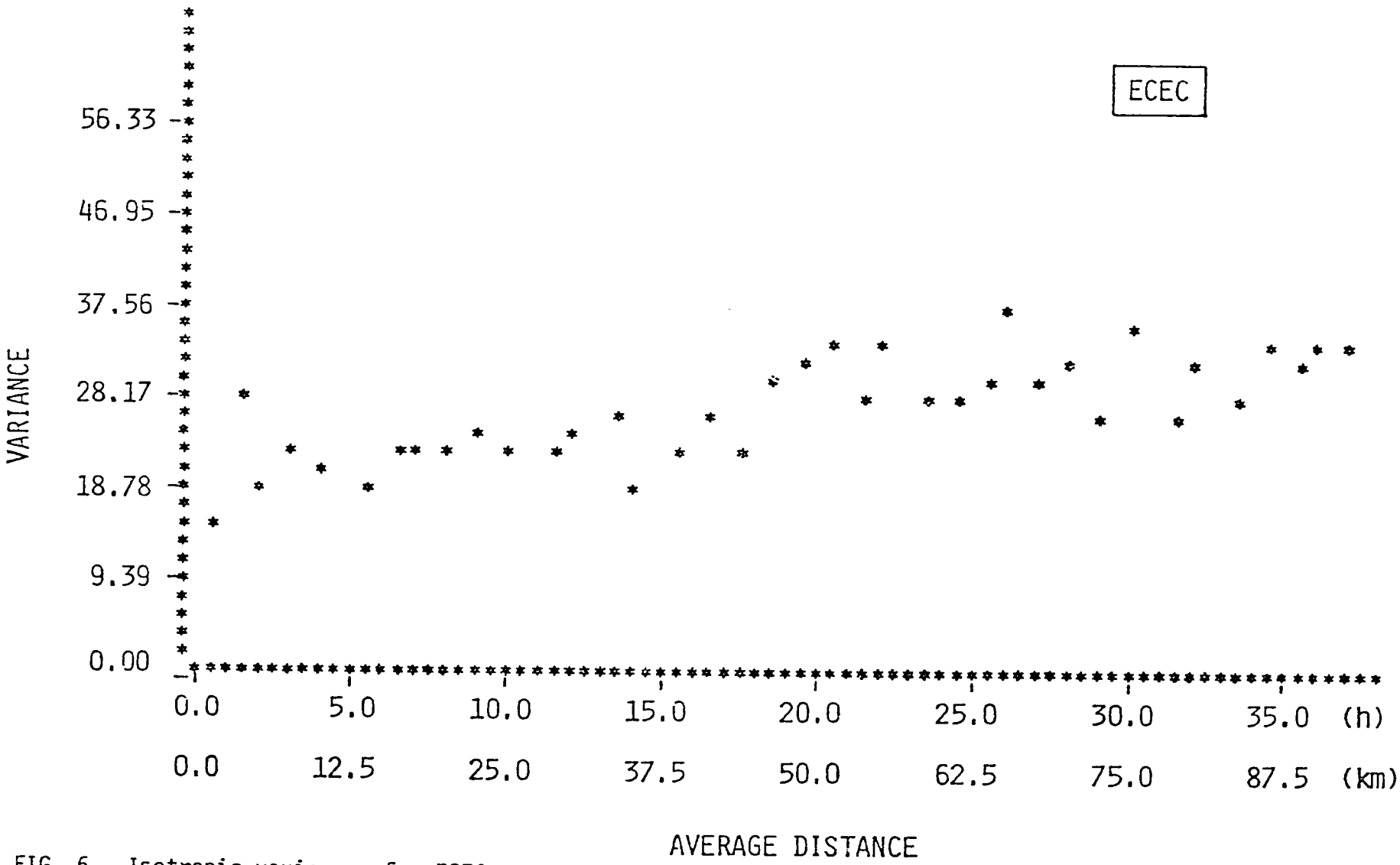

FIG. 6. Isotropic variogram for ECEC.

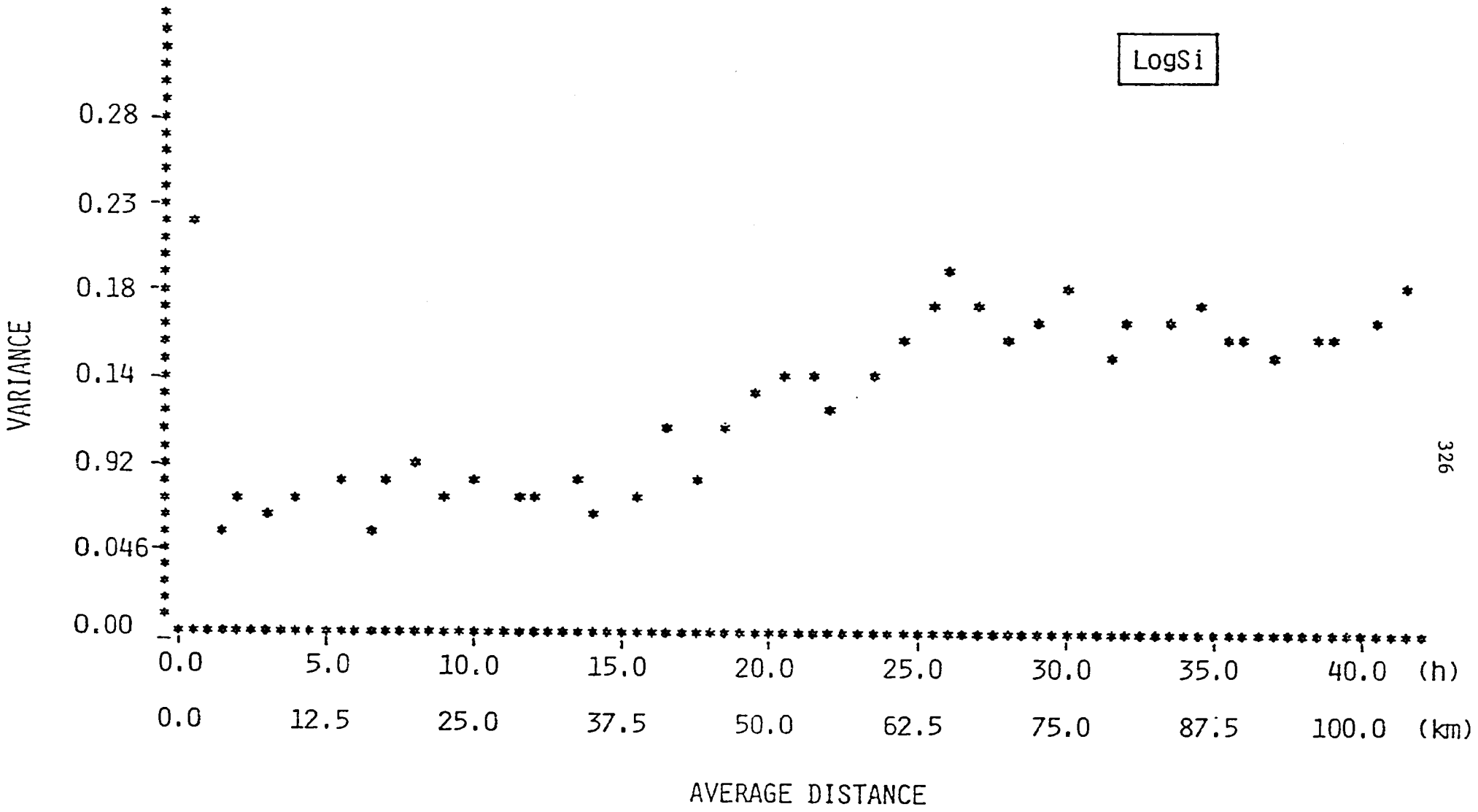

FIG. 7. Isotropic variogram for log Si.

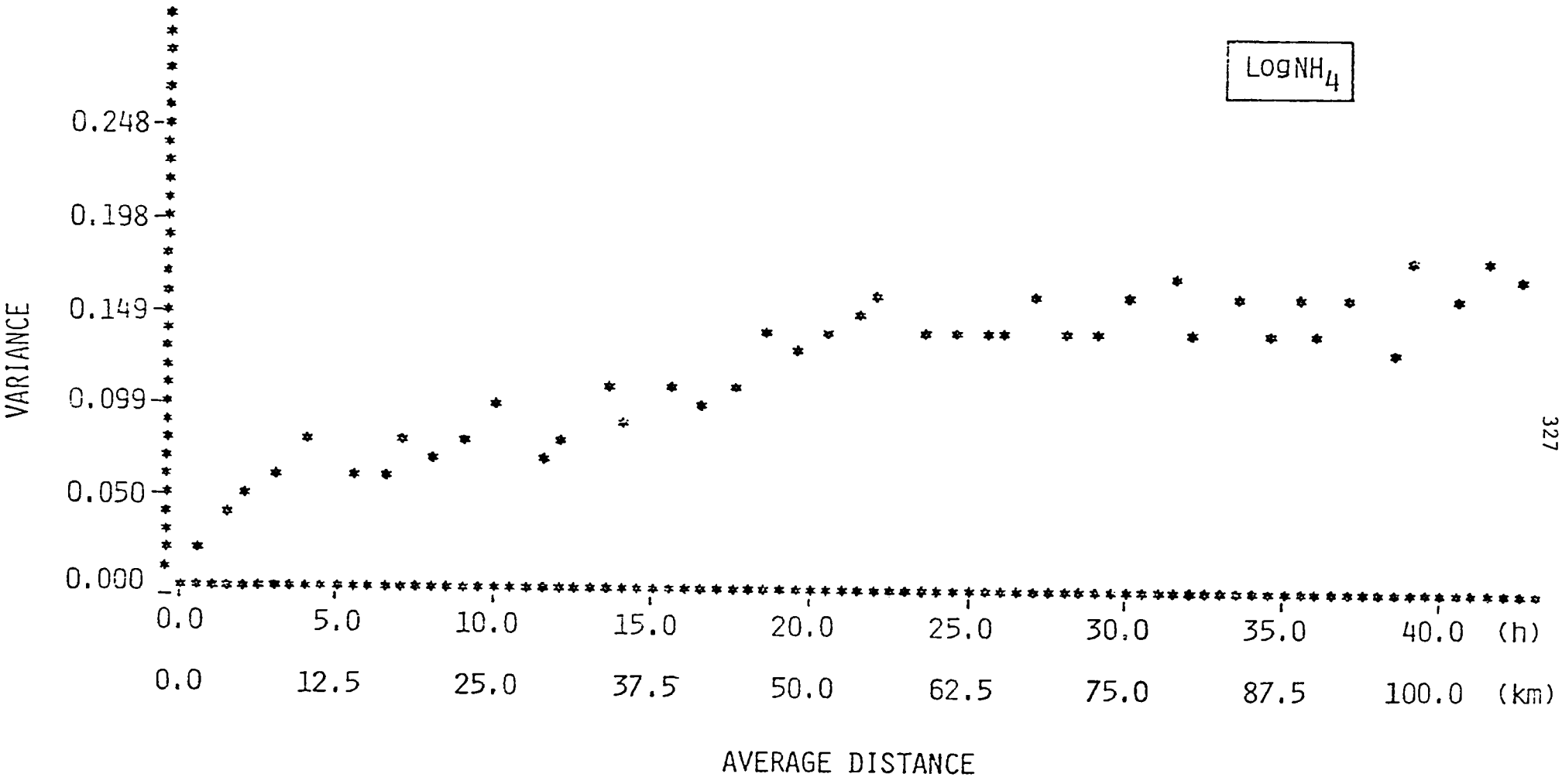

FIG. 8. Isotropic variogram for log NH_4.

Table 1. Summary of variograms. The re-expressed mean and variance for Si and NH_4 were calculated from the log data using the equations: $M = \exp(\mu_y + \sigma_y^2/2)$ and $V = \mu_x^2[\exp(\sigma_y^2) - 1]$ from Haan (1977), where M is the re-expressed mean, μ_y is the general mean of the data logarithms, σ_y^2 is the general variance of the data logarithms, V is the re-expressed variance, and μ_x is the mean of the original data values.

Variable	Intercept (C_0)	Range h	Range km	General mean	General variance	Re-expressed mean (M)	Re-expressed variance (V)
pH	0.0	15	37.5	5.71	0.783	--	--
Ca	6.29	20	50	7.14	17.69	--	--
ECEC	14.61	20	50	11.35	31.30	--	--
log Si	0.0198	25	62.5	2.22	0.153	9.96	16.4
log NH_4	0.0296	22	55	4.41	0.165	89.6	1430

of contrasting soils. This raises other questions about spatial variability in soils. Does spatial dependence change, and appear or disappear with soil management? Are there intrinsic properties that covary with large numbers of other characteristics that also resist changes in the structure of their variances? These are questions that need to be answered before the structural information contained in variograms can be exploited for making predictions about soil behavior.

Figs. 10 to 14 show iso-property contour maps for Rwanda. Webster (1977) refers to such maps as isarithm maps. These maps were constructed from kriged (predicted) data points. Kriging uses the structural information contained in the variogram to estimate values of a soil property at unsampled locations within the range of the variogram. Outside the variogram range, kriging is no better than other interpolation methods.

Maps of estimation variance are shown in Figs. 15 to 19. These maps show that estimation variance of kriged values generally increase with distance from sample points as in the northeast corner of Rwanda where no samples were collected. In the kriging equations the weighting given to the sample values decreases as the distance between sample points and kriged points increases, thus increasing the estimation variance. The similarity of contour positions among different soil properties in Figs. 15 to 19 is not surprising because of the dependence of estimation variance on distance between sample points and kriged points. The estimation variance maps clearly indicate where additional sampling points are needed. Strategically placed sample locations in regions with high estimation variance can markedly reduce the estimation variance, thereby increasing the accuracy of the kriged points.

Distribution of sample points around a kriged point also affects the estimation variance. For the same number of neighbors, the estimation variance is lower when the neighbors are uniformly distributed around the kriged point. This suggests that it is better to collect samples on a uniform grid than in clusters or in a transect. However, the sampling distance for a significant number of sample pairs must fall within the range of spatial dependence. If the minimum distance between samples exceeds the range, a nugget effect will be obtained and kriging will be no better than other interpolation methods.

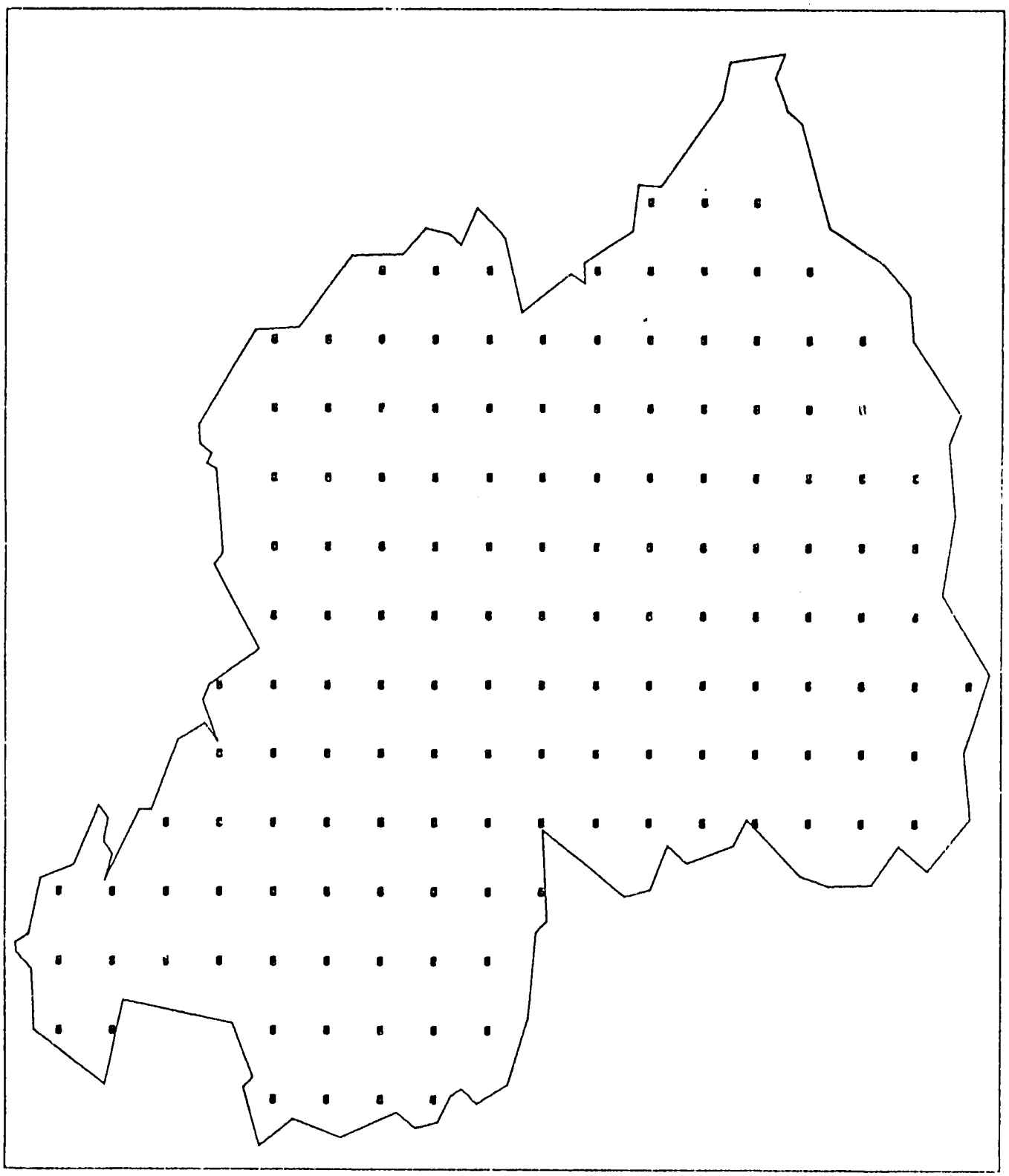

FIG. 9. Location of krige points.

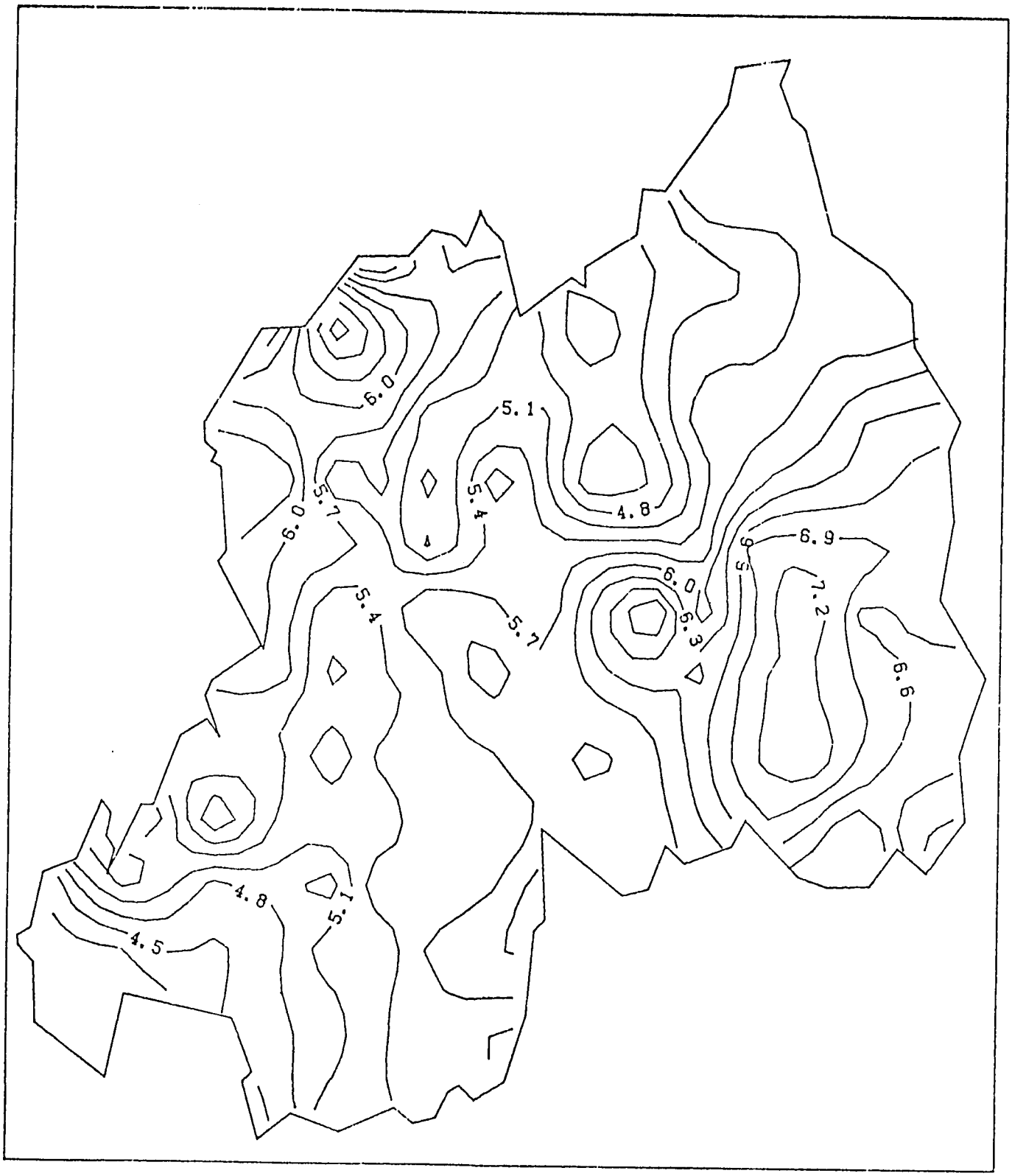

FIG. 10. Contour map of kriged pH values for Rwanda.

FIG. 11. Contour map of kriged Ca values for Rwanda.

FIG. 12. Contour map of kriged ECEC values for Rwanda.

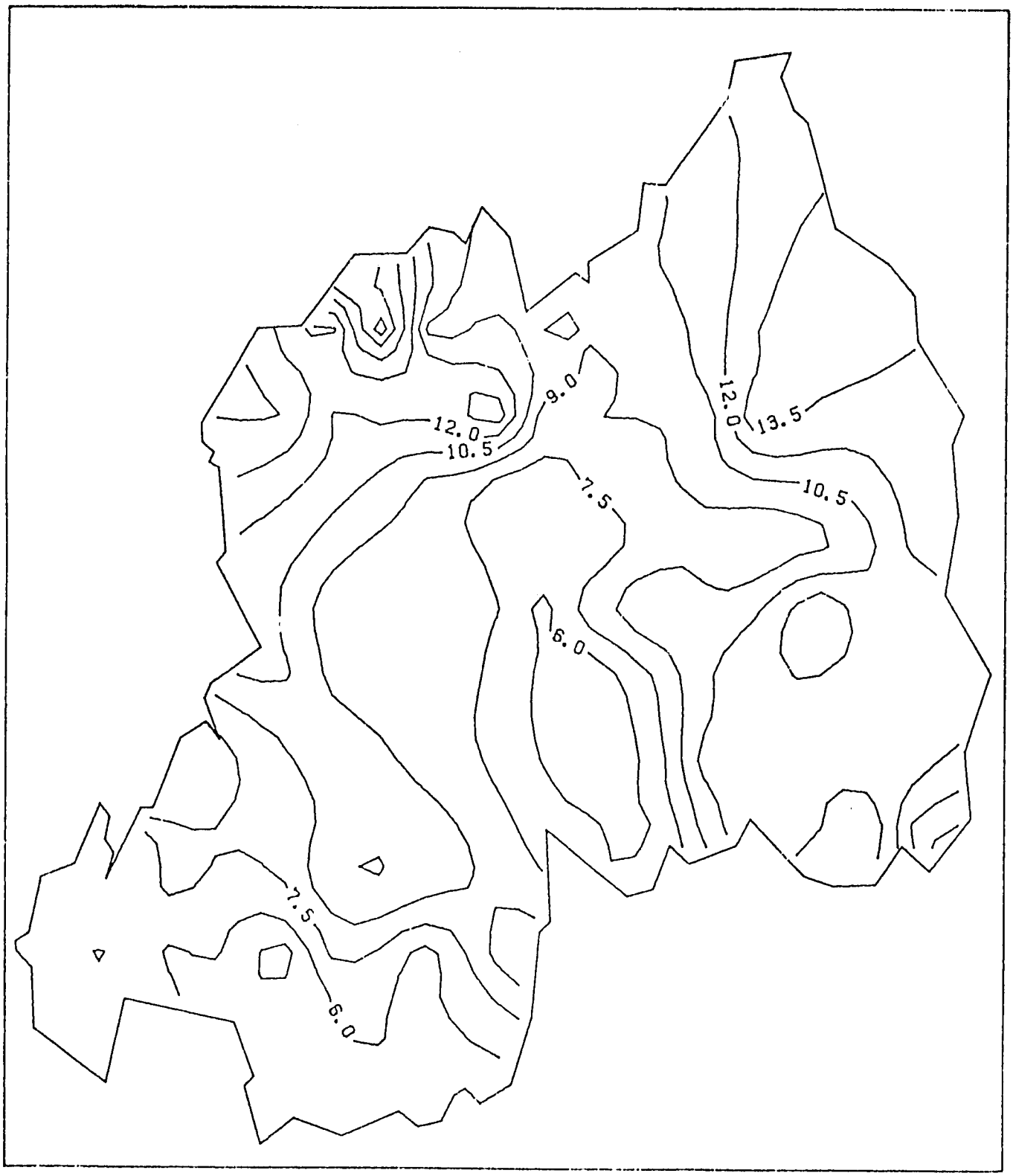

FIG. 13. Contour map of lognormal kriged Si values for Rwanda.

FIG. 14. Contour map of lognormal kriged NH_4 values for Rwanda.

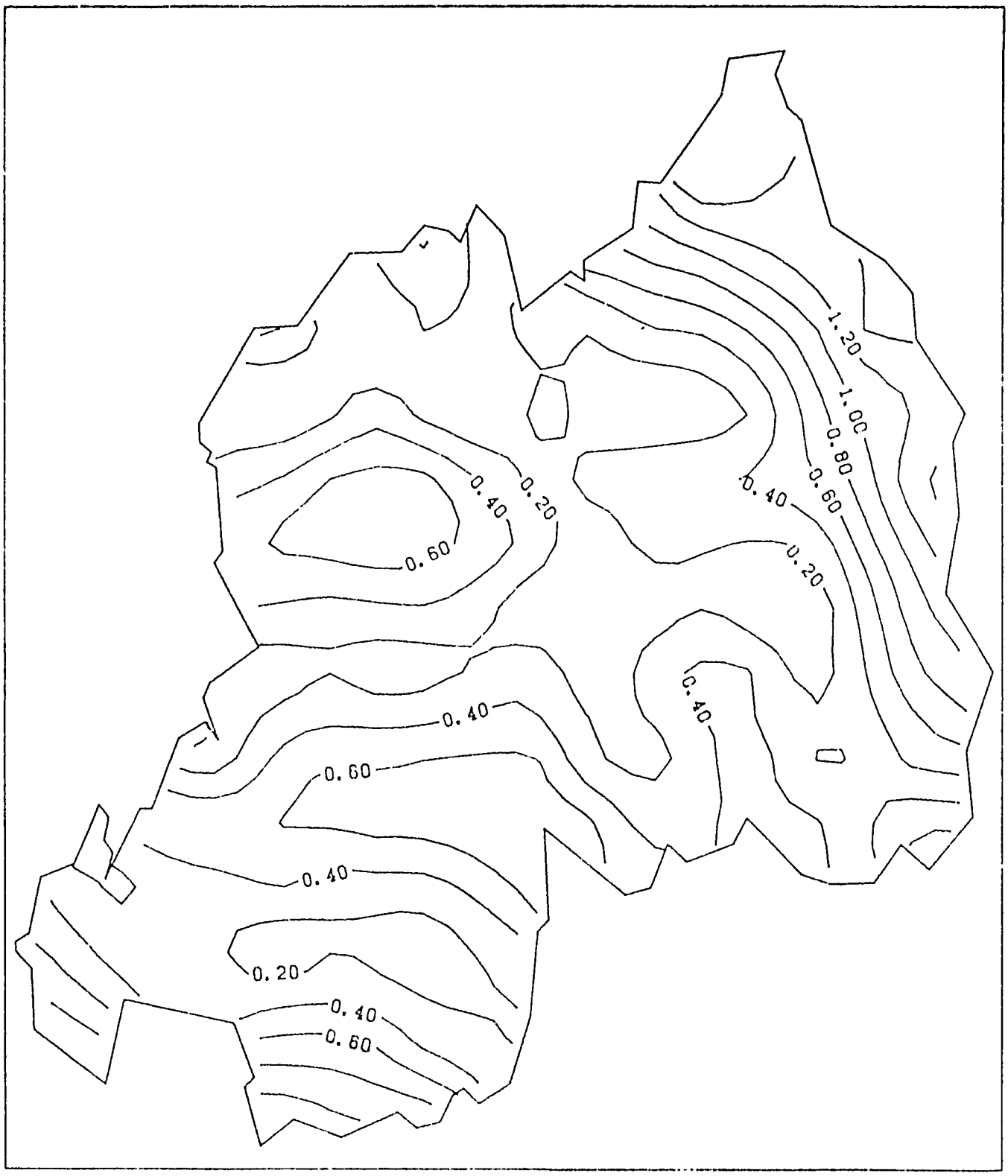

FIG. 15. Map of estimation variance for pH.

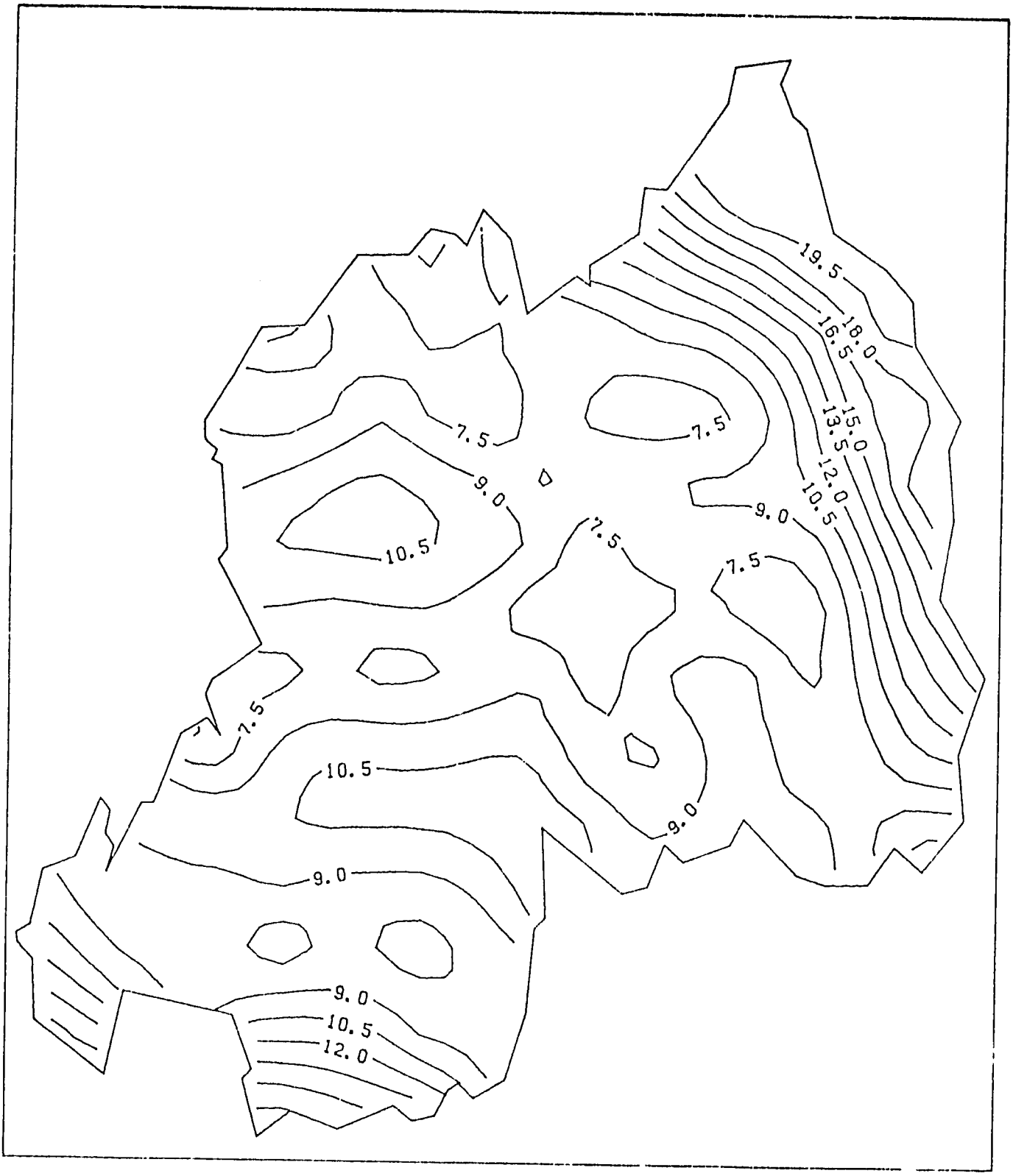

FIG. 16. Map of estimation variance for Ca.

FIG. 17. Map of estimation variance for ECEC.

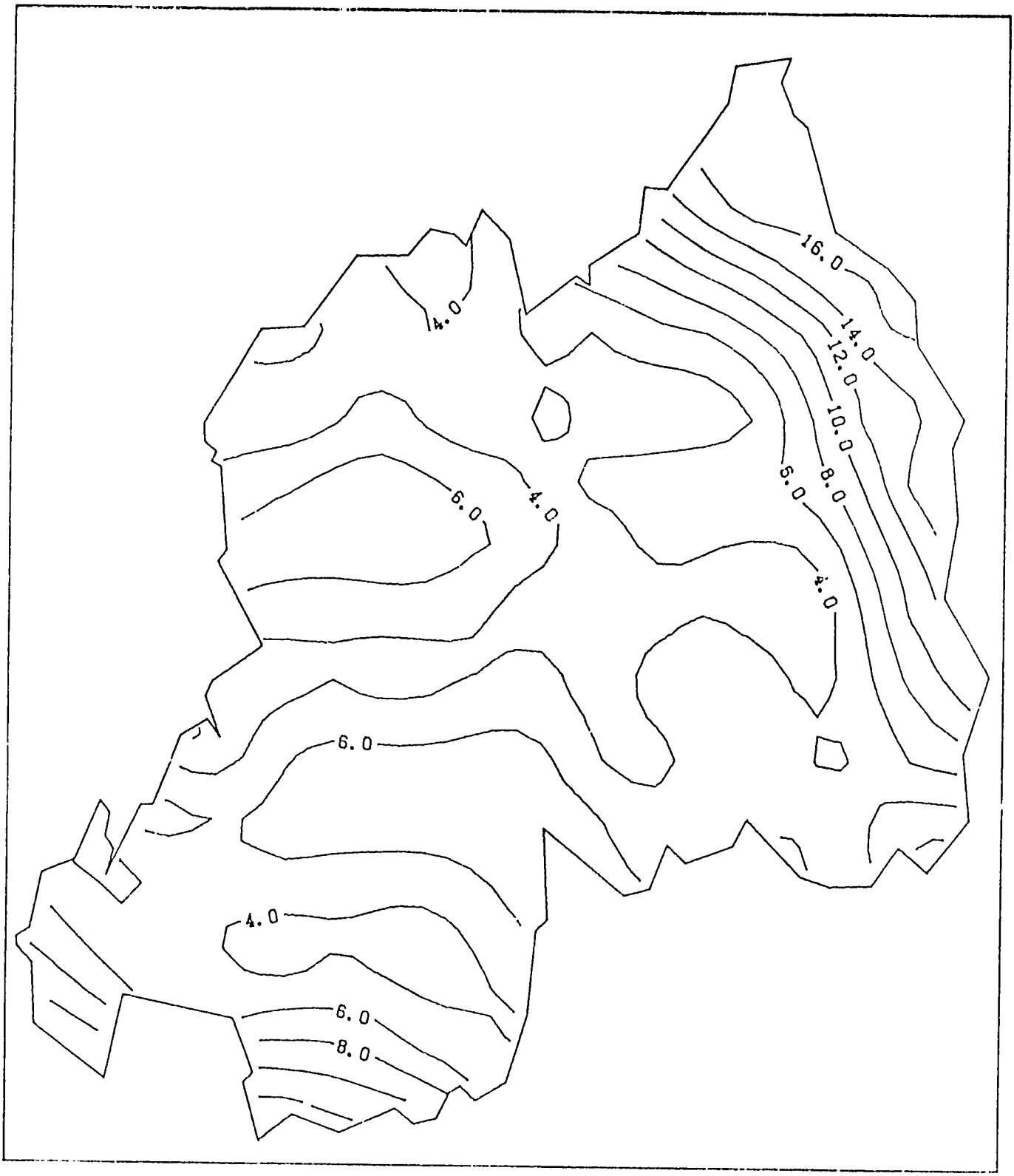

FIG. 18. Map of estimation variance for Si.

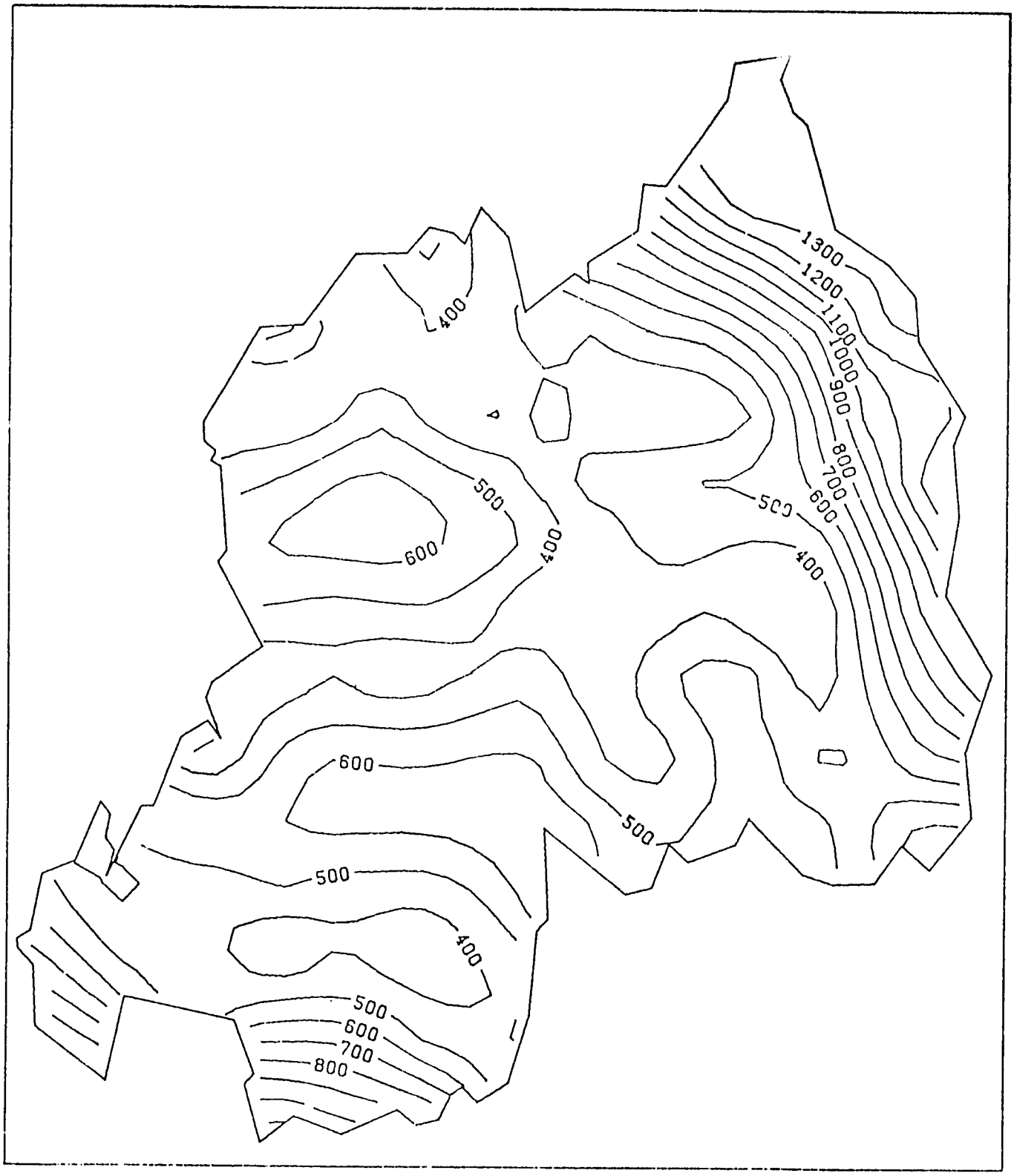

FIG. 19. Map of estimation variance for NH_4.

CONCLUSION

Geostatistics can be used to make quick, low cost, assessments of soil variability of large land areas. This technique is particularly valuable in underdeveloped areas with few roads where access for sampling is often poor. If properties measured on samples collected along roads show well-defined spatial dependence, this information can be used to estimate these properties in unsampled, inaccessible locations. The map of estimation variance gives an indication of the confidence limits of the estimated values. This map can in turn be used to locate optimum sampling sites to lower the estimation variance.

It is highly likely that many data sets amenable to geostatistical analysis already exist. These include samples collected in a grid for assessing land for large irrigation projects or land development schemes. The quantity of information that may be extracted from such data sets may be measurably increased by application of geostatistical principles.

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SURFACE CHARGE CHARACTERISTICS AS INDICATORS OF THE MINERALOGY OF SOME CLAYEY SOILS AT DIFFERENT STAGES OF WEATHERING

A.J. Herbillon and Ph. Nemry

ABSTRACT

Samples from nine pedons developed on materials derived from basic rocks and showing markedly contrasting clay mineralogy were selected for this study. After analysis of XRD, DTA and deferration treatments, these soils were placed in their respective mineralogy class which ranged from "montmorillonitic" to "gibbsitic." Their mineralogy was then compared to different surface characteristics such as positive and negative charge at the soil pH, negative charge at pH 7 and reactivity with respect to P and Si. The surface charge characteristics allowed a regrouping of these soils similar to that based on their mineralogical composition. Further, the same properties proved to be useful for the placement of these soils at levels of Soil Taxonomy much higher than the family level. The reactivity of these soils with respect to P appeared to be poorly predicted both by placement in their respective mineralogy class and by their surface charge characteristics.

RESUME

Cette étude est basée sur l'examen d'échantillors en provenance de 9 sols derivés de roches basiques et caractérisés par une minéralogie de leurs fractions argileuses très contrastée. Un inventaire minéralogique succint réalisé par diffraction X, ATD et détermination du fer libre a permis le classement des sols selon les critères en vigueur au niveau de la famille de la "Soil Taxonomy." Ces sols s'étalaient de la classe "mont-

morillonitique" à la classe "gibbsitique." Leur composition minéralogique fut alors comparée à diverses propriétés de surface telles que charge positive et négative au pH du sol, charge négative à pH 7 et réactivités vis-à-vis des phosphates et de la silice. Les propriétés de charge permirent un regroupement de ces sols semblable à celui obtenu sur base de leur composition minéralogique. En outre, ces mêmes propriétés se révélèrent utiles pour le placement de ces sols à des niveaux de classification plus élevés que celui de la famille. La réactivité de ces sols vis-à-vis des phosphates n'est bien prédite ni par leur classement en termes de familles minéralogiques, ni par leurs propriétés de charge.

INTRODUCTION

In Soil Taxonomy (Soil Survey Staff, 1975), specifically in the classification of soils under the mandate of ICOMLAC and ICOMOX, there are several criteria for soil classification based on properties that are directly or indirectly determined by the mineralogical composition of the soil (Allen, 1977). These soils are good examples of the application of the quotation of John Stuart Mill to mineralogy given in chapter two of Soil Taxonomy: "The properties, therefore, according to which objects are classified, should, if possible, be those which are causes of many properties; or, at any rate, which are sure marks of them." Soil Taxonomy, however, quotes John Stuart Mill further as stating that, although "causes are preferable...the properties which is the cause of the chief peculiarities of a class, is unfortunately seldom fitted to serve also as a diagnostic of the class. Instead of the cause, we must generally select some of its more prominent effects, which may serve as marks of the other effects and of the cause."

The most prominent effect which is used as a mark or indicator of the mineralogy of soils (used as the criterion to regroup LAC soils at the highest levels of the Taxonomy) is the CEC of their clay fraction. In the system at present an attempt is made to consider, besides this prominent effect (i.e. the CEC of the clay), the facts which determine it. This is done, at a much lower level of classification, by defining the mineralogy classes.

In a previous paper, Herbillon and Rodrique (1979) claimed that the present succinct description of the mineralogical composition of the soil or soil clay, given in the Key to Mineralogy Class, does not give sufficient information at the family level of the classification of LAC soils. The same view is also held by Pope (1978), Juo (1981) and supported by data reported by Uehara (1979) and Gillman and Bakker (1979). This present paper presents results for a few selected soils which support our previous proposal to investigate the possibility of substituting surface properties for the mineralogical data which, at present, appear in the Key to Mineralogy Class. We show that, for clayey soils at least, a reliable and convenient indication of their mineralogy may be obtained by considering simultaneously their charge characteristics and the affinity of their surface for anions.

SAMPLES

In Soil Taxonomy, the mineralogy classes are considered to only modify the information already provided by the textural classes. To be consistent with this approach, we selected for our study soils which had the same texture (clayey, very fine) but which had markedly contrasting clay mineralogical compositions. For convenience, the control section of the selected pedons was equated to their major subsurface horizon (a common approximation which is acceptable for homogeneous deep pedons).

The selected pedons and samples, developed in materials derived from basic rocks (mainly basalt), are given in Table 1. Publications or internal reports containing references to their description and characterization are also listed in Table 1. Where the definitive classification of the pedons is undertain, either the alternatives are given or else a question mark appears. It should be noted that the three Bu pedons belong to the same "red-black" soil toposequence where both the LAC and HAC soils occur side by side. Further, several of the selected pedons (i.e. Th 6, Ma 2, Kl and Au 1) qualify as "Rhodic Ferralsols" in the FAO/UNESCO Soil Map Legend.

TABLE 1

CLASSIFICATION AND ORIGIN OF SOILS STUDIED

Profile number	Sample number	Horizon and depth (cm)	Clay %	Classification	Parent material and origin	References
Bu 1	2257	A_1, 0-15	84	Paralithic Udichromustert	Basalt, Burundi	R. Frankart unpublished
	2259	C_2, 30-40	84	or Paralithic Vertic Ustropept		
Bu 2	2231	A_1, 0-8	nd	Udic Rhodustalf		
	2234	B_{22t}, 30-66	84			
Bu 3	2242	A_p, 0-14	nd	Ustoxic Dystropept		
	2244	B_{22}, 51-68	64	or Tropeptic Haplustox		
Th 6		B_{22}, 60-86	63	Typic Haplustox	Basalt Chok Chai Series Thailand	2nd Workshop [1]
Th 14		B_{22}, 50-94	57	Typic Haplorthox	Basalt Tha Mai Series Thailand	
Ma 2		B_{22}, 66-115	74	Tropeptic Haplorthox	Andesite Segamat Series Malaysia	
K 1	138-1	A_1	74	Tropeptic Haplustox	Phonolite Kenya	F.R. Moormann and A.S.R. Juo unpublished
	138-3	B_2	76	or Ustoxic Paleustult		
Au 1	GPG1	0-10	64	Krasnozem	Basalt North Queensland Australia	Gillman (1974)
	GPG3	210-240	58	Typic Acrohumox ?		
Au 2	T84-1	0-10	60	Krasnozem		Gillman and Bell (1976)
	T84-5	60-90	75	Typic Acrohumox ?		

1. Soils examined during the 2nd International Soil Classification Workshop (Beinroth and Panichapong (1979) and Beinroth and Paramananthan (1979)).

METHODS

Mineralogy

A limited mineralogical analysis was performed in order to confirm or ascertain the placement of the selected pedons according to the Key to Mineralogy Class. The free iron content (reported as % Fe_2O_3 /g clay) of the subsurface samples (f < 2 mm) listed in Table 1 was determined by atomic absorption. The samples were deferrated using the CDB procedure of Mehra and Jackson (1960) and the deferrated soils were then ultrasonicated at pH 8-9 and their clay fraction separated according to Stokes' law.

For X-ray analysis of the deferrated clays, oriented specimens were made by depositing a few drops of the clay suspensions onto glass slides. Identification of the minerals was made from diffractograms of samples which had been subjected to Mg^{2+} saturation, Mg^{2+} saturation + ethylene glycol and heating for 2 hours at 500 degrees C. Where XRD indicated the presence of gibbsite, then a semi-quantitative estimate of the mineral in the soil was made from the DTA analysis of a deferrated soil sample. The DTA calibration curve was made by mixing known amounts of kaolinite and gibbsite (Fripiat and Marcour, 1954). The results are reported as % gibbsite/g soil.

Surface Areas

The external specific surface areas of the soil samples (f < 2 mm) were obtained by the B.E.T. plot (4 points) of a portion of the nitrogen adsorption isotherm performed at -196 degrees C in a volumetric apparatus. The total (external + internal) surface areas of soil samples containing swelling clay minerals were determined gravimetrically using the EGME method of Heilman et al. (1965). Prior to the N_2 adsorption measurement the samples were outgassed overnight at 120 degrees C under vacuum. For the EGME procedure, the samples were dessicated under vacuum and at room temperature in the presence of P_2O_5.

Charge and Surface Reactivity Characteristics

Pairs of CEC and AEC values were measured by the compulsive exchange method of Gillman (1979), using unbuffered 0.002 M $BaCl_2$ and 0.0015 M

$MgSO_4$ solutions. ECEC (taken as the sum of exchangeable cations plus Al^{3+} extracted in 1N KCl) were computed from data available in the routine analytical bulletins. No data was available for profiles Au_1, Au_2 and K_1. The NH_4Ac pH 7 CEC were obtained by a percolation method. After NH_4 saturation, the soil columns (5 g) were washed with 300 ml of ethanol and, after displacement by KCl (10%) at pH 3 (Pelloux et al., 1971), the NH_4^+ adsorbed was determined by microKjeldahl.

The index of silica reactivity (ISR) was determined according to Gallez et al., 1977. The initial concentration in silica was 100 ppm and the silica remaining in solution after a 7-day contact at pH$\sim$ 9 with this solution was measured colorimetrically. ISR (in %) is 100 minus the fraction of silica (in ppm) remaining in solution. The amount of silica adsorbed by each soil sample (Si ads expressed in moles/g), at the same pH and after the same contact time, at an equilibrium concentration of 500 moles Si/1 ($\sim$ 42 ppm SiO_2) was also measured. Si ads represents a single point on the total silica adsorption isotherm and is obtained by interpolation of two measurements made in the appropriate range of this isotherm.

P ads (the amount of P in μg/g) adsorbed at an equilibrium P concentration of .02 ppm was measured using the procedure described by Fox and Kamprath (1970). It is also a single point, obtained from the P adsorption isotherm determined at the soil pH and in a 0.01 M $CaCl_2$ solution as a supporting electrolyte.

RESULTS AND DISCUSSIONS

Placement of Soils in Their Mineralogy Class

Table 2 lists the mineralogy of the soils and clays and their classification according to the Key to Mineralogy Class. It can be seen that our samples cover a broad range of mineralogical composition corresponding to the different stages of weathering experienced by the clayey soils developed from basic parent materials in the intertropical environment.

Because of the semi-quantitative nature of the methods used to determine the amounts of minerals present in mixtures, a subjective judgement was required to classify some pedons. For example, the two Australian

TABLE 2

MINERALOGY (SUBSURFACE SAMPLES) AND PLACEMENT IN THE MINERALOGY CLASSES (PEDON)

Profile number	Fe_2O_3/clay % (CED)	Gibbsite/Soil % (DTA)	Minerals present in deferrated clays. (Estimation from X-ray diffractograms [1])								Mineralogy class
			Ka	Sm	Ka-Sm	Gi	Il	Qz	Far	14 Å Chl	
Bu 1	9.6	0	x	xxx							Montmorillonitic
Bu 2	14.0	0		tr	xxx		tr				Mixed
Bu 3	15.2	0	xxx				x				Kaolinitic
Th 6	7.9	0	xxx					tr			Kaolinitic
Th 14	11.9	0	xxx								Kaolinitic
K 1	7.9	tr	xxx				x		x		Kaolinitic
M 2	15.4	∿ 10 - 15	xxx			x				x	Oxidic
Au 1	27.7	35 - 40	xx			xx					Gibbsitic
Au 2	32.6	∿ 35 - 40	xx			xx		tr			Gibbsitic

1. Ka = Kaolinite; Sm = Smectite; Ka-Sm = Interstratified Kaolinite-Smectite; Il = Illite; Qz = Quartz; Far = Feldspar; 14 Å Chl = Chlorite.

xxx > 60%; xx 20-60 %; x 5-20 %; tr < 5%.

soils could be classified as both oxidic or gibbsitic. Further, if the Key to Mineralogy Class had been strictly applied to the Bu_2 pedon, it would have been incorrectly called "Kaolinitic," since the dominant clay minerals present in this soil have all the characteristics of what had been previously termed "tabular halloysites" which are placed in the kaolinitic class by Soil Taxonomy. It has been shown by Herbillon et al. (1981) in agreement with Dixon (1977), that these "tabular" clays are, in fact, merely interstratifications of kaolinite and smectite (approximately 70% and 30% respectively in our sample). The Bu_2 pedon has therefore been classified as "mixed." Other data, given in Table 3, justify this classification. Finally, it should be noted that on the basis of the feldspar clay content of the B_{22} horizon, given in Table 2, the K_1 pedon is unlikely to be an Oxisol. No further data however, has been obtained to support this hypothesis.

Surface charge and Reactivity Characteristics in Relation to Mineralogical Compositions

In Fig. 1 the relationships between the classification of soils in terms of mineralogy classes (Table 2) and some characteristics selected from the data listed in Table 3 are presented. In this figure, attention will again be paid to the subsurface samples which, according to our earlier convention, represent the control section of the pedons under study.

Cation exchange capacity ratios. In Fig. 1A, the approximate fraction of the nonpermanent negative charge has been obtained from the ratio $CEC^2 - CEC^1/CEC^2$ where CEC^1 (the CEC measured at the soil pH in the presence of a low electrolyte concentration) has been equated to the permanent negative charge (Gillman and Bakker, 1979) and where CEC^2 is the total negative charge measured at pH 7 by the conventional NH_4OAc method. It was not unexpected that, because the samples used in this study had such a contrasting mineralogy, both the fraction of the nonpermanent negative charge and CEC^1 would provide a better mineralogical grouping than CEC^2.

It is interesting to note that the estimate of the fraction of nonpermanent charge in Fig. 1, though based on routine methods applied to soil samples, closely approaches that reported to exist for pure reference mineral colloids (i.e. 20-30% for smectites, 50% minimum for kaolinites,

TABLE 3

SURFACE CHARGE CHARACTERISTICS

Samples	Mineralogy class	So EGME m^2/g	So N_2 m^2/g	CEC [1] meq/100 g	AEC [1] meq/100 g	CEC [2] meq/100 g	ECEC meq/100 g	ISR %	Si ads µmole/g	P ads µg/g
Bu 1 A 1		522	81	48.5	0.0	68.8	58.6			
C 2	Montmorillonitic	586	93	50.8	0.0	68.6	62.6	25	63	230
Bu 2 A 1		297	62	18.6	0.0	39.9	25.1			
B 22	Mixed	405	98	18.6	0.1	30.5	15.8	48	68	420
Bu 3 A 1			29	3.9	0.1	9.4	4.6			
Bu B 22	Kaolinitic		36	2.9	0.2	7.4	3.6	41	53	455
Th 6 B 22	Kaolinitic		37	2.7	0.5	6.6	2.7	37	47	365
Th14 B 22	Kaolinitic		84	5.3	1.3	15.4	2.6	53	102	860
K 1 A 1			42	8.5	0.1	17.5				
B 2	Kaolinitic		54	3.5	0.3	13.6		69	84	620
Ma 2 B 22	Oxidic		48	0.7	3.0	7.0	1.0	54	90	690
Au 1 0-10			49	3.8	0.5	15.5				
210-240	Gibbsitic		72	0.0	3.7	2.5		71	180	750
Au 2 0-10			57	3.6	1.1	16.0				
60-90	Gibbsitic		85	0.8	1.3	5.3		68	124	345

1. CEC and AEC at the soil pH (Gillman 1979)

2. CEC by NH_4Ac at pH 7.

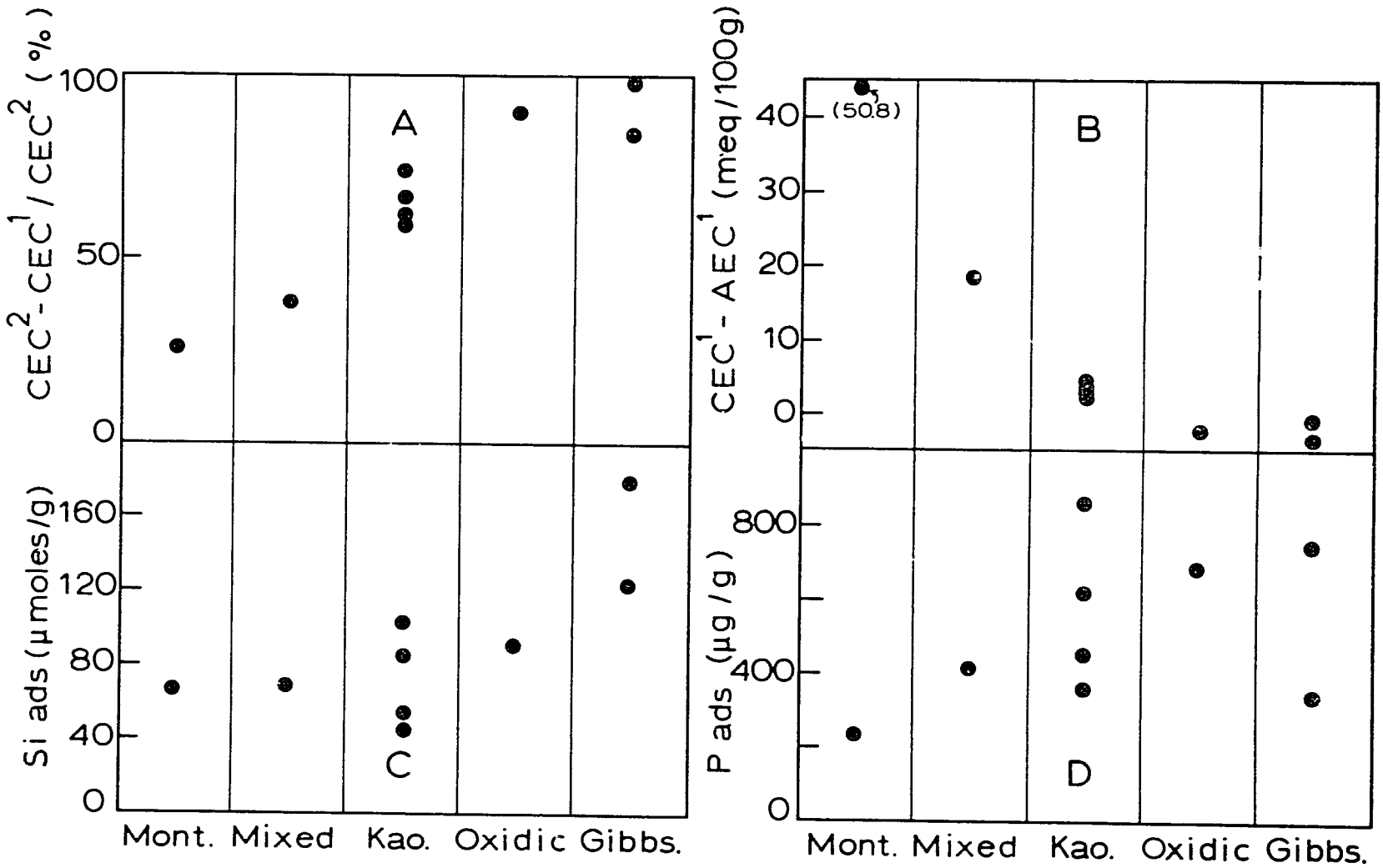

Fig. 1. A comparison between the classification of soils in terms of mineralogy classes (abscissa) and some of their surface characteristics (ordinate). A--Approximate fraction of nonpermanent negative charge at pH 7: CEC^2-CEC^1/CEC^2 (%). B--Difference between CEC and AEC at the soil pH: CEC^1-AEC^1 (meq/100 g soil). C--Si adsorbed (μ moles/g soil) at an equilibrium concentration of 400 μmole Si in solution. D--P adsorbed (μg/g soil) at an equilibrium concentration of 0.2 ppm P in solution.

and a value approaching 100% for oxides). This suggests that, besides its usefulness as a possible substitute for mineralogy classes, the CEC ratio or difference could also be used to advantage at other levels of the classification.

An attempt could therefore be made, for example, to define the limit between HAC and LAC soils by the CEC^2-CEC^1/CEC^2 ratio. Gillman and Bakker (1979) showed that the CEC^1 and ECEC of 54 LAC clay samples were highly correlated in spite of the uncertainty which exists on the exact nature of the so-called "exchangeable Al^{3+}" appearing in the KCl extracts of acid LAC soils (Amedee and Peech, 1976). Our results (Table 3) are in excellent agreement with the finding of Gillman and Bakker that the ECEC may be equated to about 0.8 CEC^1. Considering the statistical equation relating CEC^2 to ECEC obtained by Juo (in Moormann, 1978) for another group of LAC and HAC soils ($CEC^2 = 6.24 + 0.93$ ECEC), if ECEC is substituted for CEC^1 in the latter equation, then the ratio CEC^2-CEC^1/CEC^2 (the fraction of non-permanent charge measured at pH 7) is greater than 50% whenever CEC^2 is less than 16 meq/g. Also, in Juo's data, the higher this fraction, the more "oxidic" are the samples, a trend well illustrated by Fig. 1A.

Cation exchange capacity--anion exchange capacity. Fig. 1B illustrates the relation between the soil mineralogical compositions and CEC^1-AEC^1 (the difference between the two ion-exchange-capacities measured at the soil pH). For HAC soils, there is no special advantage in considering this difference rather than the CEC^1. As noted by Gillman and Bakker (1979) if the difference between CEC^1 and AEC^1 is negative, then this is a good indication of the dominance of oxide surfaces in the sample. This therefore allows the identification of an oxidic mineralogy using this property. It should be noted, however, that the CEC^1-AEC^1 difference is, by definition, a pH-dependent property and has to be interpreted in relation with the soil pH value. For example, a kaolinite may have an AEC higher than its CEC but at a pH lower than about 4-4.5 (Sumner and Reeve, 1966). The same applies if the CEC^1-AEC^1 difference is to be considered for defining the acric properties. At the acric stage of weathering, the soil surface is due mainly to oxides and its permanent negative charge (measured by CEC^1) should therefore be very low (< 1.5 meq/100 g clay). Further,

the pH of the acric soils (measured in 1 N KCl for instance) should be high enough (say > 4.8) that a negative CEC^1-AEC^1 difference could not be due to the anion-exchange-capacity of the silicates. In the present soil collection (Table 3), the reason that sample Ma_2 (which was not classified as acric) has a CEC^1-AEC^1 difference more negative than the acric Au_2 subsurface sample, could be due to the lower pH of the former sample.

A comparison of Figs. 1C and D with Figs. 1A and B illustrates that, while the charge properties are well correlated with the mineralogical classification, it is less so if the reactivity of these soils with respect to either silica or phosphate is also considered. For example, the highest P ads value (Table 3) was obtained with the Th 14-B_2 sample, a kaolinitic soil with a positive CEC^1-AEC^1 difference. By contrast, the Au_2 pedon, though gibbsitic (or oxidic) and acric, would, like the montmorillonitic Bu_1 and the "mixed" Bu_2 pedons, be classified as a medium P-fixing soil in the scale of Juo and Fox (1977). These examples demonstrate well that the mineralogical classification at the family level does not always provide information of importance for soil management. The reasons for the above discrepancies may be ascertained if the mineralogical and chemical inventories of the samples were extended. The high P-fixing Th 14 B_2 sample has a high specific surface area (Table 3) and has a ratio of Fe and Al soluble in oxalate to Fe soluble in dithionite which is much higher than that of other LAC soils (result not shown). Evidently, these properties as well as the high affinity for P are related with the "andic" features of this profile which were noted in the field but not taken into account in its "official" classification (Beinroth and Panichapong, 1979). In contrast, it is possible to propose, using Gillman's data (1974), that the relatively low P-sorption capacity of the gibbsitic Au_2 sample is due, in spite of a high surface area (Table 3), either to its high organic matter content or to the presence of adsorbed sulfate or both.

Si ads and P ads. In the present study, two parameters attempting to evaluate the "activity" of the oxide surface have been used: Si ads (whose only merit is in expanding the ISR scale; see Table 3) and P ads. These data are compared in Fig. 2 where it is apparent that the appraisal of this "activity" may be somewhat different depending on which index is used, which is not unexpected in view of the differences existing in the

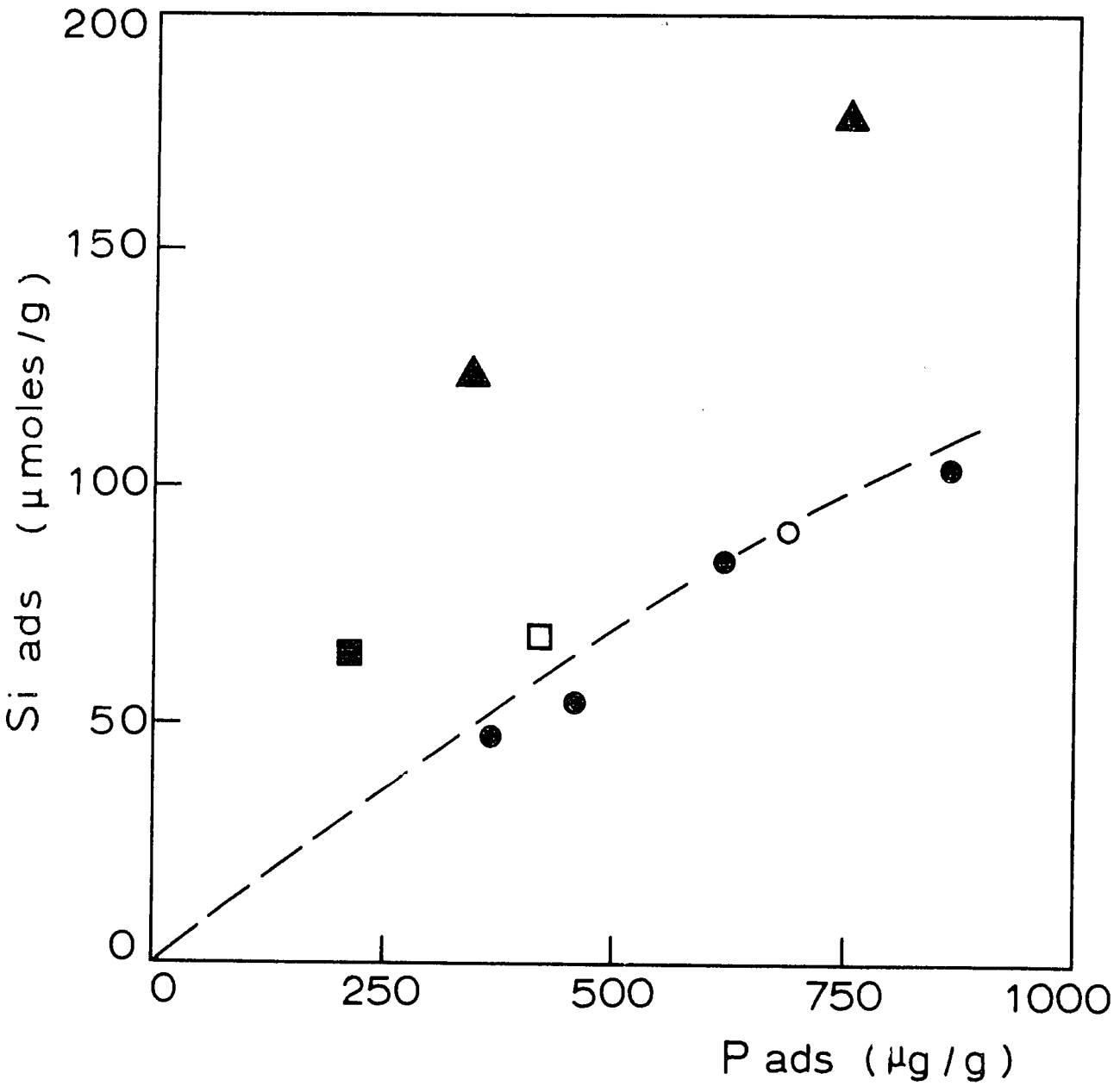

Fig. 2. Plot of Si ads (µmoles/g) versus P ads (µg/g); ■ "Montmorillonitic", □ "Mixed", ● "Kaolinitic", O "Oxidic" and ▲ "Gibbsitic" soils.

procedures adopted. Si ads, which is measured at pH 9, is better than P ads to detect the presence of free alumina "active" surfaces in the gibbsitic soils (triangle on Fig. 2). When combined with the soluble silica in the Index of Silica Saturation (ISS) (Herbillon et al., 1977) Si ads (or ISR) adequately shows which are the most desilicated soils (results not shown). If the intent is to rate the "activity" of the oxide surfaces from a soil management point of view, P ads, which has already been widely used for soil evaluation purpose (Fox, 1981), is to be preferred. It is important to note that both here and in previous papers (Juo and Fox, 1977; and Pope, 1978), P ads cannot be accurately predicted either by the free oxide content of a soil, or by its charge properties.

CONCLUSIONS

With the advantage of having a collection of clayey soils showing markedly contrasting mineralogical compositions, the primary objective of this paper was to test the practical feasibility of our previous proposals, namely substituting surface charge characteristics for the succinct mineralogical description which appears at present at the family level of Soil Taxonomy. It was shown that charge characteristics such as the permanent negative charge, the fraction of nonpermanent negative charge and the difference between CEC and AEC were all able to provide satisfactory mineralogical regroupings of these soils. This study showed that such charge characteristics, which are easily measurable routinely, may well be used at higher levels of the classification. They could determine the boundary between HAC and LAC soils and clarify the possible relationships between the acric character and the oxidic (or gibbsitic) mineralogy of soils. This is not wholly unexpected since, in Soil Taxonomy, charge properties have been selected as the prominent effect of the mineralogy and many important properties of LAC soils are due to their mineralogical compositions.

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DISCUSSION

Q. J. Bennema: What is the influence of organic matter on the soil management properties you mentioned?

A. A.J. Herbillon: The PO_4 sorption values reported in this paper are for subsurface samples, i.e., samples representative of the control section. PO_4 sorption values decrease indeed with the C content of the sample.

Q. S.W. Buol: Would you suggest a buffered pH, for example 5, to help standardize the CEC (NH_4Cl) values for the estimation of variable charge?

A. A.J. Herbillon: If a buffer is used, the effect of the buffer on the charge properties has to be known. The NH_4Cl procedure works at high ionic strength and necessitates washing steps that make it of poor value for estimating the permanent charge.

THE MINERALOGY OF LOW ACTIVITY CLAY SOILS OF ZAIRE

M.N. Makumbi

ABSTRACT

The present paper summarizes data on some chemical properties and clay mineralogy of selected soils of Zaire. It is pointed out that:

1. chemical soil properties depend on the weathering stage of materials and on climatic conditions;
2. kaolinite is a component of all soils except the youngest, where a complex mineralogical mixture exists;
3. amorphous materials (allophane, occurs only in the youngest soils;
4. soil stage is related to the amount of different clay minerals.

RÉSUMÉ

Le présent article résume les données sur les propriétés chimiques et la minéralogie de certains sols du Zaire. Il a été remarqué que:

1. les propriétés chimiques du sol dépendent de l'âge du matériau et des conditions climatiques;
2. la kaolinite constitue le minéral dominant dans tous les sols à l'exception des jeunes sols où il y a un mélange complexe des minéraux;
3. l'allophane se rencontre seulement dans les jeunes sols;
4. le contenu de différents minéraux varie avec l'âge des sols.

INTRODUCTION

The purpose of this paper is to summarize data on clay mineralogy of Zairian soils. Former publications established that ferrallitic soils are the most representative soils and contain a mixture of kaolinite and free oxides. This paper will present some additional data on the clay mineralogy of some particular old soils and some younger soils derived from recently weathered rocks Chemical and mineralogical properties will be emphasized.

Fripiat et al. (1954b) concluded that clay mineral occurrence was related to soil aging and the parent materials. Main results are reported in Table 1.

Table 1. Nature of clay fractions of some Zairian soils (Fripiat et al., 1954b).

Soil	Clay minerals	----Free oxides----		Location
		Gibbsite	Goethite	
Recent alluvial soils	Illite	-	-	Ruzizi valley
Aged alluvial soils	Montmorillonite; mixed layers, illite, kaolinite	Scarce	Scarce	Ruzizi valley
Ferrallitic soils	Well crystallized; kaolinite, illite on schist	Only high under savanna	High on slopes	Uele
Sandy bank soils	Well-formed kaolinite	-	High	Yangambi
Mountain ferrallitic soils	Kaolinite (fine clay), illite	?	Scarce	Nioka

MATERIALS

In Zaire soils derive from various parent rocks which can be classified into five main groups. According to Sys (1972) parent materials can be:

1. Sandy covers: Kalahari sands (End Tertiary), Salonga sands (Upper Pleistocene), Yangambi cover sands (Middle Pleistocene), low ground sands.
2. Mesozoic rocks: Karroo argillite, Karroo sandstone, psammitic shales.
3. Precambrian rocks: schist, epidotite, amphibolite, chlorito-schist, gneiss, basalt, granite.
4. River alluvial deposits.
5. Volcanic ashes.

Climatic conditions are very variable (Service météorique, 1961). Climate can be the Af type (Köppen) with annual rainfall of 1,600-1,900 mm and an almost constant annual temperature of 24-25 degrees C, or the Aw type (Köppen) with 2 to 6 months of dry season, annual rainfall between 1,100 mm and 1,800 mm and annual temperature between 16 and 24 degrees C, according to the altitude. Some restricted areas are under the Cm and Am climate types.

Most soils are very altered and according to the Zairian system of soil classification (Sys et al., 1961) they are mainly Ferralsols and Arenoferralsols, the most weathered soils. The moderately weathered soils are Ferrisols. On some particular sites recent tropical soils and brown tropical soils are found allowing the description of chemical and mineralogical transformations. Those soils are located in restricted areas. There are also black topical clays found on volcanic ashes.

Some properties of selected soils are presented in Table 2. Morphological and physico-chemical data are reported by Landu (1973), Makumbi and Jackson (1977), Rutunga (1975), Sys (1972). Fig. 1 shows soil location in the map of Zaire.

METHODS

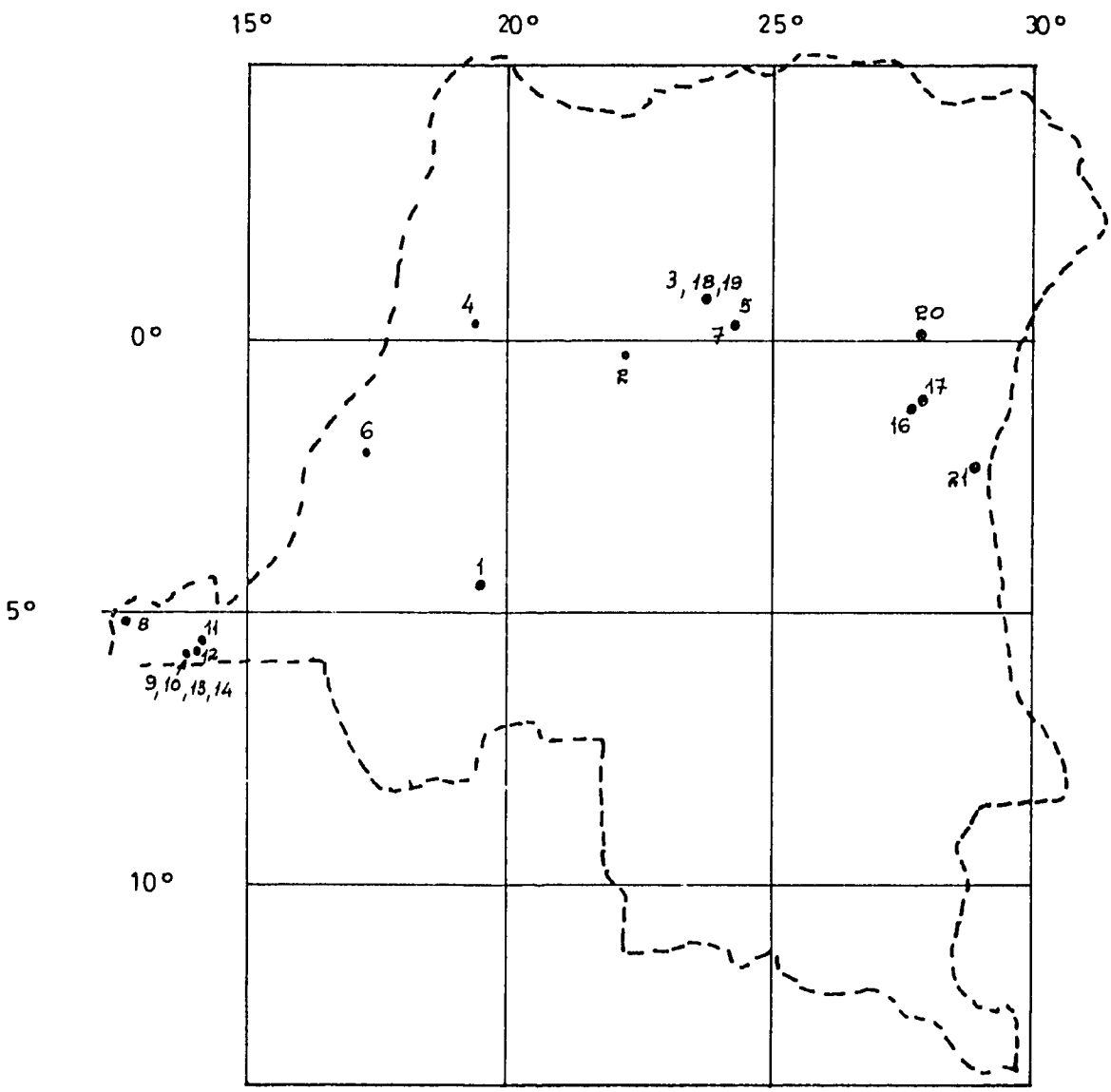
Soil pH was measured at 1:2.5 solution-soil ratio in H_2O and in 1N KCl. Exchange capacity was determined with NH_4OAc method at pH 7. Clay fraction was saturated and solved for X-ray determination according to

Table 2. Some properties of selected soils.

No.	Soil profiles[a]	Parent rocks	Location	Climate type	Clay content (%)
1	Arénoferralsol	Kalahari sand	Kwango	Aw3	6.80
2	Ferralsol	Salonga sand	Ikela	Af	23.38
3	Ferralsol	Yangambi sand	Yangambi	Af	35.40
4	Ferralsol	Low ground sand	Bolomba	Af	39.35
5	Ferrisol-brown tropical soil	Karroo argillite	Bengamisa	Af	57.86
6	Ferralsol	Karroo sandstone	Mushie	Aw3	58.12
7	Recent tropical soil	Karroo argillite	Bengamisa	Af	44.97
8	Brown tropical soil	Amphibolite	Luki	Aw4	42.07
9	Brown tropical soil	Micaschist	Matadi	Aw4	46.77
10	Ferralsol	Granite	Sohio	Aw4	52.90
11	Ferralsol	Limestone	Kimpese	Aw4	63.68
12	Brown tropical soil	Limestone	Kenge	Aw4	53.72
13	Recent tropical soil	Chloristoschist	Tshimpi	Aw4	32.65
14	Brown tropical soil	Chloristoschist	Tshimpi	Aw4	37.45
15	Ferrisol-brown tropical soil	Epidotite	Matadi	Aw4	61.10
16	Brown tropical soil	Volcanic ashes	Goma	Cf	21.30
17	Ferrisol-brown tropical soil	Volcanic ashes	Rutshuru	Am	38.17
18	Brown tropical soil	Recent alluvia	Yangambi	Af	55.00
19	Ferrisol	Recent alluvia of Zaire river	Yangambi	Af	44.00
20	Black tropical clay	Loam alluvial deposit	Semliki	Am	30.00
21	Black tropical clay	Recently weathered basalt	Bukavu	Cf	43.5

[a]Soils named according to Sys et al. (1961).

Fig. 1. Location of selected soils in the map of Zaire.



Jackson (1974). Oriented clay samples were brought to equilibrium at 45% relative humidity, glycolated and heated to 550 degrees C for 2 hours. The Li-DMSO test was used for expanding kaolinite (Abdel-Kader et al., 1976). D.T.A. of some clay samples was made in air atmosphere using Netsch analyzer at a heating rate of 10 degrees C/minute.

RESULTS AND DISCUSSION

Chemical Soil Properties

Data of the soil acidity and cation exchange capacity of soil samples are presented in Table 3.

The pH values of most soils are lower than 7 and seem to be related to the soil material weathering and to climatic conditions. The pH values are lower in KCl than H_2O (delta pH negative); more difference is shown with the youngest soils and some intermediate aged soils. According to Mekaru and Uehara (1972), when the delta pH is negative the soil colloid has a net negative charge. The negative delta pH values suggest that the soil colloid has a low point of zero charge (zpc) (Uehara and Keng, 1975). A lower zpc would be more indicated in the oldest soils than in the youngest soils. Delta pH values are mainly dependent on the clay kind and do not seem to be affected by the clay content.

According to Lin and Yu (1957) soil acidity is dependent on the presence of exchangeable aluminum related to the rainfall (Plucknett and Sherman, 1963). It is thought that the relative dehydration under the Aw type of climate could have decreased the amount of exchangeable Al by conversion to aluminous coatings on the cation exchange sites as suggested by De Villiers and Jackson (1967).

Soil CEC varies with soil stage; it is higher in the less weathered soils than in the oldest soils. The climate type seems also to influence the CEC of the youngest soils where soil CEC is lower under constant moisture regime (equatorial conditions) though delta pH values are high as shown in Fig. 2.

Fig. 2. Relationship between pH (absolute value) and CEC of clay fraction.

• weathered soils under any climatic conditions

⊙ the youngest soils under drier climatic conditions

△ the youngest soils under constant humid climatic conditions

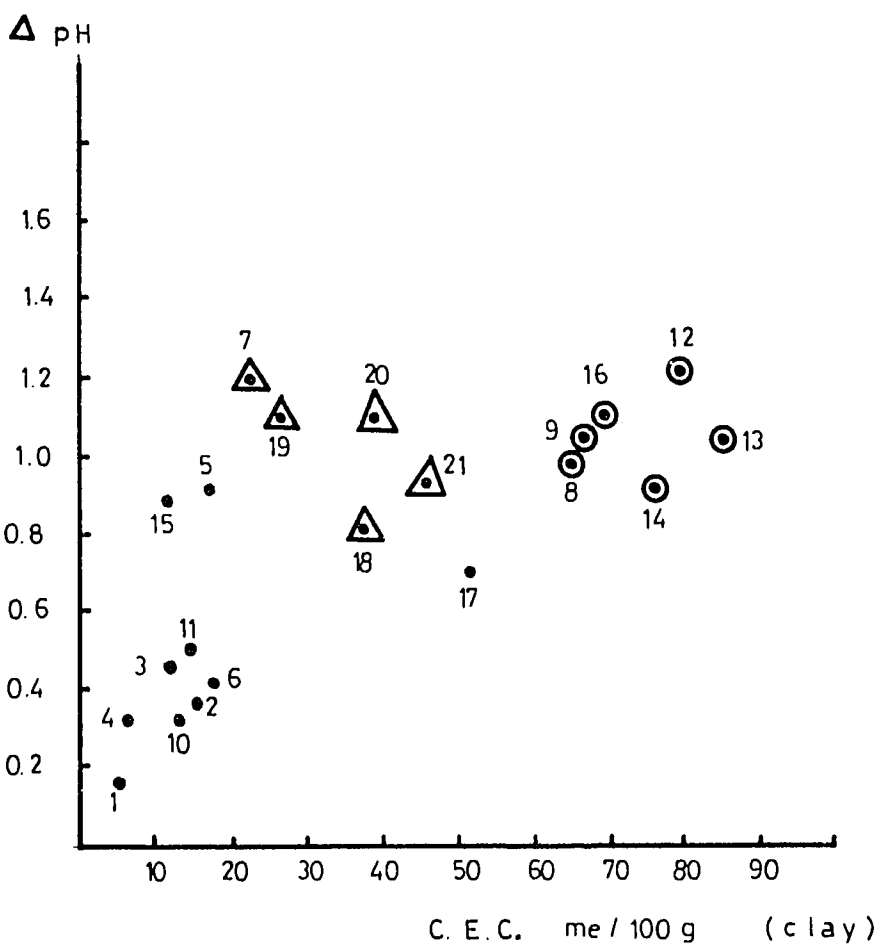


Table 3. pH Values and CEC of selected soils.

No.	Soil profiles	----pH----- H_2O	KCl	Delta pH	CEC (meq/100 g)
1	Arenoferralsol	4.16	--	-0.16	2.07
2	Ferralsol	4.40	5.15	-0.35	2.40
3	Ferralsol	4.33	3.88	-0.45	2.60
4	Ferralsol	4.90	4.59	-0.31	2.90
5	Ferrisol-brown tropical soil	4.55	3.63	-0.92	9.63
6	Ferralsol	4.60	4.18	-0.42	3.75
7	Recent tropical soil	5.09	3.90	-1.19	9.71
8	Brown tropical soil	5.78	4.80	-0.98	27.40
9	Brown tropical soil	6.49	5.45	-1.04	28.00
10	Ferralsol	4.53	4.20	-0.33	13.35
11	Ferralsol	4.48	3.98	-0.50	8.90
12	Brown tropical soil	6.77	5.55	-1.22	33.82
13	Recent tropical soil	6.33	5.29	-1.04	27.80
14	Brown tropical soil	6.76	5.84	-0.92	24.90
15	Ferrisol-brown tropical soil	6.76	5.89	-0.87	8.75
16	Brown tropical soil	6.70	5.61	-1.09	14.50
17	Ferrisol-brown tropical soil	5.55	4.83	-0.72	11.00
18	Brown tropical soil	4.70	3.88	-0.82	17.81
19	Ferrisol	4.65	3.56	-1.09	10.85
20	Black tropical clay	6.65	5.55	-1.10	11.75
21	Black tropical clay	5.75	4.82	-0.93	14.40

Soil Clay Mineralogy

Table 4 presents clay minerals of selected soils and their exchange properties. The CEC of the clay fractions is clearly dependent on the clay mineral nature. Soils containing kaolinite have a lower CEC than soils rich in open lattices such as illite, smectites and vermiculite. The youngest soils under the Af type of climate seem to develop a lower CEC

Table 4. CEC and mineralogy of soil clay fraction.

No.	Soil profiles	CEC (meq/100 g)	Clay mineralogy
1	Arenoferralsol	4.93	Kaolinite, goethite, gibbsite, quartz
2	Ferralsol	10.51	Kaolinite, goethite, (gibbsite)
3	Ferralsol	11.51	Kaolinite, goethite
4	Ferralsol	7.43	Kaolinite, goethite
5	Ferrisol	16.64	Kaolinite, goethite, (micaceous mineral)
6	Ferralsol	17.20	Kaolinite, goethite
7	Recent tropical soil	22.28	Mixed-layers containing mica, vermiculite, montmorillonite; kaolinite
8	Brown tropical soil	65.13	Smectites, halloysite, amorphous materials, (kaolinite), goethite
9	Brown tropical soil	67.25	Smectites, amorphous materials, (kaolinite), goethite
10	Ferralsol	13.50	Kaolinite, goethite, (gibbsite)
11	Ferralsol	13.98	Kaolinite, goethite, quartz
12	Brown tropical soil	79.60	Smectites, halloysite, (kaolinite), goethite
13	Recent tropical soil	84.90	Dioctahedral, smectites, irregularly interstratified chloride-vermiculite, (kaolinite)
14	Brown tropical soil	76.30	Beidellite, kaolinite, (goethite)
15	Ferrisol-brown tropical soil	11.20	Kaolinite, goethite
16	Brown tropical soil	69.04	Amorphous materials, goethite
17	Ferrisol-brown tropical	51.09	Allophane, kaolinite, micaceous minerals
18	Brown tropical soil	37.00	Micaceous minerals, (kaolinite, smectites)
19	Ferrisol-brown tropical soil	26.00	Kaolinite, micaceous minerals, goethite
20	Black tropical clay	39.16	Smectites, illite (kaolinite)
21	Black tropical clay	69.50	Allophane, (fire clay)

than other similar soils under drier climate. It is thought that exchangeable Al is the most representative cation on exchange sites of clays under constant humid conditions and tightly fixed by clay minerals.

Kaolinite is formed from various rock minerals in a leaching environment. The most weathered soils (Ferralsols, Arenoferralsols) and some moderately weathered soils (Ferrisols) contain kaolinite associated with various free oxides as reported by Fripiat et al. (1954b), Makumbi (1974). Goethite occurs in almost all soils and gibbsite is found in the very altered soils. Fig. 3 presents D.T.A. curves of clay fractions for main soil groups.

In the most acid old soils kaolinite is partially destroyed and excess alumina crystallizes as gibbsite. The latter occurs in sandy soils derived from Kalahari sand under tropical conditions and degraded savannah. According to Landu (1973) kaolinite crystals are finer in the upper horizons than in the lower horizons and seem to be "clay fire" as reported by Sys (1972). Kaolinite from other sandy materials is moderately or well formed coarse crystals (Fripiat et al., 1954b; Makumbi, 1967). Generally soils derived from volcanic ashes and alluvial deposits contain poorly organized kaolinite crystals.

Kaolinite is sometimes found in the less weathered soils. Makumbi and Jackson (1977) suggested that discrete mica occlusions exist within kaolinite crystals, particularly in fine clay of recent tropical soil derived from Karroo argillite. Deferrated fine clay shows a very small shoulder at 11.2 Angstroms. The 7.1 Angstrom peak is not much affected by the DMSO test, while deferrated coarse clay shows a complete expansion with a strong 11.2 Angstrom peak as shown in Fig. 4. Similar behavior was observed with potassium acetate intercalation in fine-grained kaolinite by Wieiwiora and Brindley (1969). It is suggested that fine and coarse kaolinite crystals derive respectively from muscovite and feldspar present in the parent rock.

Occasionally kaolinite of some young soils formed from chloritoschist appears under physico-chemical conditions (pH near to neutrality, full saturation of soil by Mg^{++} and Ca^{++}) which are far removed from those usually thought to be favorable for aluminum individualization and kaolinite synthesis (Herbillon and Makumbi, 1975; Makumbi, 1972). The presence of free alumina or silico-alumina (?) leads to the kaolinitization as a result of

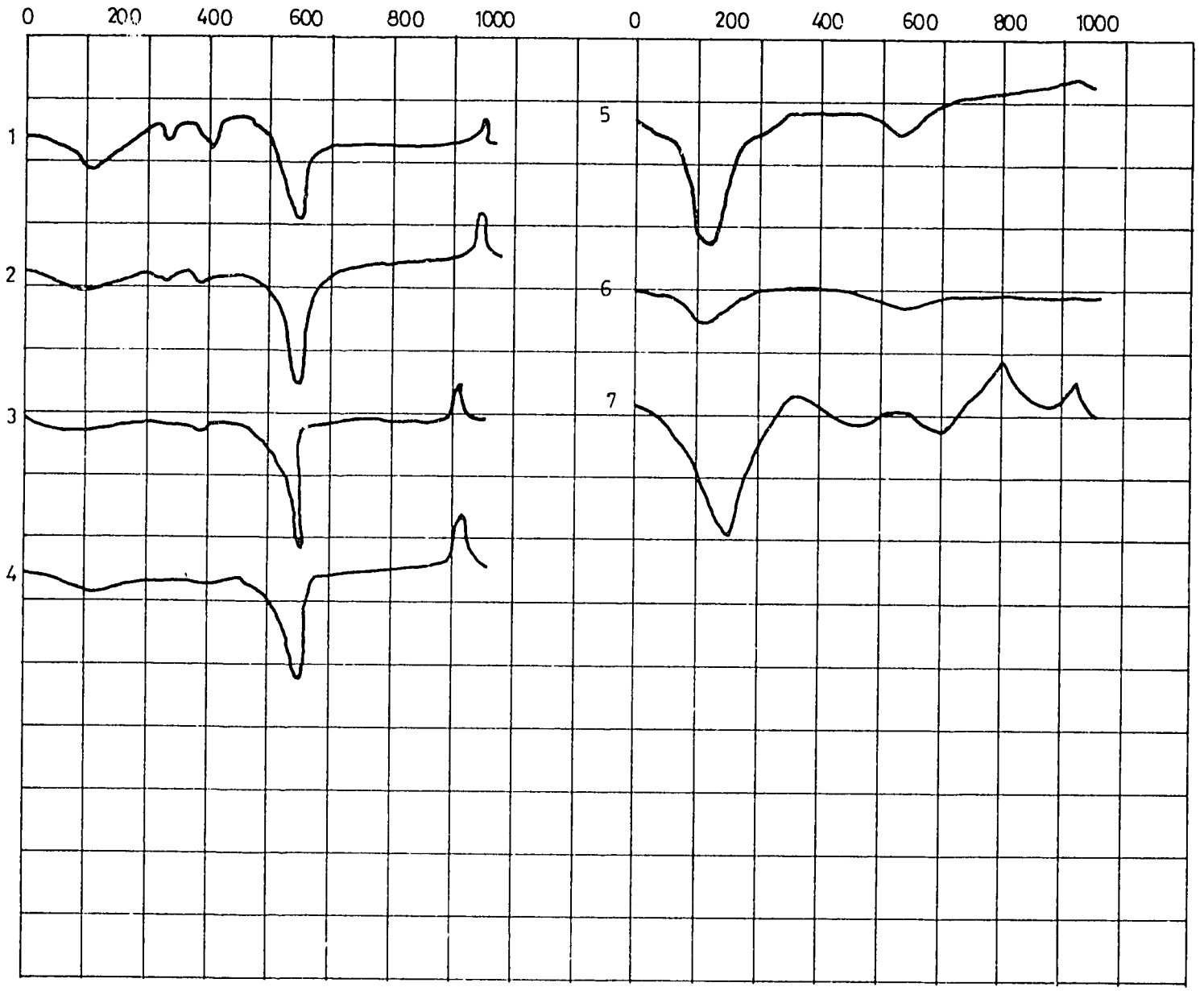


Fig. 3. D.T.A. curves of main soil groups.

1: clay fraction from Kalahari sand
2: clay fraction from Salonga sand
3: clay fraction from Yangambi sand
4: clay fraction from ground sand
5: clay fraction from volcanic ashes
6: clay fraction from basalt
7: clay fraction from chloritoschist

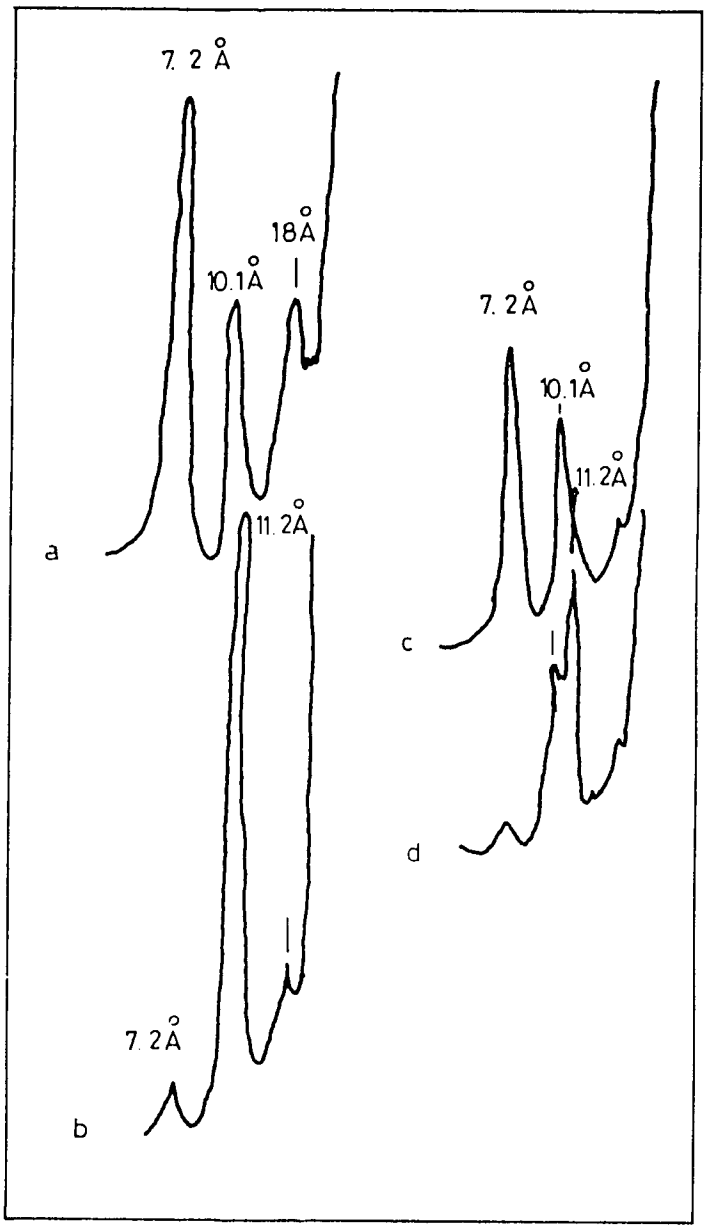


Fig. 4. X-ray diffractograms of fine clay and coarse clay of soil derived from Karroo argillite after the DMSO test.

a: nondeferrated coarse clay (sample 5)
b: deferrated coarse clay (sample 5)
c: fine deferrated clay (sample 7)
d: coarse deferrated clay (sample 7)

preferential leaching in some profile zones. Kaolinite genesis clearly progresses from bottom to top in those recent tropical soils. Smectites (beidellite) is the most important clay mineral in those soils; it occurs in mixture with kaolinite and an irregularly interstratified "chlorite-like" mineral. Magnesium is lost less rapidly than calcium; any remaining magnesium participates to the genesis of the irregularly interstratified "chlorite-like" mineral.

In some scarce particular conditions smectites occur with a mixture of halloysite and amorphous materials (Makumbi and Mvumbi-Phasi, 1973; Stoops, 1966). Halloysitization occurs in the calcium-magnesium environment (Cortes and Franzmeier, 1972; Craig and Loughan, 1964; Minato and Utada, 1972). It is observed when the parent rock is depleted of mica. Halloysite is rapidly transformed into kaolinite with the aging of soil.

Illite and micaceous minerals are present in the clay fractions of soils from the mica-rich parent rock and from alluvial deposits. Generally chemical weathering of mica is shown by broadening of the 10 Angstrom peak resulting from the presence of expanded layers as a consequence of potassium loss; the interlayers contain cations and amorphous materials.

The black tropical clays derived from volcanic ashes have allophane as the main clay mineral while those from basalt residue contain illite and kaolinite.

A prominent clay feature is the coating by free oxides which generally increases with the soil aging (Fripiat and Gastuche, 1952) and depends on the parent rock nature. Herbillon and Tran Vinh An (1967) considered that amorphous material in the oldest soils was the result of kaolinite weathering. Makumbi and Jackson (1977) illustrated clay coating occurrence in the youngest soils where coatings are seen as a result of attraction between the high negative charge of clay minerals (smectite) and positive hydrous metal (Fe, Al) oxide charge. According to Roth et al. (1968), this attraction may prevent uniform opening of the layers prior to free oxide removal. That contributes to reducing the CEC values of some of the youngest soils as reported previously. The presence of such oxides on the surfaces of micaceous vermiculite layers as a result of chemical weathering has been clearly shown (Mokma et al., 1970; Jackson et al., 1973).

Soil Stage and Clay Mineral Content

Soil stage is related to the content of various clay minerals and other associated minerals as reported in Table 5. Goethite is found in all soils. The oldest soils contain the highest kaolinite content and the most altered have gibbsite in addition. Gibbsite seems to depend on parent materials (Makumbi, 1973), and on vegetation type (savannah) (Fripiat et al., 1954a). It is pointed out that gibbsite is often associated with poorly crystallized kaolinite.

The moderately weathered soils have a mixture of kaolinite and illite, while the youngest soils are characterized by a complex association of smectites, amorphous materials and interstratified clay minerals.

Table 5. Clay mineral content in relationship with soil stage (Makumbi, 1974).

Soil stage	Percent of clay minerals				
	kaolinite halloysite	illite smectites	amorphous materials	gibbsite	fe-oxide
Arenoferralsols	80-90	-	t	10	10
Ferralsols	80-90	-	t	3	10
Ferralsols-ferrisols	70-80	-	t	3	10
Ferrisols	60-75	10-20	-	-	10-15
Brown tropical soils	10-25	65-70	10	-	10
Recent tropical soils	15	75-80	10	-	10

t: trace

CONCLUSION

Kaolinite is the most important and stable clay mineral in the most representative soils. It is found in almost all soils and its content depends on soil age. It is neoformed from rock minerals and clay lattices and its crystallization is related to the nature of the parent rocks.

Allophane appears in soils derived from volcanic ashes and rocks depleted of mica in an open leaching environment. Allophane will be transformed into kaolinite or halloysite according to the medium conditions. Halloysite can sometimes exist in a calcium-rich medium.

The youngest soils are characterized by a mixture of smectites, kaolinite and illite.

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PATHWAYS OF OXISOL FORMATION

S.W. Buol

ABSTRACT

Utilizing a combination of available data and hypotheses, processes are proposed to explain how argillic and "argillic-like" horizons develop in soil material with mineralogical and chemical properties of oxic horizons. In the scenarios proposed soils that have saturation $\rightleftarrows$ desiccation cycles within about 25 cm to 2 m of the soil surface form blocky structure and stress cutans often identified as clay skins. Free drainage is considered a requirement for true Oxisol formation. Mechanisms are proposed to explain why Oxisols are seldom found on *in situ* acid igneous rock or coastal plain sediments. A mechanism is also proposed to explain how Oxisol materials can develop "argillic-like" horizons on side slopes via lateral-flow saturation.

INTRODUCTION

Almost without exception references to Oxisols state that they are highly weathered soils. Soil Taxonomy (Soil Survey Staff, 1975) does not inject this pedogenetically biasing term "weathering" in its discussion of Oxisols except in the context of describing Oxisols as deep soils. Many of the connotations associated with weathering, such as low base saturation or humid moisture regimes, are not present throughout the soils that classify as Oxisols (Eswaran and Tavernier, 1980).

As with individual pedons of any soil order, no single pedogenic pathway is seen as universal for all Oxisol pedons. It is probable that any attempt to characterize pedogenic pathways will overlook certain significant members of the population. However, it appears that certain scenarios

can be discussed. This paper attempts to update concepts of Oxisol formation from data new since our last meeting (Buol, 1979a).

PLINTHITE SCENARIO

Plinthaquox are Oxisols that are not required to have an oxic horizon. The pedogenic setting needed is one with an aquic soil moisture regime and enough iron in the groundwater system to provide for the accumulation of continuous phase plinthite within 125 cm of the soil surface. Such soils are described in the 7th approximation (Soil Survey Staff, 1960) as "occurring in wet sites, on flood plains, or at the base of slopes where there is or has been seepage, as in old paddy fields. A few may occur on slopes where erosion has perhaps truncated a soil and left plinthite close to the surface."

Such soils seem to be rare in nature and examples were not found in the literature. Soil approaching Plinthaquox characteristics have been studied in the Llanos Orientales of Columbia (Mejia, 1975). There plinthite formation was found to approximate the water table depth observed in the topographically low portions of the toposequence but the plinthite was not a continuous phase, resulting in the classification of the soils as Plinthic Umbraquox. Although the Subgroup Superic Plinthaquox was proposed for Plinthaquox with continuous phase plinthite within 30 cm of the surface, I have not been able to obtain any published description of an actual occurrence.

MODAL OXISOL GENESIS

Having disposed of the plinthite scenario that defines a very few of the Oxisols we can concentrate on the major characteristics associated with Oxisols and possible pedogenic pathways.

Texturally, the pathways of Oxisol formation are limited to those parent materials that either contain more than 15% clay or upon weathering yield more than 15% clay. Mineralogically it is necessary that kaolinite

be created or preserved as the dominant silicate clay. Various admixtures of gibbsite, iron oxides and other silicate clays often are present but no more than about 10% vermiculite or smectite can be present to attain an apparent CEC/100 g clay of less than 16 meq at pH 7. The mineral composition of the clay fraction of Oxisols at some time in its history follows one of the pathways of kaolinite formation outlined in Fig. 1.

While a great deal of study has been focused on the mica → kaolinite transformation in glacial materials (Jackson et al., 1952) it has only been recently that the feldspar → kaolinite pathways have been studied in the context of soil formation (Eswaran and Bin, 1978; Calvert et al., 1980). These studies clearly show that the clay-sized particles formed by *in situ* weathering of granite several meters below the soil solum attain the mineral composition and CEC properties defined as oxic horizon properties. This pathway of kaolinite formation forces soil science to alter the strongly held concept that kaolinite is the product of exceedingly severe and prolonged weathering required to produce kaolinite from mica. Simply, the weathering environment below the argillic horizon in Ultisols of udic soil moisture regimes will produce kaolinite from feldspars contained in granite rock. Evidence of clay mineral suites of oxic composition formed in Ustalfs and Ustults indicate that this transformation is probable in ustic moisture regimes although detailed mineral transformation studies have not been carried out.

Once earthy material that meets the mineralogical requirements of low CEC and near absence of weatherable minerals has been produced we are well along the pathway of Oxisol formation except for the requirement that an Oxisol not have an argillic horizon.

FORMATION OF THE ARGILLIC EXCLUSION

It has been amply demonstrated to this group during our meetings in Brazil, Malaysia and Thailand that B horizons having oxic mineralogy often have the morphology of argillic horizons. Further, much to our consternation, we are not always able to agree on the placement of many profiles as either Oxisol or Ultisol-Alfisol.

Figure 1: Pathways of Mineral Transformation Leading to Kaolinite Formation in Soil. (After Eswaran and Bin, 1978; Calvert et al., 1980).

Parent Rock Mineral:

Muscovite → Vermiform Kaolin → Kaolinite

Feldspar → Halloysite → Kaolinite

↘ Gibbsite → Halloysite → Kaolinite

Some soil scientists hold the idea that argillic horizons form in oxic materials. Pathways for the formation involve freeing the silicate clays of iron oxide coatings via sheer (Beinroth, Uehara and Ikawa, 1974), or short term reduction of iron oxides on hillslopes by laterally moving water (Lepsch, Buol and Daniels, 1977). An opposing scenario of disruption of blocky structural argillic horizons on stable geomorphic surfaces by faunal pedoturbation has also been proposed (Lepsch and Buol, 1974). Regardless of the contrasting scenarios proposed, all the situations reported substantiate the observation that the Oxisol profiles, with clearly no argillic horizon, occur on nearly level surfaces while argillic, or "argillic-like," horizons occur adjacent to these surfaces on side slopes (Bennema, Camargo and Wright, 1962).

A more recent study of two Oxisol-Ultisol toposequences in São Paulo, Brazil, incorporates parts of these previous investigations and offers a more complete explanation of the pathway of Oxisol formation (Moniz, 1980).

Free drainage is critical to the formation of Oxisols with low bulk density, free of well-defined blocky structure. In order to have free drainage the subsurface layers of soil that are subjected to transpirational water loss cannot become saturated. During a period of time when the soil material is saturated there is no strength (apparent cohesion, Lambe and Whitman, 1969) given to soil structural units (peds) by capillary tension. Thus, in the absence of cementing agents such as silicate, iron or carbonate, the soil particles are individually separated from each other by water films. As water is withdrawn via transpiration or slow percolation out of the saturated material, larger pores empty first and a certain amount of cohesion develops. Desiccation cracks start forming as the tensile strength of the water surfaces is overcome in the larger pores, which as the material shrinks are along the desiccation cracks. Desiccation or shrinkage cracks so produced are precursors of blocky structure (White, 1966 and 1967; Sleeman, 1963; van de Graaf, 1978). The shrinkage cracks close during the next wetting. The contact between the surfaces is not perfect and contact occurs first on the high points on the sides of the cracks. At these contact points pressures are high, even under light total pressure, and plastic deformation occurs (Lambe and Whitman, 1969). The deformation is accomplished primarily by the relative sliding and rolling

of particles. The net result of the deformation is the migration of larger particles, sand, into the ped leaving the ped surface enriched with clay particles that may also undergo gradual reorientation into parallel orientation because of their platy shape. This alignment of fine particles normal to the pressure is similar to that which occurs in a shear surface (Hills, 1963; Williamson, 1978 and 1980). Real difficulty exists in detecting between deformation caused by orientation at the surface of blocky peds, called stress cutans (Brewer, 1960), and illuviationargillans which may form over the stress cutan. Also, illuviation argillans are subject to deformation by this process.

Full development of a blocky ped surface occurs when these planar voids are maintained in the same place through several saturation and desiccation cycles. After a ped surface is fully developed it seems reasonable to expect it to persist through successive wetting and drying cycles (Robinson, 1949; Cseratzki and Frese, 1958 and Gotschalk, 1957). For maintenance, any tendency of the blocky peds to break down during wetting has to be neutralized by confinement in all directions by neighboring peds.

Near the soil surface there is space for the peds to partially slake during saturation and reform upon desiccation into granular structure because they are free of confining pressure of overlying material. Also, a higher degree of compression is favored by a slow rate of drying. This favors less compression in surface layers because of their exposure to more rapid evaporation and transpiration of shallow-rooted plants. It is observed that A horizons of granular structure are usually found over compressed blocky structured B horizons even though the A horizon may occasionally become saturated.

The foregoing scenario of blocky structure formation by requiring repeated saturation and desiccation effectively removes soils subject to slow saturation $\rightleftarrows$ desiccation cycles from our present consideration as Oxisols because they develop morphological features, i.e. blocky structures, clay skin "like" features on blocky ped faces, and greater bulk density than associated, if not defined in, "true" Oxisols.

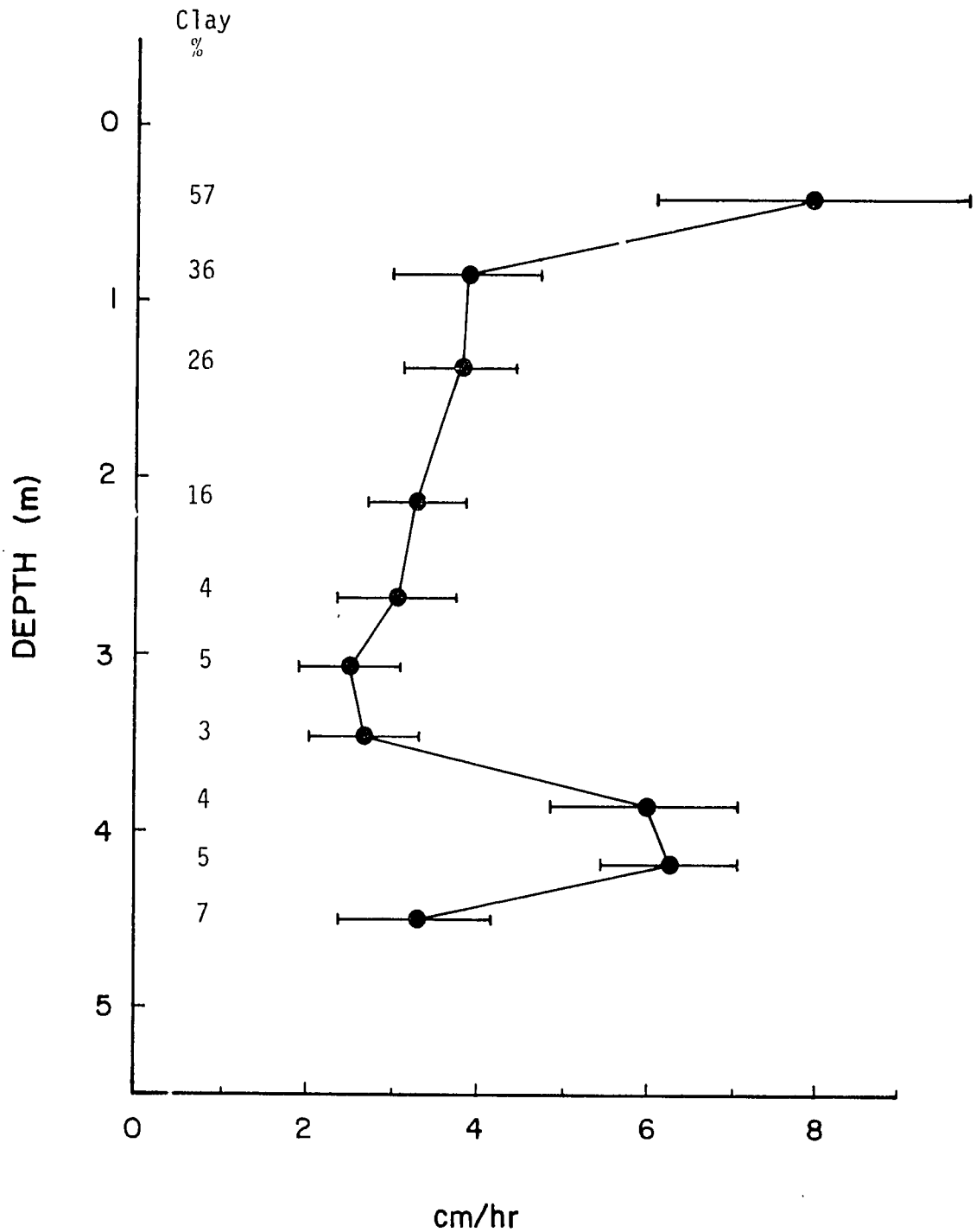
ANALYSIS OF SETTINGS WITH RESPECT TO PROPOSED PATHWAY

We need to examine the physical setting where conditions favor this saturation ⇄ desiccation cycle in order to determine where we do not form Oxisols and then by elimination identify those situations where Oxisols should be expected.

In Situ Formation on Acid Igneous Rock

Landscape positions conducive to saturation ⇄ desiccation are common in materials that have CEC and mineralogical properties defined as Oxic. The first is the *in situ* formation of soil over saprolite weathered from granite in climates where rainfall exceeds evapotranspiration during some part of the year. Such a situation occurs in the udic moisture regimes in southeastern U.S. Hapludults with CEC/100 g clay values less than 16 meq are common over granite (Buol, 1979b). The clay content in such soils commonly is found to be like that in Fig. 2. The amount of clay is not inversely related to the saturated conductivity of the material in and below the B horizon (O'Brien, 1978). Note the pronounced decrease in saturated hydraulic conductivity below the B horizon as the clay content decreases from some 57% to less than 10%. The reason for this reduction in hydraulic conductivity is seen in thin sections as an absence of root channels (compound voids) probably related to lack of Ca and/or Al toxic conditions in the saprolite (Fig. 3). Thus after a rain event water is perched above this slower conducting saprolite creating saturated conditions. It is obvious that saturation does not persist for very long because reduction of iron does not take place and the soil is red in color (Daniels, Gamble and Buol, 1973). It is common experience, however, to dig a pit at such a site the day after a rain and find that water flows freely from the material above the saprolite while the saprolite itself is not saturated. Blocky structure is well developed in such soils and little concern for placing them as Oxisols would be expressed except for the fact that they have oxic CEC and clay mineralogy. Note specifically that the reduction in hydraulic conductivity takes place within less than 1 m of the surface. It is hypothesized that the closer the low conductivity layer is to the surface the more frequent the temporary saturation occurs and the more fre-

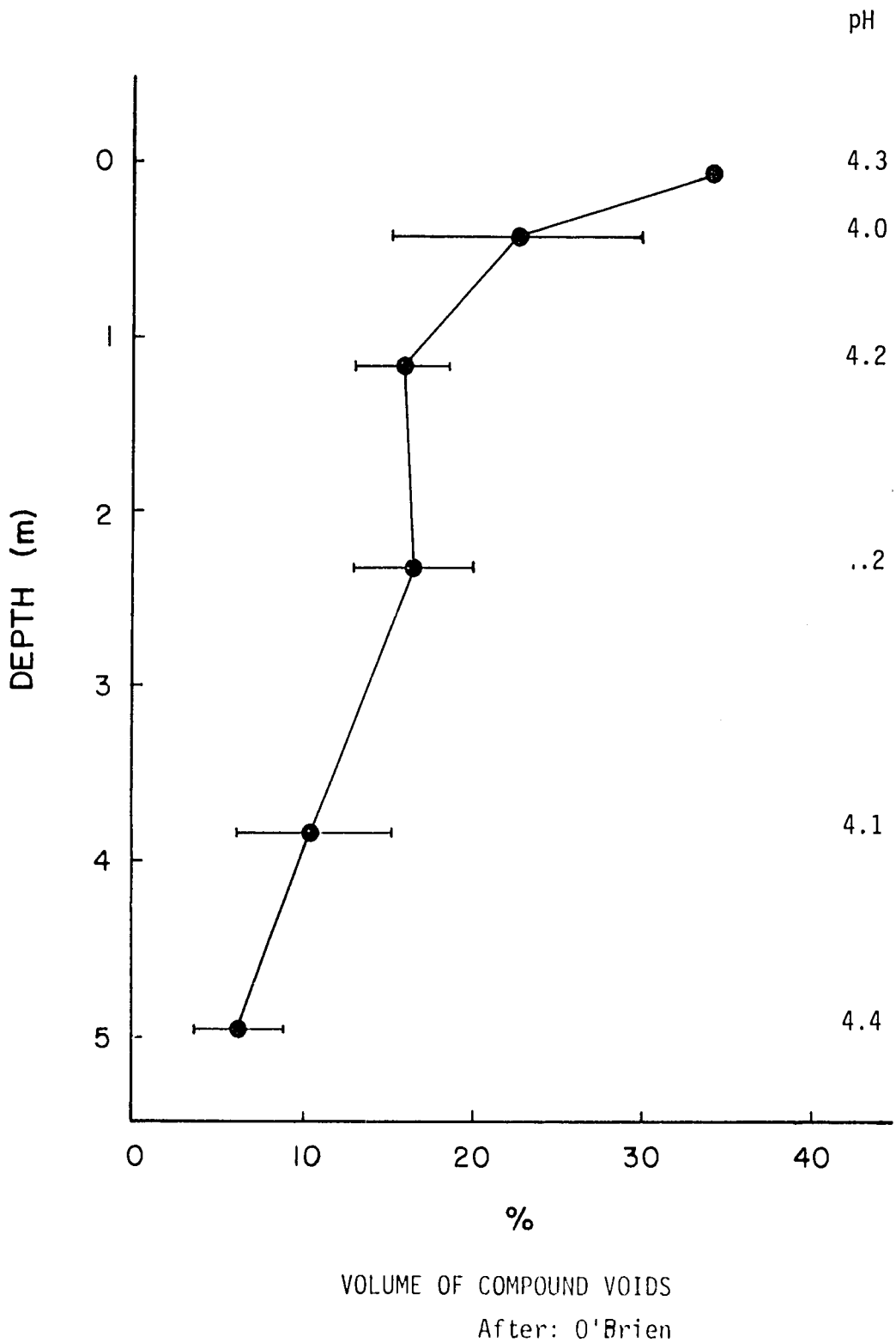
Fig. 2. Clay content and saturated hydraulic conductivity of a Typic Hapludult-Saprolite sequence. (After O'Brien, 1978)



SATURATED HYDRAULIC CONDUCTIVITY VERSUS DEPTH

After: O'Brien

Fig. 3. Volume of compound voids in a Typic Hapludult-Saprolite sequence. (After O'Brien, 1978)



quently the entire saturation $\rightleftarrows$ desiccation cycle is carried out given the same rainfall distribution pattern. Also proximity to the surface should contribute to greater desiccation and thus greater compression upon desiccation during prolonged dry periods. It is critical, however, that it occur deep enough so that overburden weight provides containment and prevents free slaking.

In Situ Formation Over Basic Rocks

There are Oxisols reported as forming *in situ* on basic rock. Certainly the Nipe (Typic Acrothox) formed over serpentinite has influenced our thinking in this regard. The weathering of basic rocks into saprolite perhaps produces less root toxic conditions than those present in acid rock saprolite. Thus, there would be more deep rooting and greater hydraulic conductivity in saprolite produced from basic rocks than in acid saprolite. It should not be concluded that this is a rooting vs. no rooting situation. Certainly some roots penetrate acid saprolite. The volume and proliferation of roots is in question and data appears lacking. More prolific rooting in saprolite would lead to more rapid percolation in and through the saprolite and a lesser chance of developing saturated conditions immediately above the saprolite.

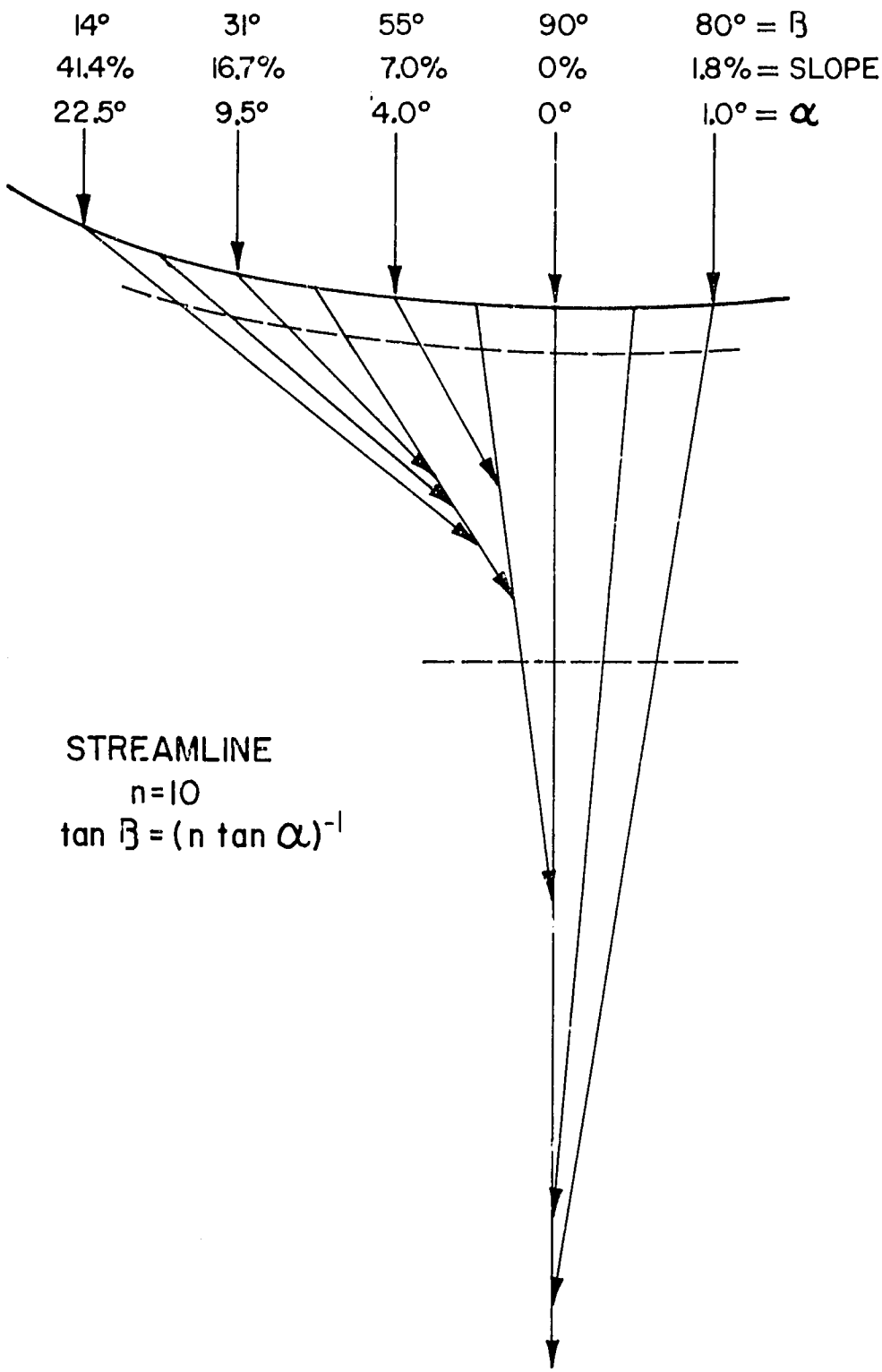
Development of Blocky Structured B Horizons in Oxic Sediments

Blocky structured B horizons in materials of oxic composition occur on the side slopes in deep, well-drained sediments. Saturated conditions appear probable near the soil surface on these side slopes as a result of lateral flow as predicted by Zaslavsky and Rogowski (Fig. 4, 1969). The saturation near the surface appears to be further enhanced via the double-water flow model proposed by Moniz (Fig. 5, 1980).

Formation of Argillic Horizons in Coastal Plain Oxic Sediments

Paleudults and Paleaquults of oxic composition often develop in coastal sediments (Buol, 1979b). Here the developmental sequence often involves nearly level surfaces that have high water tables. As surface drainage increases via river entrenchment, regional water tables deepen

Fig. 4. Lateral flow as predicted on slopes with vertical hydraulic conductivity heterogeneity. (After Zaslavsky and Rogowski, 1969)



After Zaslavsky and Rogowski, 1969

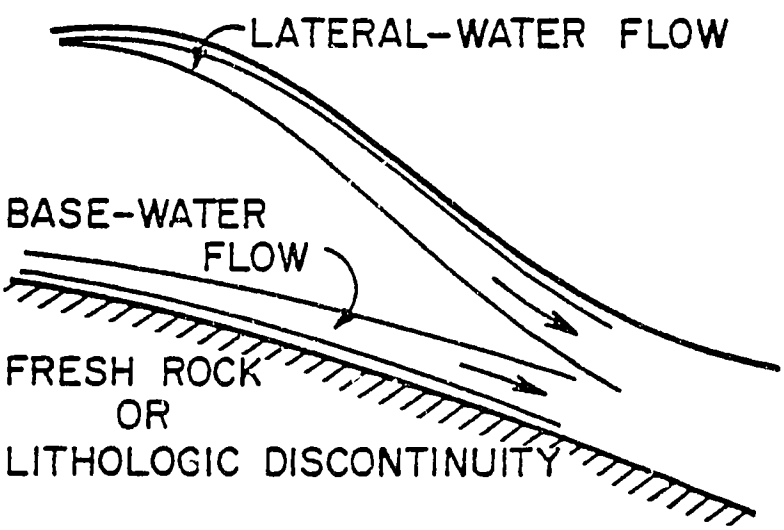


Figure 5. Directions of the double-water flow along the slope (after Moniz, 1980)

and many soils become well drained. This process may extend over several millions of years. As we view these Paleudults today they have argillic horizons with weak blocky structure devoid of clay skins. More importantly they are now freely drained to several meters and saturation in the B horizon (within a meter or two of the surface) seldom takes place. The blocky structure appears weak, grading to a massive structure. Clay skins and pressure orientation are evident only on the slowly down-cutting side slope of Hapludults where it could be reasoned that lateral interflow produces saturation in the B horizon near the soil surface.

SUMMARY OF ARGILLIC EXCLUSION

In summary, it is concluded that Oxisols are excluded by "argillic-like" horizon formation if alternating saturation $\rightleftarrows$ desiccation cycles frequently take place in materials of oxic composition within approximately 25 cm to 2 m of the soil surface. The critical depth is probably less in more humid areas than in strong ustic areas. Saturation $\rightleftarrows$ desiccation cycles are postulated as occurring most frequently on *in situ* formation of soil over acidic saprolite of lower hydraulic conductivity than the overlying soil; on side slope positions because of lateral water flow (sometimes called interflow) and soils with a history of high water tables. Oxisols are confined to nearly level slopes in materials with uniform hydraulic conductivity to depths that allow the upper 2 m to remain unsaturated.

This proposed pathway needs to be critically examined throughout the occurrence of Oxisols and the proposed Kandi great groups. In this discussion a mechanism of excluding soils from Oxisol formation has been used in an attempt to show where and how compressed, blocky structured B horizons with clay skin or " clay-skin-like" ped faces normally excluded from Oxisols form.

In the author's experience this scenario fits the landscape pattern of Oxisol-Ultisol occurrence on the deep sediments in central Brazil and explains why "argillic-like" horizons are formed in other areas. It also seems to be capable of explaining the formation of the profiles with oxic horizons over argillic horizons as described by Eswaran and Bin, 1978.

In their profiles they postulate significant restriction of hydraulic conductivity at 275 cm and record subangular blocky structure without clay skins above that depth, a feature common to Paleudults in the U.S. (Cady and Daniels, 1968; Gamble et al., 1970). The proposed reason for weak or nearly absent blocky structure in the upper B horizon is that the restrictive hydraulic conductivity is presently so deep that the saturation $\rightleftarrows$ desiccation cycle is not often complete and a strong grade of blocky structure that may have been present before the B horizon-saprolite or water table contact deepened is not presently maintained in these free-draining Paleudults (Kandudults).

Yet to be explained is the vertical increase in clay content associated with Ultisols and Alfisols of Oxisol mineralogy and CEC properties. A possible scenario is that when the argillic horizon is in the saturated portion of its saturation $\rightleftarrows$ desiccation cycle, saturation may extend to the surface. The surface layer having more organic matter and also being subjected to higher daytime temperatures becomes a preferred media for biological activity and thus reduction of iron. As the iron is reduced it frees clay for lessivage. This point is something the author has not been entirely successful in demonstrating. One years' data with platinum electrodes in A2 and B22t horizons of Ultisols near Raleigh, N.C., USA, found that the A2 horizon was very close to the $Fe^{+++} \rightarrow Fe^{++}$ stability line (Collins and Buol, 1970) especially in the early summer while the B22t remained well in the Fe^{+++} stability field all year. In fact, some of the individual electrodes in the replication net of electrodes in the A2 horizon did reach the Fe^{++} field but the average remained in the Fe^{+++} field throughout the year.

Lessivage is not the only pathway of reducing the clay content of the surface. Preferential removal of clays by surface erosion and/or dissolution (appauvrissement) can certainly explain some of the textural coarsening of surface horizons on side slopes.

CONCLUSIONS

It has been reasoned, utilizing a combination of available data and hypotheses, that unquestioned (modal) Oxisols without clay content increase

with depth, blocky structure, bulk densities greater than approximately 1.3 gm/cm^3, and few if any clay skins develop where:

1. parent materials have, or weather to >15% clay;
2. there is no decrease in the hydraulic conductivity between about 25 cm to 2 m of the surface of such magnitude as to create saturation without reduction under the ambient climatic regime;
3. lateral (subsurface) flow of water does not cause saturation within about 2 m of the surface as on side slope positions;
4. the low CEC and lack of weatherable minerals is achieved either by present or past weathering of minerals. Extraordinary weathering is not needed in the case of feldspar alteration to kaolinite.

All Oxisols are subject to further alteration by the formation of argillic or pseudo-argillic horizons via compression by desiccation if saturated conditions are created as in side slope positions upon expected geomorphic succession of hill slopes and associated lateral (interflow) saturation. Plinthaquox are special conditions requiring high iron content and lateral flow of reduced water near the surface.

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DISCUSSION

Q. W.G. Sombroek: 1. Is it not possible that, in the São Paulo situation, the sideslopes are younger than the flat tops and hence show less advanced soil formation? 2. Could it be that in the coastal sediments of North Carolina the presence of some Na and Mg induces a solonetzic-solodic soil development, preventing further weathering to Oxisols?

A. S.W. Buol: 1. Detailed morphological work on these positions in the São Paulo studies by Moniz contain convincing data that we have pedogenic formation of 2:1 clay minerals on these sideslopes which of course is interpreted as a younger stage of soil formation. I hope Moniz' work will soon be available for your examination. In some cases I am quite sure less weathered material is exposed on the sideslopes where they truncate saprolite. 2. I have tended to discount this concept because the systems are now dominated by Al^{+++}. But I have not explored this in detail since your visit to North Carolina.

Q. J. Bennema: 1. Most Oxisols have an increase in clay with depth. As far as I am concerned, this does not necessarily have to be the result of clay illuviation but may also be caused by surface erosion and the action of termites and ants. 2. Soil structure is also strongly influenced by termites (coprogenic elements). In some soils termites go deeper than in other soils; in good Podzolic soils they are not going so deep.

A. S.W. Buol: 1. I am sorry I had to delete my discussion on this point because of time limitations. I hope my discussion in the full text will address this matter to your satisfaction. 2. I appreciate your remarks, but we have not studied this point. The question regarding termites seems to be, don't they go deep in the Podzolic soils because of the compression structure, or is there no compression structure because the termites destroy it?

Q. C. Sys: I believe that the transition of an argillic to an oxic horizon is related to progressive weathering expressed by a specific in-

teraction between clays and iron oxides forming stable aggregates and immobilizing clay. A better hydraulic conductivity in the oxic horizon is not the origin of this process but seems to be a consequence of this aggregation. Also, the process appears to be reversible, particularly under the influence of organic matter and a medium to high base saturation.

A. S.W. Buol: I also believe the process is reversible but am suggesting the soil mechanics of saturation/dessication may be the cause. Certainly not all "reversed" structural horizons have higher organic matter and base saturation.

MINERALOGY AND MICROMORPHOLOGY OF A GIBBSIORTHOX

S. Paramananthan and H. Eswaran

ABSTRACT

Detailed mineralogical and micromorphological studies were made of a soil developed on rhyo-dacite and characterized by a high amount of gibbsitic gravel. Semiquantitative estimates show that the gravel fraction contains the most amount of gibbsite. There is an apparent increase of kaolinite relative to gibbsite in the clay fraction of the surface horizon. It has been established, with the scanning electron microscope, that this is partly related to the silicification of gibbsite to produce kaolinite. The soil is classified as a Typic Gibbsiorthox according to Soil Taxonomy.

INTRODUCTION

The Gibbsiorthox (Soil Survey Staff, 1975) has, within 1.25 m of the soil surface, sheets of gibbsite that contain 30% or more gibbsite or a subhorizon that has 20% or more by volume of gravel-size aggregates that contains 30% or more gibbsite. The concept of the great group was developed from the Kapaa and Pooku Series of Hawaii, both of which are developed from basic igneous rocks. Pedon 105 in Soil Taxonomy (Soil Survey Staff, 1975) gives an example of a clayey, oxidic, isohyperthermic family of a Typic Gibbsiorthox from the Island of Kauai, Hawaii. This soil has a high gibbsite content--35 to 45% in the whole soil--but has, in addition, a very high free iron content (about 45%). As a result the soil's net negative charge is very low and at the pH of the soil results in a net positive charge. Consequently, the soil has both "gibbsic" and "acric" properties. In Soil Taxonomy, as the gibbsi- great groups are keyed out earlier than

the acri-, the soils are classified accordingly and in this contribution, this is questioned.

Unpublished soil survey reports indicate the occurrence of Gibbsiorthox or other gibbsi- great groups in Jamaica, Madagascar, and Zaire. There are, however, no detailed studies of these soils. The objective of this study is to characterize a Gibbsiorthox from Peninsular Malaysia. As many of the attributes of the soil are determined by the mineralogy, the study is directed to the mineralogical and micromorphological evaluation. Based on this study and the little published information, some suggestions are made to improve the classification of the soils.

MATERIALS AND METHODS

Subsequent to a survey of the Penggerang area in the southeastern part of Peninsular Malaysia, the pedon is selected for the study. It is situated at an elevation of 122 ft (40 m) and the soil is developed on weathering products of rhyo-dacite. The mean annual rainfall in the area exceeds 2,500 mm and is distributed uniformly throughout the year. The soil moisture regime is perudic and the soil temperature regime is isohyperthermic. The area is characterized by a vegetation dominated by the Bornean floristic element (Wyatt-Smith, 1964) which reflects the very wet humid tropical climate.

The soils represented by the sampled pedon occur on low isolated hills which rise from the coastal alluvial plain. The pedon was sampled from the upper part of a gentle convex slope, and the profile description is given in Appendix I. Bulk samples and undisturbed samples were taken for soil characterization and fabric analysis studies, respectively.

The soils were analyzed according to procedures of the United States Department of Agriculture (Soil Conservation Service, 1972). Clay, silt, and sand were separated for the mineralogical analyses. X-ray diffraction (XRD), differential thermal (DTA), thermo-gravimetric (TGA), and transmission electron microscopic (TEM) analyses were done on the clay fraction and the first three kinds of analyses on the silt and sand fractions. The

gravel faction was also separated quantitatively and total elemental analyses (TEA) were made on the gravel, fine earth, and clay. Employing the results of these analyses, estimates of the mineralogical composition were made by the procedure of allocation (Jackson, 1956).

Thin sections were made from the undisturbed samples according to the procedure described by Stoops (1975) and studied with a Leitz petrographic microscope. Descriptions were made according to the terminology of Brewer (1964) with modifications of Eswaran and Baños (1976). Observations at higher resolutions were made with the scanning electron microscope (SEM) and sample preparation for this technique is given by Eswaran et al. (1977).

RESULTS

Morphological and Physico-Chemical Properties

The pedon shows a gradual reddening with depth, suggesting some epi-aquic conditions as defined in Soil Taxonomy (Soil Survey Staff, 1975). This color variation with depth is related to the perudic soil moisture regime. There is a distinct change in texture with depth, and though the apparent clay increase meets the requirements for an argillic horizon, there are no clay skins in the subsoil. There is a general increase of gravels and stones with depth. These coarse fragments are easily broken with a hammer and consist of sugary crystals of gibbsite with veins of reddish goethite or haematite. The gravels in the B_{32} horizon crumple easily under gentle pressure and are completely gibbsitized rock fragments.

The physico-chemical properties are given in Table 1. Despite the low base saturation, the pH is slightly high due probably to the relatively high amounts of free iron. The delta pH is negative and suggests a net negative charge, though recent work has indicated that the net charge may be positive when the delta pH is ≥ -0.2. The soil is almost devoid of exchangeable bases, and KCl-extractable aluminum is also low.

The effective cation exchange capacity (ECEC), which is estimated by the sum of bases and aluminum, is low and less than 1.5 meq/100 g clay,

Table 1. Physico-chemical properties of the soil.

Horizon	Particle Size Fractions					
	Clay	Silt	Sand	Gravel	O.C.	N
	- - - - - - - - - - - - - - - - percent- - - - - - - - - - - - - - - -					
Ap	21.9	13.9	64.2	12.5	1.04	0.07
B_{21}	27.5	12.5	60.0	15.8	0.63	0.06
B_{22}	57.0	9.1	33.9	25.6	0.57	0.03
B_{23}	56.4	8.9	34.7	47.7	0.35	0.03
B_{31}	44.6	8.8	46.6	34.2	0.19	0.02
B_{32}	37.5	11.1	51.4	27.3	0.19	0.02

Horizon	pH		Fe_2O_3 (%)	Exchangeable cations				KCl Extractable
	H_2O	KCl		Ca	Mg	Na	K	Al
				- - - - - meq/100 g soil- - - - - -				
Ap	4.6	4.2	4.6	0.05	0.04	0.09	0.17	1.60
B_{21}	5.0	4.5	4.7	0.02	0.08	0.08	0.05	0.52
B_{22}	5.0	4.9	8.4	0.04	0.02	0.01	0.04	0.31
B_{23}	5.0	4.8	7.6	0.05	0.04	0.04	0.04	0.48
B_{31}	4.8	4.5	7.3	0.07	0.02	0.05	0.03	0.57
B_{32}	4.6	4.4	6.0	0.16	0.06	0.11	0.12	0.21

Horizon	CEC of soil			
	NH_4Cl	CEC7	CEC8.2	ECEC
	- - - - -meq/100 g soil - - - - - -			
Ap	2.4	3.5	12.5	1.95
B_{21}	1.7	3.4	9.8	0.75
B_{22}	1.9	3.8	9.6	0.62
B_{23}	1.1	2.8	9.9	0.55
B_{31}	1.3	2.8	8.4	0.74
B_{32}	1.8	2.1	8.2	1.66

indicating acric properties. It is to be noted that the CEC NH_4Cl is a measure of the CEC at the pH of the soil, and at the pH of this soil, the soil already has significant amounts of pH-dependent charges. The high pH-dependent charge is indicated by the high CEC at pH 8.2.

Mineralogical Properties

XRD analysis of the clay, silt, and sand fractions indicate a general uniformity in the mineralogy of all the horizons. The clay fraction is composed of gibbsite, kaolinite, and goethite with some small amounts of quartz in the B_{32} horizon.

As the soil is dominated by gibbsite, a quantitative estimate of this and other minerals is obtained by the procedure of allocation (Table 2). There is more than 60% gibbsite in the gravel fraction, and the interesting feature is that there is also a significant amount of kaolinite. To be placed in the great group of Gibbsiorthox, only 30% gibbsite is needed.

In comparison to the gravel fraction, the fine earth fraction (less than 2 mm) has much less gibbsite and the reason is related to the aggregation of gibbsite crystals to form the coarser aggregates. This mechanism will be elaborated in the micromorphological study. As in the fine earth, there are about equal amounts of gibbsite and kaolinite in the clay fraction.

Micromorphological Properties

Apart from a distinct increase in the amount and size of gibbsite crystal nodules, the micromorphological features are relatively uniform with depth. The plasma is reddish yellow and in many places speckled with haematite crystallites. The plasmic fabric is isotic and locally argillasepic.

The grains are dominantly quartz, fine to medium sand-sized, angular and heavily fractured. In some voids, the original grain is replaced by silt-sized fragments of quartz adhering to the void wall. Under high magnifications, some of the quartz grains have a weak pitted appearance, suggesting dissolution. The gibbsite is present as aggregates of silt-sized crystals. The aggregates are mostly round, though a few sheets are also

Table 2. Allocated minerals in the different particle size fractions.

Horizon	Quartz	Kaolinite	Gibbsite	Goethite	Unallocated
In gravel	(%)	(%)	(%)	(%)	(%)
B22ox	15	14	63	3	3
B23ox	6	10	76	5	3
B31ox	8	23	60	5	4
B23ox	[illegible]	18	64	4	4
In fine earth					
Ap	50	30	8	3	7
B21ox	46	30	19	5	0
B22ox	28	28	31	10	3
B23ox	28	24	35	9	4
B31ox	41	21	29	8	1
B32ox	36	21	36	7	1
In clay					
Ap	2	52	36	6	4
B21ox	–	40	43	12	5
B22ox	–	37	42	17	4
B23ox	–	40	43	16	1
B31ox	–	38	44	15	3
B32ox	–	34	46	15	5

LIST OF FIGURES

Fig. 1. (a-b) SEM of gibbsite crystal nodule.
a x 2,000; b x 5,000

(c) SEM of gibbsite crystal sheet
x 10,000

(d) Etch surface of gibbsite
x 5,000

Fig. 2. (a) Etch surface of gibbsite
x 10,000

(b-c) Kaolinization of gibbsite
b x 10,000; c x 20,000

(d) Etch surface of quartz
x 15,000

Fig. 1

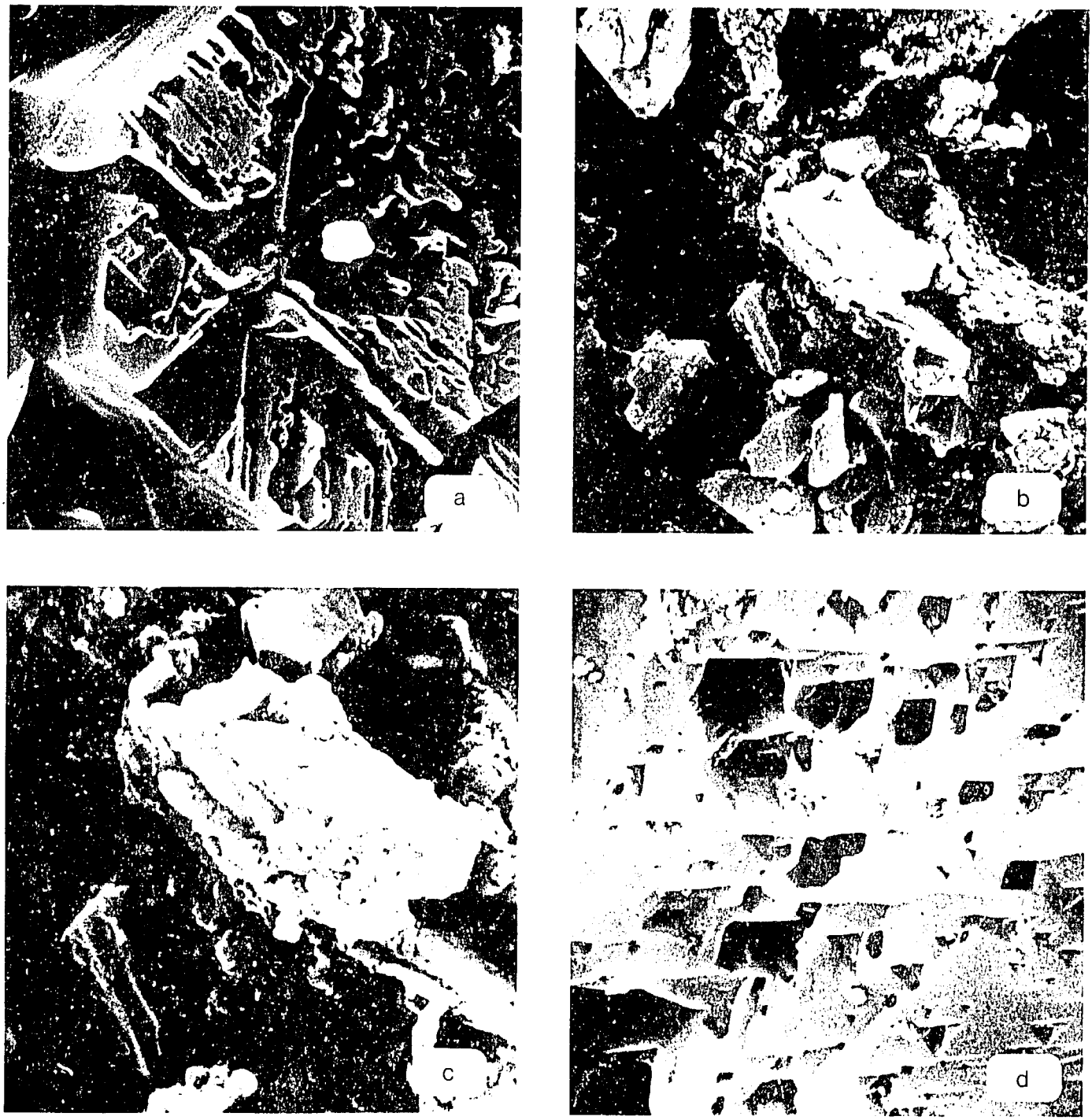

Fig. 2

present. An interesting feature of some of the nodules in the surface horizon is that they appear to have a thin coating of kaolinitic plasma. The gibbsitic nodules are also invaded by goethite and haematite, which sometimes are present in a concentric preferred distribution pattern.

There is a marked increase in the amount of gibbsite with depth. In the B_3 ox horizon, the s-matrix is almost completely composed of gibbsite; the small amounts of plasma fill up the spaces between the gibbsitic nodules.

There is no evidence of clay translocation in the soil. The plasma is stable and is not even subject to stress orientation. Biological activity is only confined to the surface horizons. Few, fine aggrotubules are present in the Ap horizon.

The gibbsitic crystal nodules were studied with the SEM to evaluate the crystal morphology and to make comparisons with previous studies (Eswaran et al., 1977). Figs. 1a and b show the morphology of the gibbsite crystals in the B_3 oxic horizon: all euhedral, some with slight etching on the surface (Fig. 1b). In the same horizon, there are also gibbsite crystal sheets, which have been described previously by Eswaran et al. (1977). Fig. 1c is an example of a gibbsite crystal sheet where individual silt-size crystals are joined together to form a sheet.

The etching of gibbsite seems to be best expressed in the B_2ox horizon. Fig. 1d and Fig. 2a show crystal surfaces which are very deeply etched. The etching seems to show a distinct pattern as has been observed previously with quartz (Eswaran et al., 1977). The etch surfaces were observed at magnifications of X25,000 to look for secondary products. None were identified in this sample.

The gibbsite crystals in the Ap horizon, however, show a different morphology. In thin sections, the gibbsite crystal nodules appeared to have a thin coating of kaolinite. Fig. 2b and c show the fabric of the gibbsitic nodules. At a higher magnification (Fig. 2c) it is seen very clearly that the gibbsite crystals are coated with kaolinite. Booklets of kaolinite crystals seem to grow from the cracks and crevices of the gibbsite crystal and suggest silicification of the gibbsite to form kaolinite. Although this has been postulated for a long time, it is the first time that it has been established. This probably accounts for the observation earlier that the surface horizon has less gibbsite and more kaolinite.

The source of silica for the silicification of gibbsite could be the recycling of the silica by plant roots. Dissolution of quartz, as established previously by Eswaran et al. (1977), is another possible source. In the thin section study, the quartz grains were noted to be fractured and even pitted. Fig. 2d shows a quartz grain from the Ap horizon. The surface is completely etched. Etching releases silica which could be responsible for the neoformation of kaolinite.

CLASSIFICATION

In Soil Taxonomy, the presence of sheets of gibbsite, or more than 20% by volume of gibbsite gravels, in any subhorizon within 1.25 m of the soil surface is currently considered at the great group level. The presence of such large amounts of gibbsite is probably attributed to be indicative of an extreme stage of weathering; hence the importance given to it. However, the presence of even larger amounts of petroplinthite or lateritic gravels is only considered at the family level. This in our opinion is incorrect. Lateritic soils are by far more common than soils with gibbsite and these lateritic gravels should be accorded the same status as gibbsite gravels. Both should be considered either at the great group level or at the family level.

Some of the soils which are currently classified as Gibbsiorthox may also have "acric" properties. The soil described in this paper is such an example. Currently the Gibbsiorthox is keyed out earlier than the Acrorthox. It is therefore important to consider which of these two soil attributes is more important. If the "acric" properties are considered more important then these should be keyed out earlier.

CONCLUSION

The study clearly shows that the soil is at an advanced stage of soil formation where the mineralogy is dominated by gibbsite. From the point of view of cation exchange characteristics, gibbsite is inert; so the net

charge of the soil is low, giving rise to some acric characteristics. In this particular soil, the acric characteristics are not sufficiently well expressed to consider the soil as an Acrorthox.

The detailed micromorphological study indicates that gibbsite is not stable in the present environment and is being kaolinized. Formation of gibbsite represents the end of a weathering cycle, and the kaolinization represents the beginning of a new cycle.

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DISCUSSION

Q. A.N. Rukaka: Is it not a contradiction to say, on the one hand, that gibbsite represents an ultimate state of weathering, and on the other hand, that it is not stable and can be transformed into kaolinite?

A. H. Eswaran: Gibbsite has been used at a high level of Soil Taxonomy because it was considered to represent an ultimate stage of weathering. However, gibbsite has been found in many soils and in many stages of weathering. Our work has also shown that gibbsite is not stable.

Q. F.R. Moormann: Do you consider the profile you discussed to have a kandic horizon?

A. H. Eswaran: Yes; but I should mention that we had a poor rate of dispersion. It is also possible that the presence of fine gibbsite nodules of fine sand or silt size may be responsible for the low clay content.

Comment. G. Stoops: It is questionable if gibbsite can always be related to an ultimate stage of weathering as it is commonly observed that gibbsite occurs in Andisols in horizons with a large amount of argillans and in saprolites still containing many weatherable minerals. In my opinion, the presence of gibbsite is related to drainage.

Comment. J. Bennema: In Brazil, gibbsite is found in soils with cambic and argillic horizons but not in Latosols with a high SiO_2/Al_2O_3 ratio. In older Latosols with very low SiO_2O_3 ratios of the clay fraction gibbsite is common. In this case, it is present only together with kaolinite and sesquioxides and the ultimate weathering stage is reached.

Comment. C. Sys: Gibbsite seems to indicate a kind of weathering rather than a stage of weathering. Pécrot has indicated that under conditions of free drainage on basalt, the plagiclases are immediately transformed into gibbsite, and Deloigne has shown that on granite and again with free drainage the feldspars are also immediately transformed into gibbsite.

APPENDIX 1

Profile Description

Ap	0 - 18 cm	-	Sandy clay loam; strong brown (7.5YR 5/6); very weak crumbly with very weak subangular blocky; friable; very few roots; little biological activity; in the lower part of the horizon are a few large holes made by millipedes; diffuse boundary.
B_{21ox}	18 - 40 cm	-	Sandy clay loam; strong brown (7.5YR 5/6); few fine gravels; very weak subangular blocky to structureless; very friable; no roots; practically no evidence of biological activity; abrupt boundary.
B_{22ox}	40 - 100 cm	-	Gravelly clay; yellowish-red (5YR 5/6); fine gravels make up about 35% of the matrix and there is about 10% stones; structure difficult to discern; friable; no roots; no biological activity; gravels increase in size with depth; diffuse boundary.
B_{3ox}	100 - 200 cm	-	Stony clay; yellowish-red (5YR 5/8); large completely gibbsitised rock fragments are present; the core of these is red (2.5YR 4/8); the stones crumble easily to fine sand; diffuse boundary.
BC	200 cm+	-	As above but more stones; no change up to a depth of 4 m.

NOTES: The depth at which the gravels occur varies from the surface to about 70 cm. Bauxite mines are present in the area. The mining is confined to those areas where the gravel and stones extend to a depth of more than 2 m. "Swamp bauxite" is mined from soils with aquic moisture regimes (Gibbsiaquox ?) and here the stones of gibbsite are rounded and without iron coating.

ANALYTICAL TECHNIQUES FOR SOILS WITH VARIABLE CHARGE

John M. Kimble

I was asked to review analytical techniques that can be used for soils with a variable charge. The term "variable charge soils" refers to the colloid composition of the soils that are amphoteric. The surface charge of these soils arises from the adsorption of potential-determining ions --primarily hydrogen and hydroxyl ions (Uehara, 1979), and it can vary widely with pH. This variability with pH is important in managing soils because it is possible to manipulate the charges. From a soil characterization point of view, special analytical techniques are needed, especially in soils dominated by the variable charge colloids. Some of these techniques are discussed by Theng (1980) and Uehara and Gillman (1981).

In the proceedings of the first two International Soil Classification Workshops (Beinroth and Panichapong, 1979; Beinroth and Paramananthan, 1979; and Camargo and Beinroth, 1978) and in the different circulars for the International Committee on the Classification of Soils with Low Activity Clays, International Committee on Oxisols, and International Committee on Aridisols inadequacies of the present techniques were highlighted and some new methods were discussed. I intend briefly to list the methods we use at the U.S. Department of Agriculture, Soil Conservation Service, National Soil Survey Laboratory (NSSL), in Lincoln, Nebraska, and to give some of the newer methods others have proposed for use.

I will also address two questions asked of Dr. Holzhey at the 2nd International Soil Classification Workshop held in Thailand and Malaysia in 1978 regarding some of the methods we use at the NSSL. (1) Does the volume of ethanol used in the NSSL procedure affect the CEC measured by ammonium acetate? and (2) Does the NSSL procedure for dithionite-extractable iron measure all of the free iron?

ANALYTICAL METHODS

Fig. 1 gives the standard analyses run by the NSSL.

Physical Analysis

Particle-size analysis has limitations for well-aggregated tropical soils and soils high in amorphous materials or soils that have low activity clays and a high iron oxide content. Aggregation of these soils is discussed by Eswaran and Banos (1976) and Eswaran (1979). Clay, as a size fraction, may not be very meaningful in these types of soils, and the concept of clay's being discrete < 2μ particles breaks down in allophanic soils. Soil Taxonomy (Soil Survey Staff, 1975) says that if the ratio of 15-bar water to clay is less than 0.6, dispersion is adequate. The data of the Rwanda soils (Appendix I) show that for both the Oxisols and Ultisols, the ratio is less than 0.6. Profiles 6, 7 and 8, however, have ratios much greater than 0.6, particularly profiles 7 and 8 (Table 1).

For materials that disperse poorly, Soil Taxonomy suggests using 2.5 x 15-bar water to estimate the clay percentage. For samples 811157, 811158 and 811159 (Table 1), clay percentages obtained by this procedure would be 97, 122, and 119, which are not realistic. So, the relationship of 15-bar water and clay needs to be reevaluated.

On the other hand, using 2.5 x 15-bar ratio to estimate the clay in some Oxisols and Ultisols can underestimate the clay. In samples 811122, 811123, and 811124 (Appendix I), measured clay is 32.4, 40.1, and 45.8, and the estimated clay is 21.0, 26.3, and 28.5%. The discrepancy is evident, and there is an obvious need to reconsider the relationship. For the Oxisol samples in Rwanda, regression analysis shows a good correlation (Fig. 2); but for the Ultisols, the relationship is not significant (Fig. 3). The low water-holding capacity of these soils is related to low specific surface and their tendency to form water-stable aggregates (Uehara and Gillman, 1981) may be the reason for the unreliable estimation of clay using 15-bar water.

Profiles 6, 7, 8 and 9 have high organic matter contents, but the organic matter does not completely explain the high 15-bar to clay ratio. Profiles 7 and 8 are primarily amorphous. Amorphous material in this paper

Fig. 1

LABORATORY DATA THAT CAN BE PROVIDED BY NSSL

NSSL

PHYSICAL

- Particle size analysis
- Fabric-related analysis
  - Bulk density
    - Field, 1/3 bar & ovendry
  - Coefficient of linear extensibility (COLE)
  - Water content
    - Field, 1/10, 1/3, 2, & 15 bar
- Micromorphology
- Plasticity index

ION EXCHANGE ANALYSES

- Cation-exchange capacity
  - NH_4OAc pH 7.0
  - Sum of cations
  - NH_4Cl
  - Base plus KCl-Al
- Extractable bases
  - Ca, Mg, Na, & K
- Sodium - absorption ratio (SAR)
- Sodium - saturation exchangeable sodium percentage (ESP)

CHEMICAL

- Organic carbon
- Nitrogen
- Dithionite-extractable Fe, Al, Mn
- Calcium carbonate
- Gypsum
- KCl-extractable Al
- Extractable acidity
- Phosphorus adsorption coefficient
- Carbonates
- Chlorides
- Sulfates
- Nitrate
- Fluorides
- Calcium
- Magnesium
- Sodium
- Potassium
- Total sulfur
- Silicon

MINERALOGICAL

- X-ray diffraction
- Differential thermal analysis
- Total analysis
- Surface area (EGME)
- Optical analysis

MISCELLANEOUS

- Conductivity
- Resistivity
- Reaction (pH)
  - Soil suspensions
    - H_2O
    - $CaCl_2$
    - KCl
    - NaF
  - Organic materials
    - $CaCl_2$
- Mineral content
- Fiber volume
- Pyrophosphate color

Table 1 - Effect of two dispersing agents on measured clay of four Rwanda soil samples

NSSL No.	Field Soil Texture (1)	Dispersing Agent: Sodium Hexametaphosphate % clay	Sodium Hexametaphosphate 15-bar/clay ratio	Hydrochloric Acid % clay	Hydrochloric Acid 15-bar/clay ratio	HCl/Na-Hexa Ratio (2)	AD/OD Ratio (3)
		PROFILE - RWANDA - 6					
811152	clay loam	7.5	1.09	7.2	1.14	0.96	1.04
811153	clay loam	10.7	0.90	8.0	1.20	0.75	1.04
811154	clay loam	10.1	0.78	8.2	0.96	0.81	1.04
811155	clay loam	11.6	0.78	6.1	1.48	0.53	1.03
811156	clay loam	9.5	1.00	5.4	1.76	0.51	1.04
		PROFILE - RWANDA - 7					
811157	clay loam	14.5	2.68	16.6	2.34	1.14	1.38
811158	clay loam	12.8	3.82	15.4	3.18	1.20	1.37
811159	clay loam	6.0	7.93	16.2	2.94	2.70	1.38
		PROFILE - RWANDA - 8					
811160	clay loam	11.4	3.41	21.1	1.84	1.85	1.27
811161	silty clay loam	10.1	3.68	17.8	2.09	1.76	1.21
811162	silty clay loam	3.3	13.42	22.9	1.93	6.94	1.33
811163	silty clay loam	0.6	98.67	20.9	2.83	34.83	1.55
811164	gr-silty clay loam	1.6	30.31	15.8	3.07	9.88	1.36
		PROFILE - RWANDA - 9					
811166	clay	26.1	1.38	11.0	3.27	0.42	1.21
811167	clay	22.6	1.59	11.4	3.15	0.50	1.23
811168	clay	28.0	1.05	10.1	2.91	0.36	1.17
811169	clay	19.8	1.84	11.1	3.29	0.56	1.22
811170	clay	28.3	0.98	10.0	2.76	0.35	1.15
811171	clay	26.9	0.75	9.3	2.18	0.35	1.09

(1) Field estimation of the soil texture.
(2) Ratio of clay dispersed with Hydrochloric Acid to Sodium Hexametaphosphate.
(3) Ratio of air-dry soil weight to ovendry soil weight.

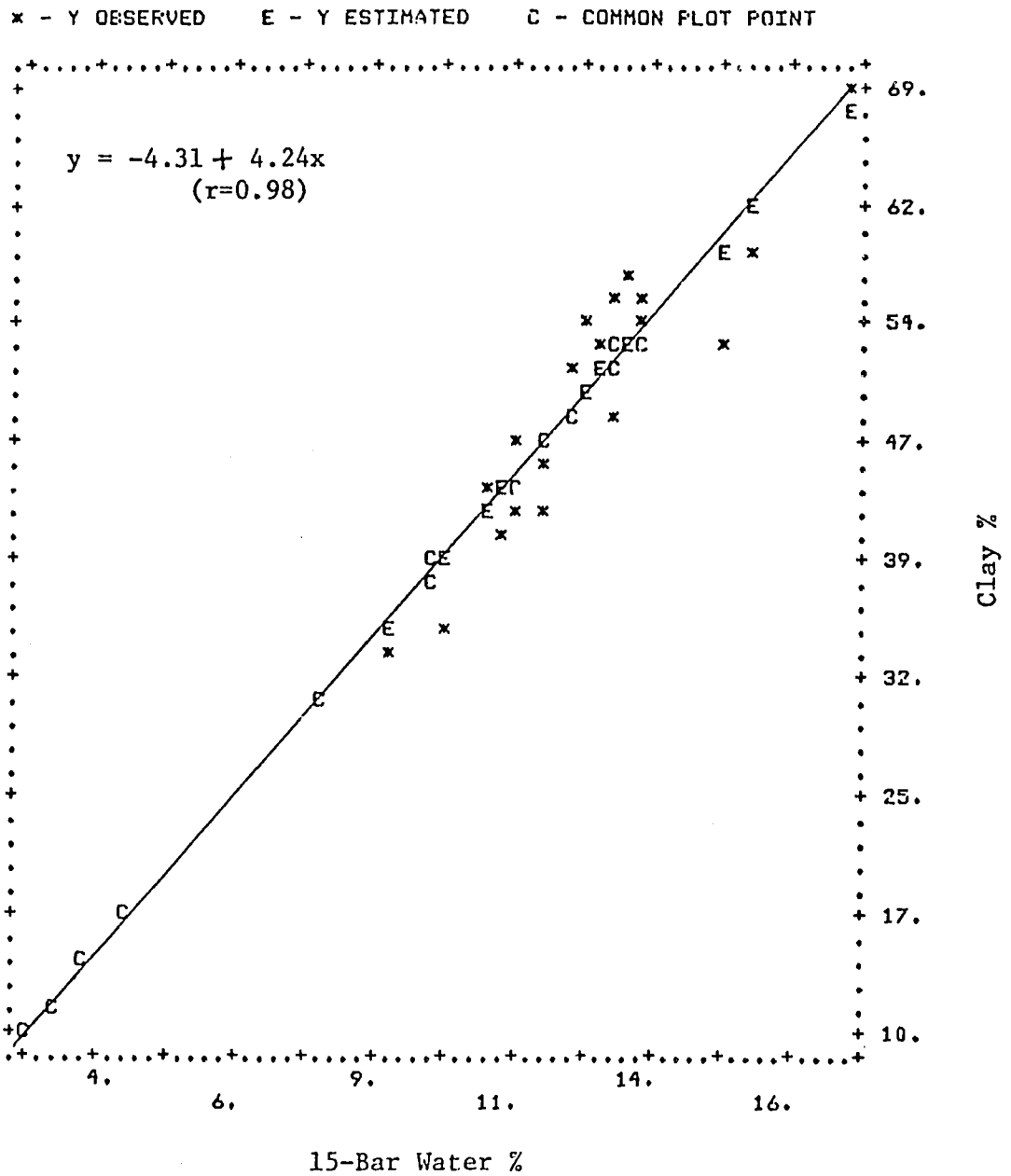

Fig. 2 - Comparison between 15-bar water and measured clay in some Oxisols from Rwanda.

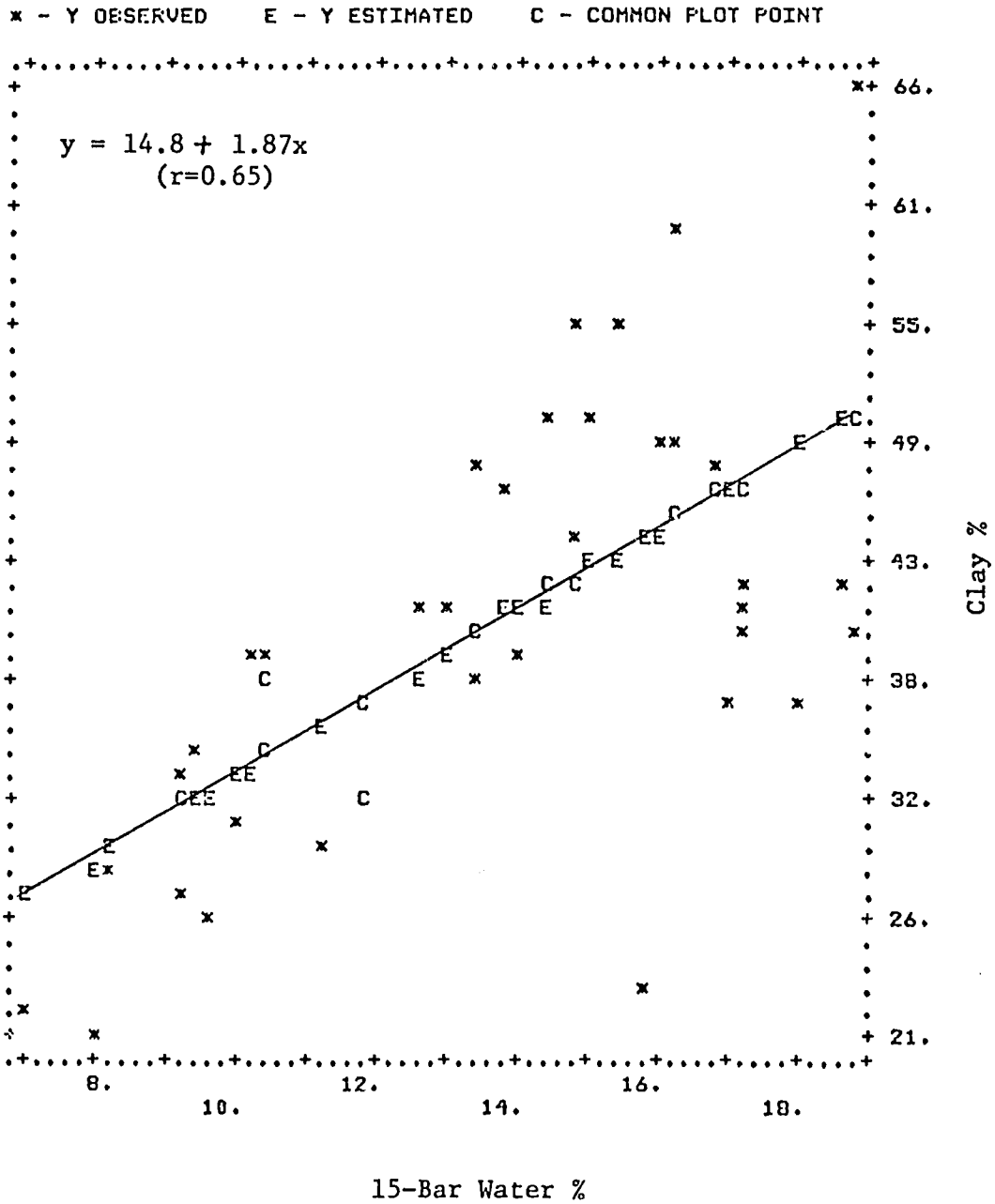

Fig. 3 - Comparison between 15-bar water and measured clay in some Ultisols from Rwanda.

includes allophane (Van Olphen, 1971) and other material that is generally amorphous under X-ray analysis even with some crystalline materials that may cause small and disordered peaks (Soil Survey Staff, 1975). Dispersion was also tried in an acid medium. Enough HCl was added so that it was 2% of the volume. In allophanic soils, better dispersion is obtained in an acid rather than an alkaline solution (personal communications with H. Eswaran). In profiles 7 and 8, with HCl dispersant, the measured clay was greater but still not the percentage that would be expected from the field texture. In profiles 6 and 9, which have halloysitic mineralogy, the measured clay was reduced with HCl dispersion, whereas in 7 and 8 it was increased. Although the acid technique disperses the allophanic colloids it appears that any crystalline colloids flocculate.

The ratio of percent clay dispersed with HCl to the percent clay dispersed with sodium hexametaphosphate or polyphosphate is greater than one for allophanic soils and less than one for other soils. This ratio could be used as a test for soils with high amounts of these short-range order colloids. The actual amount of clay is not important or relevant in such soils.

Another interesting feature of profiles 7 and 8 is the ratio of air-dry soil to oven-dry soil. It ranges generally from 1.21 to 1.55, but it is about 1.04 in profile 6 and about 1.20 in profile 9. For all of the other soils, the ratio is from 1.01-1.05. All NSSL data are reported on an oven-dry basis and, with ratios this high, the results are 21 to 55% higher than if they were based on an air-dry weight. For practical purposes, it may be best to base the results on both an air-dry and oven-dry weight. Some of the water lost in these soils when they are oven-dried is water of hydration. If we look at sample 811163 and compare values based on air-dry weight with AD/OD values, organic carbon values are 4.92% vs. 7.62%, while CEC (NH_4OAc pH 7) values are 30.6 vs. 47.5%. Data based on oven-dry weight do not really indicate what would be found under field conditions. If the data are only used for classification purposes, this may be all right; but, for other uses, it is not. Uehara and Gillman (1981) state that "Because some soil materials dry irreversibly in the tropics, the rule of thumb is not to air-dry or oven-dry samples prior to analysis."

Ion Exchange Analysis

Cation exchange capacity (CEC) is commonly measured by either (1) saturating the exchange complex with a single ion, then displacing the ion, and measuring the amount displaced [ammonium acetate (NH_4OAc), pH 7, for example] (the NSSL uses NH_4OAc, pH 7 and measures the ammonium by direct distillation of the soil) or (2) measuring each of the exchangeable cations and summing to compute the total exchangeable cations (CEC by sum of cations).

CEC procedures that use different pH or different cations will produce different results. Nearly all soils have higher CEC at higher pH. The change in CEC with change in pH is generally least in clay minerals that have 2:1 lattices, greater in those with 1:1 lattices, and greatest in organics and amorphous silicates. Different methods of extracting exchangeable bases produce similar values unless carbonates of Ca and Mg, gypsum, or more soluble salts are present.

The NSSL routinely uses three methods to measure CEC: (1) NH_4OAc, pH 7, (2) sum of bases plus extractable acidity, and (3) sum of extractable bases plus KCl-Al. The last one also is called the effective CEC (ECEC). The methods used are described in SSIR No. 1, rev. 1981. If asked, we can run CEC by NH_4^+ retention using 1N NH_4Cl, a fourth method.

Some general comments about these methods follow:

1. An aqueous solution of 1 normal NH_4OAc is weakly buffered in the range of pH 7. Hence, the CEC of all soils by this method is determined in the range pH 7 but not at pH 7.

2. The CEC by sum of cations is effectively the CEC at pH 8.2, because it is the sum of bases extracted by NH_4OAc and pH 7 plus the acidity extracted by a barium solution buffered at pH 8.2.

3. NH_4^+ retained from 1 normal NH_4Cl measures the negative charge CEC near the soil pH. This is a neutral salt; and results are generally, but not always, close to the sum of bases plus Al. High values are obtained in allophanic clays because of specific retention of chlorides.

4. In acid soils, the sum of bases plus Al extracted by 1 normal KCl is the effective CEC of the soil in the field, and some have used the value as an estimate of permanent charge.

CEC is of interest for two reasons. One is to characterize the cation exchange complex. The other is to evaluate the mechanisms that operate

under field conditions. The former is often accomplished best by more than one CEC measurement to enhance and measure pH dependence of the CEC. The latter requires a measurement near field pH and sometimes at a second, higher pH if liming is a practice of the area. Uehara (1979) reviewed the use of NH_4OAc pH 7 for measuring the CEC and concluded that even with all its faults, this method did stratify soils into groups based on their clay activities. Because of its reproducibility, it will continue to be used to classify soils for the foreseeable future, but it should be accompanied by other measurements such as sum of bases plus KCl aluminum.

Knowing these problems with CEC measurements by NH_4OAc pH 7, we should be careful in extending the results to agronomic recommendations unless they are correlated with those of other measurements for acid soils. The CEC will not be related to the soil pH unless the measurement of the acidic components is near the field pH. The same is true of other techniques that measure CEC at a pH significantly different from the natural pH if the CEC is highly pH dependent.

The problems with using NH_4OAc pH 7.0 for measuring CEC have been pointed out and reviewed by Bache (1976) and Uehara and Gillman (1981). Uehara and Gillman also discussed problems with the other methods of CEC measurement. Some of these problems are as follows: (1) when a buffered salt is used, the CEC is not measured at the pH of the soil; (2) the presence of free salts which cannot be removed without affecting the exchangeable cations; (3) hydrolysis of the index ion, such as NH_4^+ in the washing steps; and (4) reduction in electrolyte concentration during the washing. Also, the fact that for all of the methods listed, the salt concentration is much greater than found in the soil environment. The ECEC may be the closest to the field CEC but also has many of the same problems. We assume that Al extracted by 1 normal KCl approximates exchangeable Al, but Amedee and Peech (1976) found that some of the Al measured by 1N KCl may be from amorphous aluminum. Because KCl is an unbuffered salt, it usually affects the soil pH only one unit or less, so the extraction is made near the pH of the soil. Another point to be kept in mind when measuring the CEC by the sum of bases method is that acidity is measured and added to the bases. Nearly every procedure for measuring extractable acidity produces different results. The procedures for determining extractable acidity listed in Soil Survey Investigations Report No. 1 are so similar that results are comparable, but other procedures generally are not comparable.

To replace these methods, Uehara and Gillman (1981) suggest a compulsive exchange procedure described by Bascomb (1964). This procedure was also discussed by Gillman and Bakker (1979) at the 2nd International Soil Classification Workshop in Thailand, and by Gillman (1979). Bache (1976) felt that the $BaCl_2/MgSO_4$ method of Bascomb (1964) was outstanding.

The NSSL has not tried this method. Details of this procedure are given by Uehara and Gillman (1981).

Advantages of the compulsive exchange procedure are that exchangeable cations can be measured in the extract after the barium exchange, and the anion exchange capacity can be estimated. Measurement of the anion exchange capacity would be of real interest in variable charge soils.

Extractable bases are measured in the extract obtained from the NH_4 OAc pH 7 CEC exchange procedure. They could also be measured in the extracts obtained from the ammonium chloride or barium exchange procedures. One advantage of analyzing the $BaCl_2$ extract in the compulsive exchange procedure is the smaller chance of measuring nonexchangeable cations. Carbonates of Ca and Mg are somewhat soluble in solutions containing acetate. So when ammonium acetate is used, the extractable Ca and Mg include exchangeable Ca and Mg plus some soluble Ca and Mg acetate. The Ca from carbonates is much larger than Mg, although calcite frequently has some Mg impurities. When dolomite is present, the carbonates contribute significant amounts of Ca and Mg. Gypsum is slightly soluble in water. Other salts of Na, K, Mg, and Ca are highly soluble in water. Hence, extractable bases measured by any procedure employing aqueous solutions include Ca from gypsum, and Ca, Mg, Na, and K from the soluble salts, if present.

Another problem in measuring the cations with NH_4 is that some oxidic soils appear to have a specificity for divalent cations (Uehara and Gillman, 1981). This gives a lower measure of Ca and Mg than when barium is used. The buffering effect will also cause the surface charge density to rise and result in incomplete removal of the cations.

The following figures show the relationship between some of the different CEC measurements on the Rwanda samples. All horizons and all profiles were compared. There is a good correlation ($r=0.99$) between the CEC measured by NH_4OAc pH 7 (CEC pH 7) and the sum of cations CEC (Fig. 4). This is to be expected if we consider that the bases summed were measured in the extract from the NH_4OAc pH 7 exchange. The correlations are not

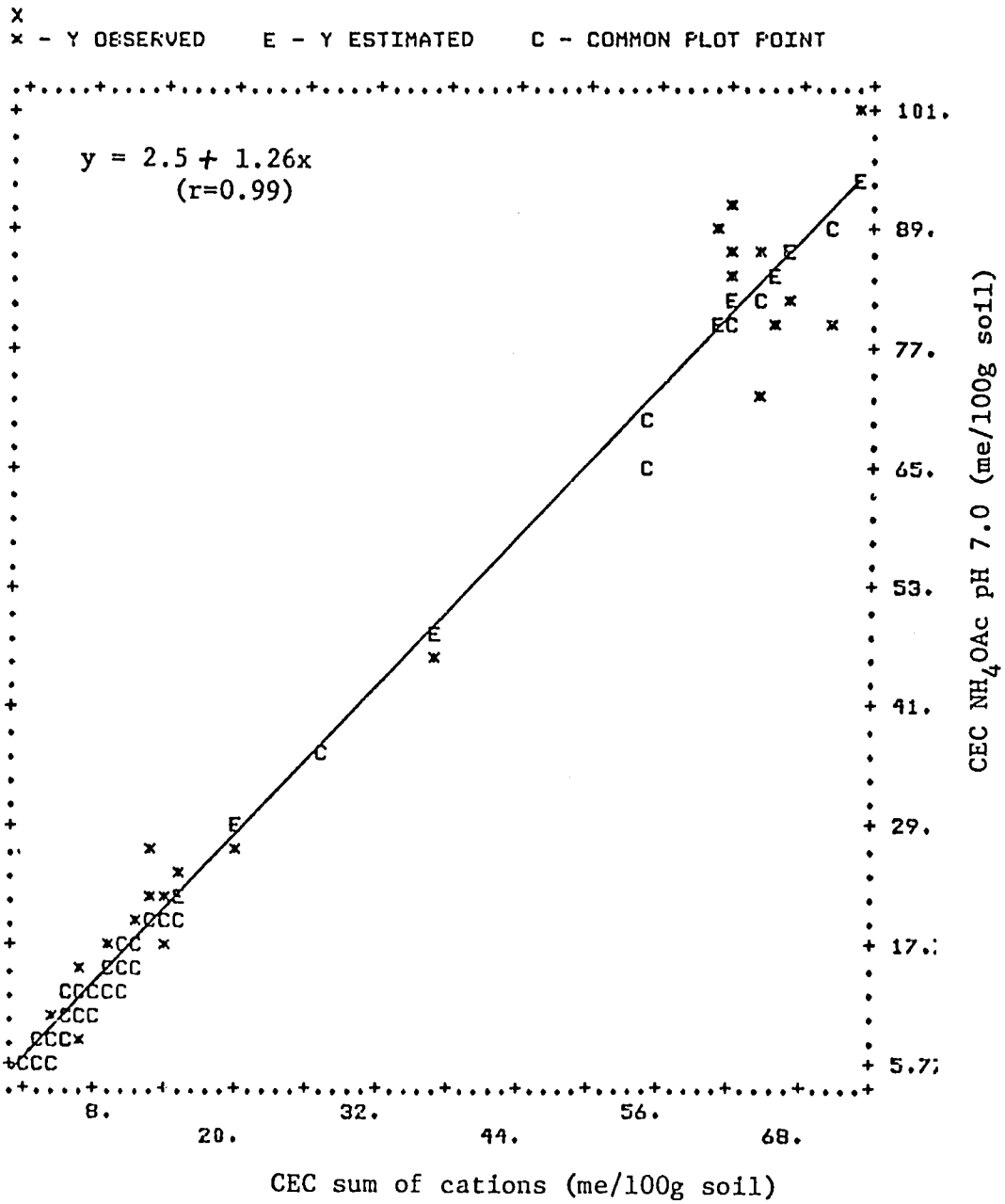

Fig. 4 - Comparison between CEC's measured by the sum of cations plus extractable acidity and by 1N NH_4OAc (pH 7.0).

as high between the effective cation exchange (ECEC) and CEC pH 7 (Fig. 5) or between CEC pH 7 and NH_4Cl (Fig. 6). When the ECEC was compared to the CEC by sum of cations plus extractable acidity, the lowest r was obtained, 0.89 (Fig. 7). In both of these methods, the cations from the CEC pH 7 procedure were used. The difference between these two methods can be called the variable charge. The comparison of the CEC determined by NH_4Cl to the sum of cations was low (r=0.90) (Fig. 8). Comparing the CEC measured by NH_4Cl to the ECEC shows an r of 0.96 (Fig. 9). For variable charge soils, ECEC or CEC by NH_4Cl may be better.

These figures were presented to show that, as already stated, there is a wide range in CEC measured by different methods in different kinds of materials. All methods have both good and bad aspects. For classification purposes, a combination of methods is best. Because of the differing relationships in using one method to predict results of another, it is best not to use one method to estimate another. Regressions can be run and equations developed for determining one CEC from another, but that may not help greatly.

Does the volume of ethanol used in the washing during the CEC measurement by NH_4OAc pH 7 affect the results? We compared the volume of ethanol (95%) used for washing when measuring CEC using 1N NH_4OAc pH 7 using two different methods. The purpose was to see what effect the volume of ethanol had on the measured CEC using the semiautomatic multiple syringe extractor used by the NSSL and to compare it with a similar procedure that used a centrifuge to separate the soil and extractant. The methods used were:

1. Centrifugation. Weigh 2.5 g sample into the centrifuge tube. Add 15 ml NH_4OAc pH 7. Shake 5 minutes, centrifuge 5 minutes, decant, repeat four times. Samples were then washed with ethanol in the amounts of 100-, 200-, and 300 ml in 25 ml increments. Samples were centrifuged and decanted between each ethanol wash step. Ammonia was determined by Kjeldahl distillation as described in SSIR No. 1, rev. 1981.

2. The NSSL procedure, 5A8 in SSIR No. 1, rev. 1981, uses the semiautomatic multiple syringe extractor described by Holmgren et al. (1977). The volumes of ethanol used for washing were 100, 200, and 300 ml.

The results show that as the volume of ethanol is increased, the CEC measured using NH_4OAc pH 7 is reduced (Table 3). This finding agrees with that of other workers (Smith et al., 1966; Peech et al., 1962; Frink, 1964;

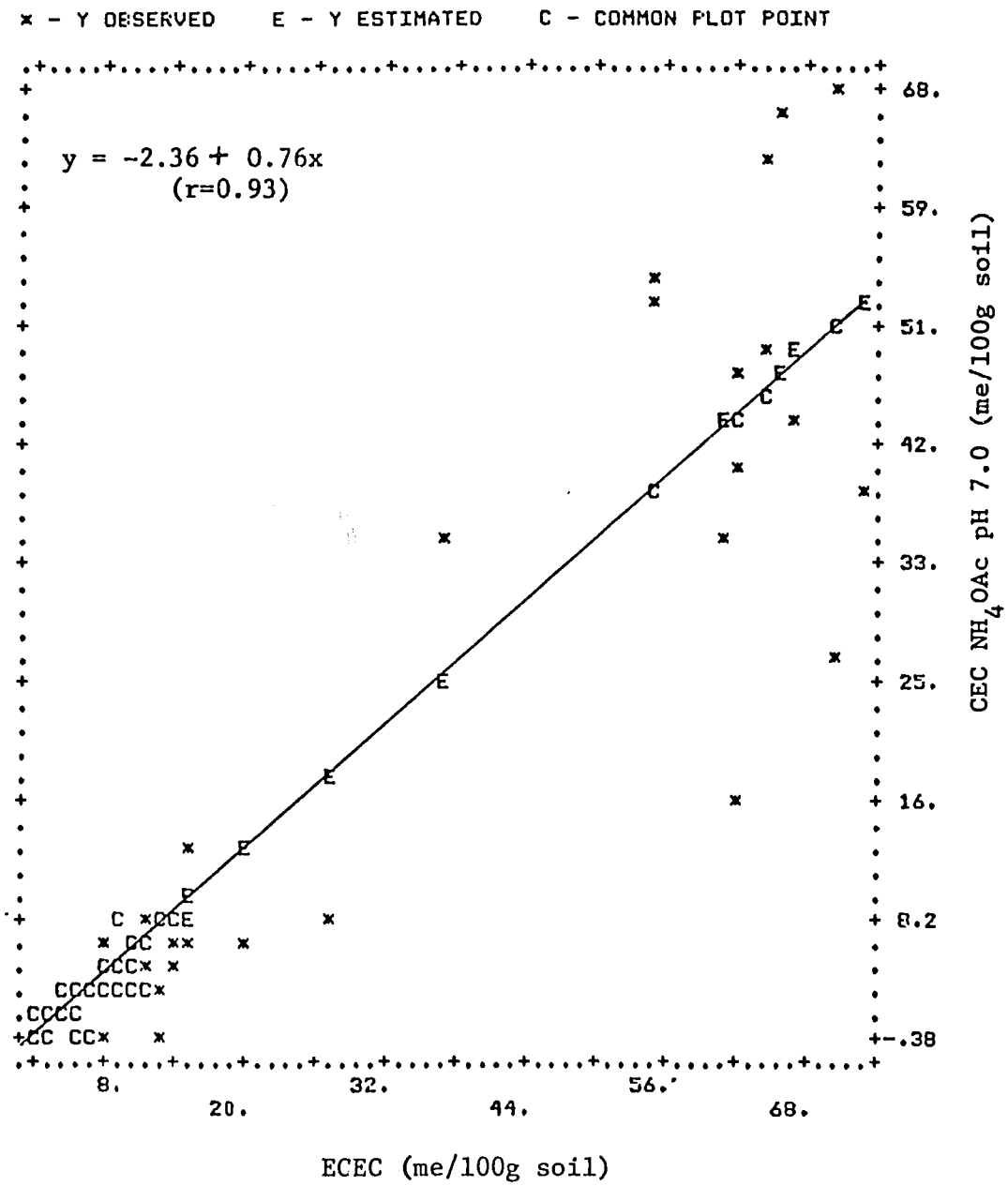

Fig. 5 - Comparison between CEC's measured by the sum of cations plus KCl aluminum (ECEC) and by 1N NH_4OAc (pH 7.0).

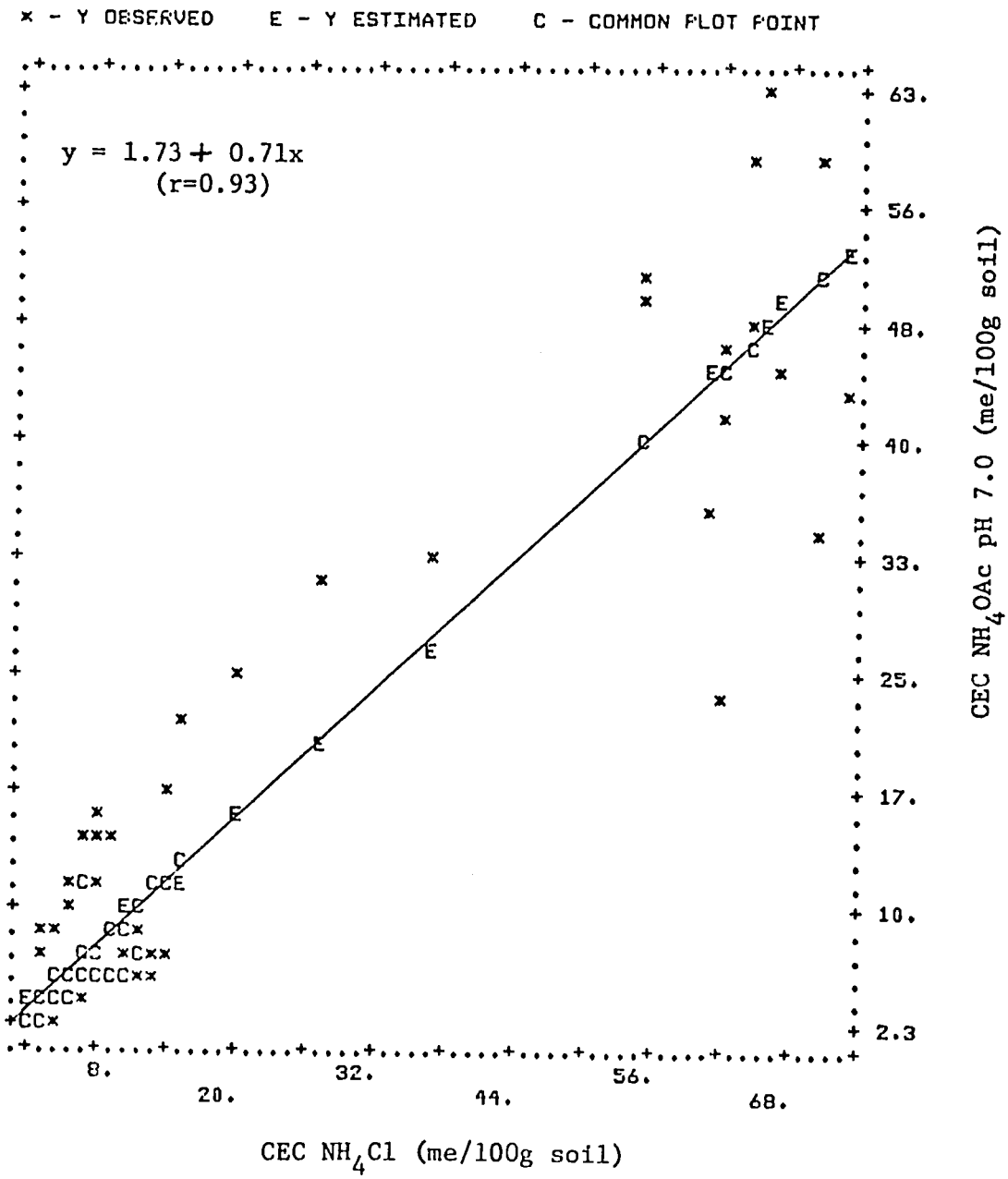

Fig. 6 - Comparison between CEC's measured by 1N NH_4Cl and by 1N NH_4OAc (pH 7.0).

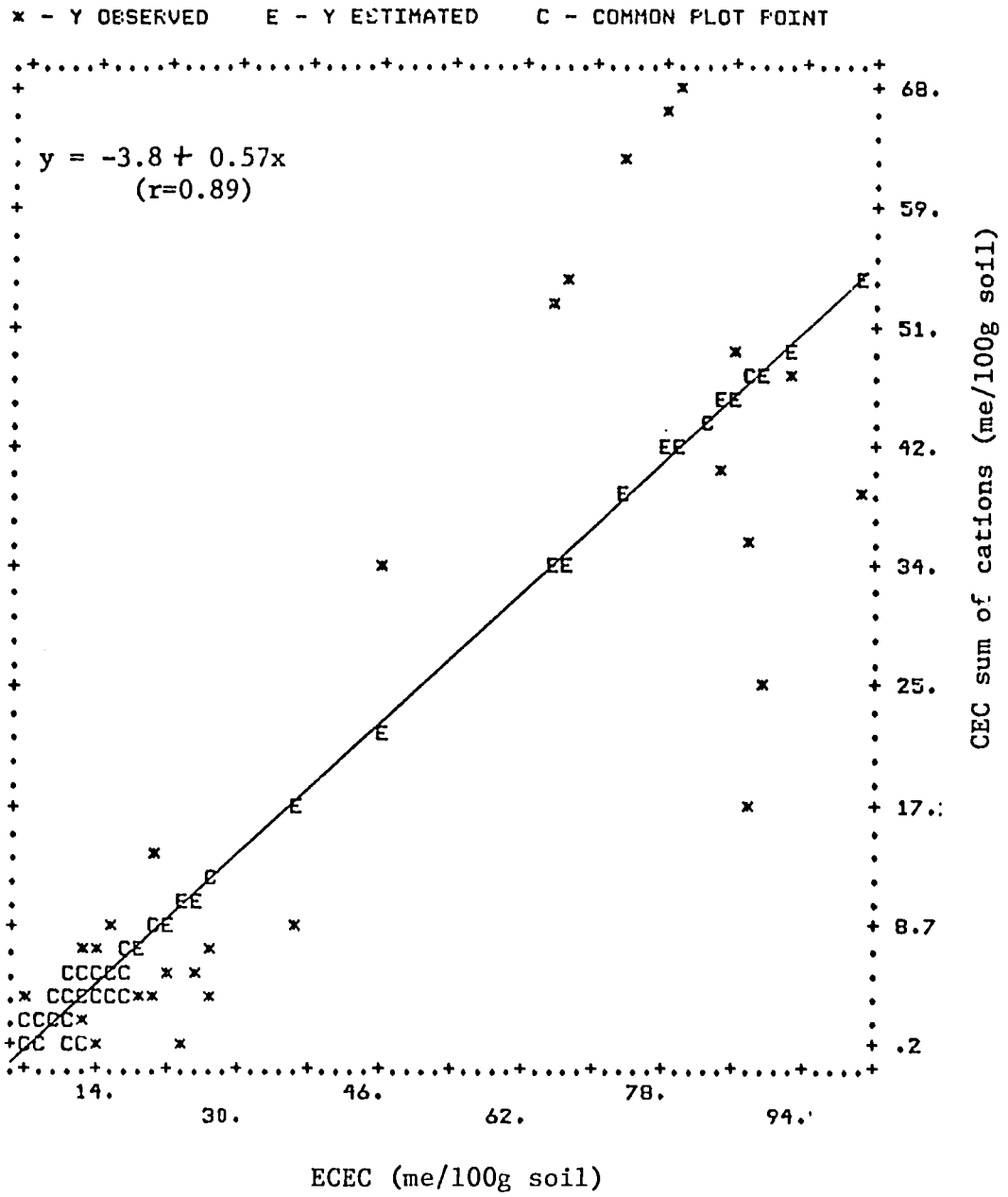

Fig. 7 - Comparison between CEC's measured by the sum of cations plus KCl aluminum (ECEC) and by the sum of cations plus extractable acidity.

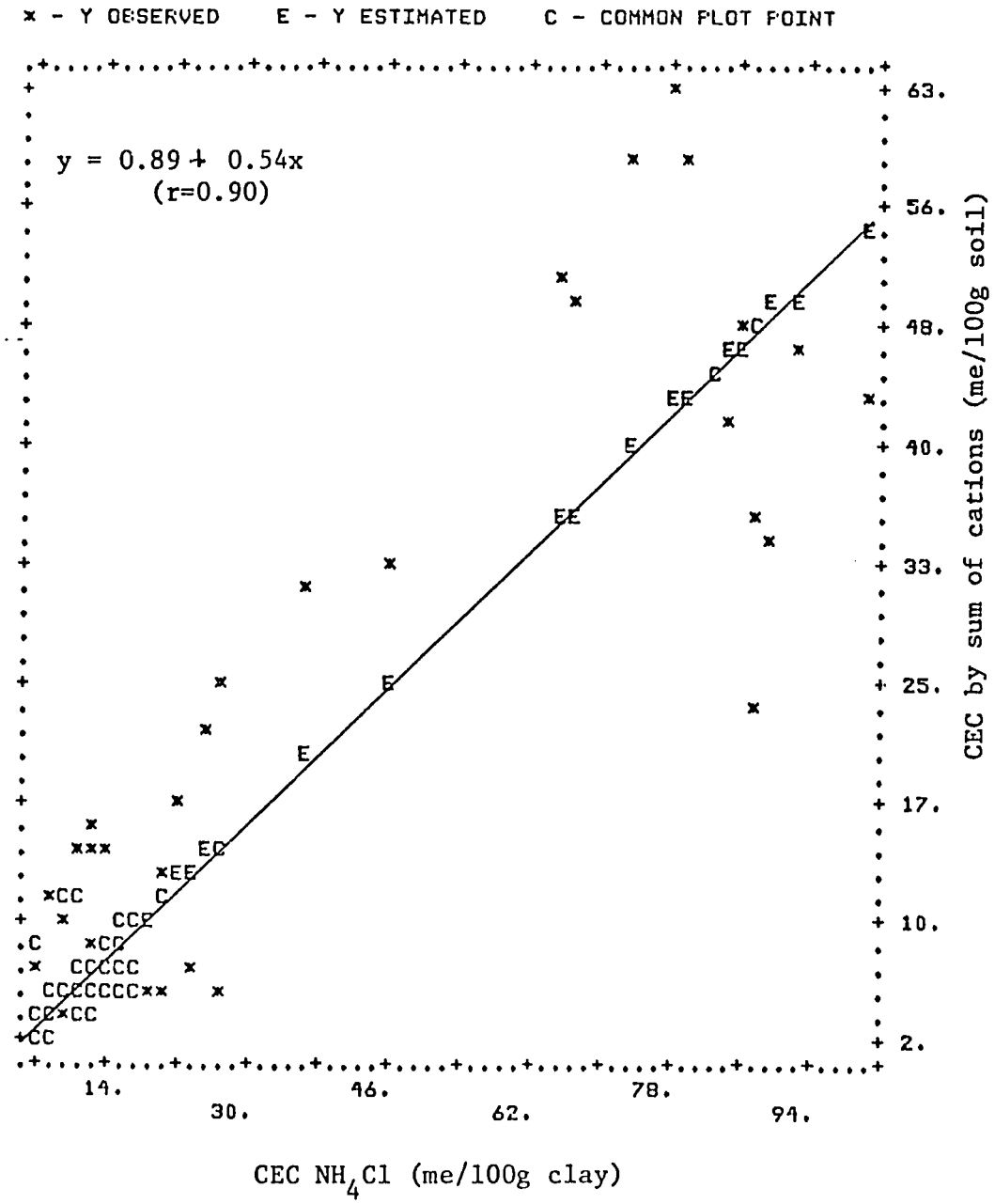

Fig. 8 - Comparison between CEC's measured by 1N NH_4Cl and by sum of cations plus extractable acidity.

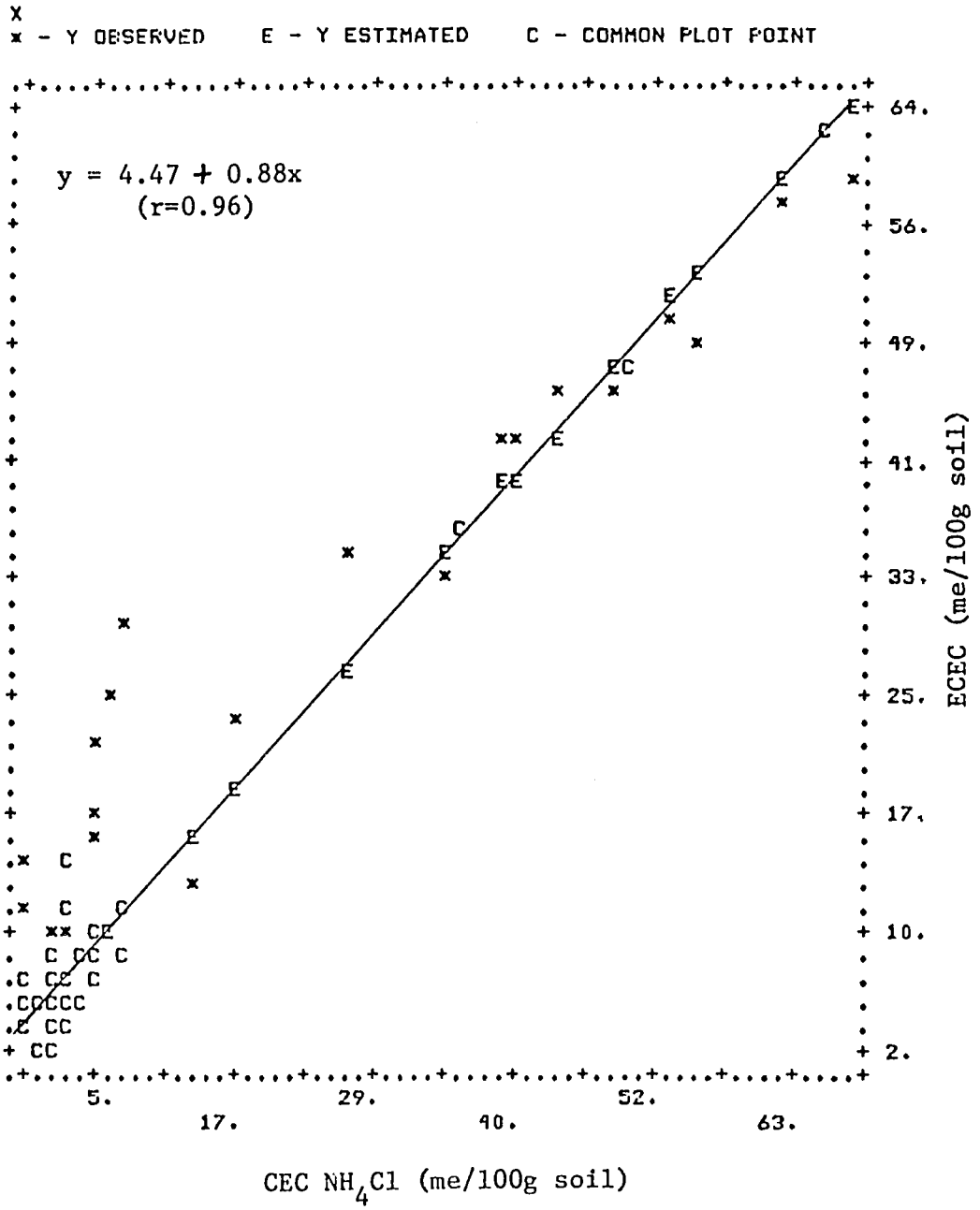

Fig. 9 - Comparison between CEC's measured by 1N NH_4Cl and by the sum of cations plus KCl aluminum (ECEC).

Okazak et al., 1963; and Bache 1976).

Table 3. Effect of volume of alcohol used for washing on CEC values measured by two methods.

	Method					
	Centrifuge			Extractor		
	ml alcohol used					
NSSL No.	100	200	300	100	200	300
	meq/100 g soil					
77P1254	7.3	5.2	4.7	8.2	5.1	4.8
77P1259	18.4	15.0	14.2	17.9	14.1	13.6
80P1089	3.9	3.0	2.9	3.2	3.4	2.9
78P1717	11.2	9.9	9.0	10.9	9.7	9.5
78P1746	2.7	2.3	2.6	2.8	2.6	2.3

The reduction can be caused by (1) hydrolysis of NH_4 during the alcohol washing, (2) sample dispersion and loss, and (3) salt retention (Smith et al., 1966) and/or loss of ammoniated organic constituents upon washing with 95% ethanol (Peech et al., 1962).

The wash volume of alcohol should be kept as constant as possible, and only the minimum volume necessary should be used. In standard analysis at the NSSL, 100-120 ml of ethanol are used for the washing step. In soils high in clay and/or organic matter, the sample is washed with the ethanol volume only until a check with Nessler's reagent shows no detectable ammonia in the leachate.

In summary, regarding CEC measurements, we need to develop a new method that is accurate, precise, inexpensive, and superior to the methods now being used.

Chemical--Mineralogical--Miscellaneous

The analyses under these three headings are not specific for variable or permanent charge minerals in soils. Information gained from these analyses can be used for classifying any soil.

Information on these is in SSIR No. 1, rev. 1981 or rev. 1972. One that I will cover is dithionite-extractable Fe analysis, and this is to answer another question asked of Dr. Holzhey at the second conference.

Does the procedure the NSSL uses for measuring dithionite-extractable Fe (SSIR No. 1, rev. 1981) measure all of the free iron in samples high in such iron? This procedure uses dithionite-citrate to extract free iron

oxides. Free iron includes iron weathered from primary minerals in the form of discrete particles or as coatings and cementing material for mineral particles that form complexes with organic matter and exchangeable iron. The method uses a single extraction in which the addition of citrate buffers the reaction and extends the usefulness to soils with high dithionite-extractable iron contents, including Oxisols (Holmgren, 1967). Holmgren found that a second extraction measured only about 2% of the iron measured by the first extraction in the soils he tested.

Because of the question raised, a triple extraction was run with the standard procedure as described in SSIR No. 1, rev. 1981, on five samples from Rwanda that had, on the initial extraction, levels of dithionite-extractable iron ranging from less than 1% to more than 10%. The weights of the samples were 2 and 4 g. Super floc was omitted in the first and second extractions. The iron extracted was measured in the centrifugate from each extraction. The results are shown in Table 4. Dithionite-citrate-extractable iron is reported to the nearest tenth of a percent. The standard deviation for samples run by the NSSL is about 0.1, representing about a 3% average analytical variation among replicated samples.

Table 4. Extractable iron measured by citrate-dithionite.

NSSL No.	Sample Weight	1st Extraction	2nd Extraction	3rd Extraction	Sum 1, 2, 3
		----------% Fe----------			
811132	2	0.8	0.1	0.0	0.9
811132	4	0.8	0.1	0.0	0.9
811142	2	4.5	0.2	0.1	4.8
811142	4	4.3	0.3	0.1	4.7
811160	2	6.2	0.5	0.3	7.0
811160	4	5.9	0.8	0.3	7.0
811163	2	10.7	0.8	0.2	11.7
811163	4	10.3	1.2	0.2	11.7
811164	2	10.4	1.1	0.2	11.7
811164	4	10.0	1.5	0.3	11.8
811211	2	6.9	0.9	0.3	8.1
811211	4	6.9	1.3	0.5	8.7

With 2-g samples, the first extraction extracts roughly 95% of the iron extracted by two extractions when the total Fe is < 10%. When iron is > 10%, the first extraction gets roughly 90% of the iron in 2-g samples and 86% of the iron in 4-g samples.

The third extraction gets a little more, but the amount is small and there is the problem of too rigorous a treatment. Some of the samples have ferromagnesian minerals, and they may yield some iron with a very rigorous extraction. In the third extraction, the amount did not vary more than the expected standard variation except in sample No. 811211. If the amount extracted is summed for the three extractions, the differences again are within the accepted standard variation for all samples except No. 811211.

For samples high in dithionite-extractable iron (over 5%), you should use a 2-g sample, and if the values are very high, it may be better to use a 1-g sample. The original procedure also was run on samples ground to pass a 50-mesh sieve (Holmgren, 1967). This may also be a good idea. If the sample has more than 10% dithionite-extractable iron, you could add 10% of what was extracted by the first extraction and not be very far from what you could expect with a triple extraction.

To summarize, one extraction does not always measure all of the dithionite-extractable iron, but the amount extracted by a second and a third extraction does not seem to warrant the time required. One other point is that in the original procedure, the analysis was run on fine-ground samples (<½ mm). This would increase the surface area and improve the extraction, but the grinding might degrade the ferromegnesian minerals and increase the iron extracted. In soils with some iron concentration and the presence of microgranule, this step (fine grinding) should be a help.

Several other analytical methods covered in the book by Uehara and Gillman (1981) are listed below. None of these except for specific surface are run by the NSSL at present. They present these as procedures for use on variable charge soils.

1. *Anion exchange capacity.* Most soils can have an anion exchange capacity (AEC), though it is insignificant or small in dominantly permanent charge soils. This can be measured by a method similar to CEC. Saturate the exchange sites with an index anion and then replace it with some other anion and measure the displaced anion. It can also be estimated by the compulsive exchange procedure already mentioned.

2. *Surface net charge and* pH_o. Samples are titrated with H^+ and OH^- at different electrolyte concentrations. When the amount of H^+ and OH^- absorbed are equal, the surface has a zero net charge, and this is referred to as pH_o.

3. *Sign of net charge* $pH = pHN_2 - pHN_1$. The pH is measured in a diluted and in a concentrated solution, and the difference is determined. This may be determined from the pH KCl and pH H_2O on the data sheet. Δ pH = pH KCl - pH H_2O. If pH is negative, the soil has a net negative charge; if positive, a net positive charge. All samples from Rwanda had a net negative charge.

4. *Measurement of permanent charge in a mixed system.* This is measured at pH_o and is based on the assumption that at this pH there is an equal adsorption of cations and anions. When there is an excess of cations or anions adsorbed, they must result from permanent charge sites.

5. *Zero point of charge.* Point of equal adsorption of cations and anions from an indifferent electrolyte.

6. *Specific surface.* This can be measured by the ethylene glycol monethyl ether (EGME) procedure in SSIR No. 1, rev. 1981. The surface area is determined from the amount of EGME retained as a single monolayer on the sample.

SUMMARY

Variable charge soils are unique--or at a different part of the spectrum than most other soils--and if we are to improve their classification, we need to improve the physical and, in some cases, the chemical analyses used. However, we need to remember that new techniques must be simple, accurate, inexpensive, and superior to methods now in use. Also, we should try to develop methods that can be used with a minimum of equipment and, wherever possible, can be related to observed field properties or have a simple field technique that can be used. Our goal should be to help the field person, because if we develop a system that requires complicated laboratory analytical methods, it will only be used in academic circles. We are trying to improve agrotechnology transfer; therefore, the person in the field must be able to use the system with a minimum of support. In no survey have I ever had too much characterization data. Many mapping decisions are based on observed soil characteristics, and we need to relate our analytical methods to these.

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DISCUSSION

Q. E. Schlichting: 1. Wouldn't the nitrate sorption be an important property of these soils? 2. Doesn't the fact that the delta pH is the numerical difference between logarithmic values imply the risk of wrong conclusions?

A. J. Kimble: 1. I have no idea if nitrate sorption would be of use. It is just a measurement of anion exchange capacity or the positive charge of the soil, but these soils have both a cation and anion ex-

change capacity. We would need to study data from some 50 to 100 pedons to see if the idea is worth trying. 2. pH depression in most soils results from the effect of salt as more H^+, Al^{+++}, Fe^{+++}, etc. go into solution with higher salt concentration. If a strong salt does not depress pH it tells us something about that soil.

Q. B.T. Kang: I suggest to include in soil characterization also data on potential Mn mobility in order to be able to indicate, at the family level, those soils that have or will have Mn toxicity if acidified. One could use a 0.5 M HNO3 extraction.

A. J. Kimble: I don't know what values could be expected and how they could be used in soil classification. We would need to examine some 50 to 100 pedons to develop some class limits.

Q. R.F. Isbell: Do you think there is a possibility of using chemical analyses instead of the time-consuming mineralogical analyses to obtain an estimate of "weatherable minerals" in low activity clay soils?

A. J. Kimble: Yes; I don't feel that grain counts are that easy and would be interested, therefore, in the results other people have obtained with chemical methods such as boiling HCl or the French method (H_2SO_4, HCl, HNO_3). Data on several pedons would have to be analyzed to compare and correlate the results obtained by chemical extraction and by grain counts.

Q. A.J. Herbillon: Why not use pH in 0.01 N KCl and 1 N KCl, as pH in water is often not very stable?

A. J. Kimble: I think it would be a good idea to check this out as it would make pH measurements more stable and easier to compare. We might want to use 0.001 N KCl.

NOTE: For analytical characterization data of the profiles mentioned, see Part II of the Proceedings

AGRICULTURAL POTENTIAL OF LOW ACTIVITY CLAY SOILS OF THE HUMID TROPICS

James M. Spain

INTRODUCTION

Much attention has been given to the disadvantages of the well-drained upland soils of the humid tropics. Some characteristics do constitute important limitations to productivity, while others, which appear to most observers to be limitations, can be used to advantage by skillful management and thus enhance the agricultural potential of such soils.

DOMINANT SOILS OF THE HUMID TROPICS

The climatic conditions which have prevailed in the humid tropics generally favor the development of deep, highly leached soils, poor in weatherable minerals, characterized by 1:1 type, mainly kaolinitic, low activity, clay minerals, and iron and aluminum oxides, thus the term "low activity clay" or LAC soils. Sanchez (1976) estimates that approximately 70% of all the soils in regions of rainy and seasonally wet tropical climates (2.5 out of the 3.6×10^9 ha total) are comprised of Oxisols, Ultisols and Alfisols. An even higher percentage (estimated at $\pm$ 75%) of the soils in humid tropical South America are comprised of these three orders. The balance is made up of very sandy and shallow soils, moderately weathered soils with medium to high base status, hydromorphic and alluvial soils.

Moormann and Van Wambeke (1978) in a review of the areal distribution of major soils in rainy tropical climates, contend that the Oxisols are characteristic of the South American and African tropics with udic (nearly continuously wet) moisture regimes. However, they also state that they are dominant in the stable areas of the central plateau of Brazil and ex-

tensive in the Llanos of Colombia and Venezuela, areas characterized by a ustic (wet-dry) moisture regime.

Aubert and Tavernier (1972) present a map which indicates approximately equal areas of Oxisols (over 500 x 10^6 ha) on each continent. In contrast, Oxisols occur only rather sporadically in the Asian humid tropics as inclusions developed on highly weatherable parent rocks. Sanchez (1976) has made calculations based on the Aubert and Tavernier map which indicate that Ultisols are apparently more extensive in Asia ($\pm$250 x 10^6 ha) and the Americas ($\pm$200 x 10^6 ha) than in Africa ($\pm$ 100 x 10^6 ha). The Alfisols which are similar to the Ultisols but less weathered and generally more fertile are far more extensive in Africa ($\pm$ 550 x 10^6 ha) than in the American tropics ($\pm$ 150 x 10^6 ha) and Asia ($\pm$ 100 x 10^6 ha). These differences are due primarily to variations in stability of land forms in the three areas. South America, with its two major old continental shields (Guianan and Brazilian) and very large basins of sedimentary soils between these shields and the Andean uplift, is the more stable area. The African landscape is characterized by more general orogenic activity, but again there are extensive plateaus and large basins of sedimentary materials which are deeply weathered (e.g. the Niger and Congo basins). Tropical South Asia has relatively few extremely weathered soils due to intense orogenic activity which has interrupted the weathering process except for relatively small areas. The same is true of continental and insular Southeast Asia (Moorman and Van Wambeke, 1978).

These major differences in soil resources are reflected in agricultural productivity and land use patterns. Farmers in the Asian tropics have for centuries produced food for large populations and managed to produce surplus grain and other products. At the other extreme, the African humid tropics generally support a very sparse population with little or no surplus production of food or other products.

Within the vast areas of highly weathered soils on the old shield surfaces and in some of the sedimentary basins, more productive soils often occur, usually on steeper slopes, rejuvenated by the erosion process which strips away weathered materials and exposes primary minerals as sources of plant nutrients. These soils and those formed on recent alluvium have served as the basis for the development of traditional agriculture in the

tropics. Where population pressures are great, the more productive soils with higher inherent fertility are nearly all used intensively. In South America, where population pressure on a continental scale is not nearly as high as in other tropical areas, there are still rather fertile soils which remain unused primarily due to distance to markets and lack of access routes or because of poor drainage or other conditions too costly to alter at present cost/benefit ratios.

"NEW LANDS" FOR INCREASED AGRICULTURAL PRODUCTION

In regions where large areas remain unexploited, there are two major strategies for increasing agricultural productivity. One is to increase the productivity of lands presently being farmed through adoption of modern agricultural technology along with necessary credit and technical assistance. The other strategy is to increase production through expanded area either by draining alluvial lands, developing irrigation projects or by opening frontier areas with new access routes.

At the Centro Internacional de Agricultura Tropical (CIAT), both strategies have been pursued. Work with beans, rice and corn is directed almost exclusively toward increasing production in traditional agricultural areas. In cassava, both strategies are followed, with emphasis on increased production on marginal soils in existing agricultural areas and on expansion into new areas of low fertility soils. In the Tropical Pastures Program the effort is almost exclusively directed to the expansion of production in the "new lands," which are generally marginal for most annual crops with respect to soil fertility and acidity. Therefore, much of the present discussion relates to the very large expanses of Ultisols and Oxisols which currently contribute very little to total food production but which promise great potential for the future when economic conditions favor their use.

CHARACTERISTICS OF DOMINANT SOILS AND MANAGEMENT IMPLICATIONS

Large areas of Alfisols, which are characterized by low activity

clays, occur in Africa. Unlike the Ultisols and Oxisols, they usually combine good to excellent native fertility with favorable physical properties. Their inherent fertility is due to parent material and/or rainfall regimes which have resulted in less leaching. They constitute a major potential for increased crop production, their major restraint being their relatively low water-holding capacity. When reference is made to low fertility and/or extreme acidity in the balance of this discussion, the Alfisols are excluded.

The Oxisols and Ultisols will be treated together even though there are some important differences between the two. The Oxisols are generally older soils, more highly weathered and better drained with more favorable physical properties than the Ultisols.

The major characteristics of these low activity clay soils are shown in Table 1 and reference is made to the advantages and/or limitations of each characteristic.

Low Fertility

It may be difficult to imagine that low fertility can be turned to an advantage. However, just such an example is found in recent research conducted in the eastern plains of Colombia in the development of low cost methods of pasture establishment on Oxisols (CIAT, 1977). These soils remain weed free for many months after native savanna is broken for planting if no fertilizer is applied. This is due primarily to low fertility but also to the general lack of weed seeds in savanna-dominant regions. Several trials have demonstrated the feasibility of preparing land and seeding a number of pasture species at very low density, applying fertilizer only to the "mother" plants, creating optimum conditions for the development of these plants to provide coverage for the entire area via seed, stolons or trailing stems. In the initial trial, populations of 1000 hills/ha were used with fertilizer applications of 0.2 to 4.0 kg of P and 0 to 1.2 kg of K/ha, all applied in the hill, with the balance of the fertilizer applied only after pasture establishment was assured. From 1000 plants of *Andropogon gayanus*/ha planted in September of 1977, stands of 150-200 plants/m^2 were obtained in April 1978. Most of the species were ready for permanent stocking by June of 1978.

Low inherent fertility does constitute a major limitation and initially is much more serious in savannas than in jungle regions where most subsistence farming is found. The major reason for this is that a much greater biomass is accumulated in jungle growth than in savanna. Savanna vegetation rarely accumulates more than 5 t/ha dry matter and nutrients released when it is burned are not sufficient for even one cycle of cropping. However, when the jungle is cleared and burned, the release of nutrients which have accumulated in up to 500 t/ha of dry matter in above ground growth brings about a drastic change in soil fertility and chemical properties in the upper part of the horizon. The ash neutralizes the acidity in the top soil and provides a good supply of essential plant nutrients. The fertility thus created is surprisingly stable as indicated in recent work reported by Toledo and Morales (1978) and Serrão et al. (1978). The major decline in productivity after 2-3 years is reported to be due to a very rapid reduction in phosphorus availability after the jungle is felled and burned, due to fixation. In the past, it has been thought that the reason for abandoning cleared areas after only a few years of cropping was primarily due to a general decline in soil fertility and increasing acidity. However, this recent information would indicate that phosphorus may be the principal limiting fertility factor.

Extreme Acidity

Very acid soils are generally characterized by high levels of exchangeable aluminum and/or excessive concentrations of active manganese. Both elements are quite toxic at high concentrations to most cultivated crops. To overcome this problem, farmers have for centuries taken advantage of species that are acid soil tolerant to reduce or eliminate the need for lime and to assure deep rooting, thereby reducing the effects of drought. In recent years, scientists have become aware of the possibility of selecting species and cultivars within species for acid soil tolerance as well as systematic breeding for this characteristic to reduce production costs in areas where distance or lack of transportation routes make the use of lime economically unacceptable (Spain, 1977). This concern for acid soil-tolerant species will perhaps become less important with time if and when relative costs of inputs are reduced and absolute yields become

Table 1. Major characteristics of low activity clay soils of the humid tropics and resultant advantages and limitations.

Characteristics	Advantages	Limitations
1. Low fertility	Low initial weed potential.	Limited range of adapted species. High initial cost of fertilizer required by non-adapted species.
2. Extreme acidity	Permits use of low solubility P sources. Increases the availability of minor elements with exception of Mo. Controls some soil-borne diseases. Fewer adapted weed species.	Limited range of adapted annual crop species. Al and Mn toxicity. High initial cost of lime required by non-adapted species.
3. Low cation exchange capacity	Lower lime requirement. Lower initial fertilizer requirement. Ca and Mg more easily leached to ameliorate subsoil infertility.	Limited reserve and retention of bases.
4. High P-fixing capacity		Low efficiency of P fertilizers.
5. Low water-holding capacity		Crops are susceptible to even short drought periods. Susceptible to high leaching losses.
6. Lack of primary minerals		Limited reserve of nutrients.
7. Predominance of 1:1 type clay minerals	Soils are generally friable and easily tilled.	Lack the basis for recovery of structure once it is lost.
8. High sesquioxide content	Stable micro-structure. Good internal drainage and aeration, easily tilled.	Weak macro-structure; very susceptible to erosion. Very susceptible to leaching losses.
9. Relatively smooth topography	Easily mechanized.	

Table 1 (cont'd)

Characteristics	Advantages	Limitations
10. Deep profiles generally free of physical obstacles to root penetration	Permits deep rooting of adapted species. Good subsoil moisture reserve.	
11. Presence of laterite	Very useful for road building and general construction.	Impedes tillage and cultivation.

more important. It should be noted that subsoils are very difficult if not impossible to lime; therefore the importance of acid soil tolerance in dought resistance is not likely to change much with time in areas of considerable drought hazard where irrigation is not possible or economical.

Extreme soil acidity can also be advantageous. Recent work at CIAT has shown that rock phosphate can be used very efficiently by acid soil-tolerant perennial species. The rock is "acidulated" by the soil, thus increasing markedly its agronomic value. Micronutrients are also more available in an acid soil medium, with the exception of molybdenum. However, micronutrient reserves are often extremely low in highly weathered soils and are usually required to maintain yields in extractive cropping systems.

Several plant diseases are absent in acid soils but become serious when these soils are limed. Examples include "Take all" of wheat (*Ophiobolis graminis*, *Gaumenomyces graminis*), potato scab(*Synchytrium endobioticum*) and certain fusarium wilts of tomato.

It must be emphasized that even the most acid soil-tolerant species still require Ca, Mg and K as nutrients and that these elements are almost always deficient in extremely acid soils.

Low Cation Exchange Capacity

This characteristic can be an advantage in that less lime is required to neutralize exchangeable acidity. Therefore, when it is necessary to lime for annual crops, relatively low rates are required for adequate crop performance. Low CEC results in less retention in surface horizons of nutrient cations such as K, Ca and Mg in regions of high rainfall. The leaching of bases from the surface can ameliorate the extreme subsoil infertility common to many Oxisols and Ultisols, thus increasing rooting depth of acid soil-tolerant species. However, it is usually more difficult to maintain adequate surface horizon fertility in these soils than in soils with greater cation exchange capacity. It is also more difficult to meet the nutrient requirements of annual crops such as corn during their periods of very rapid growth when rates of nutrient uptake are extremely high.

High P-fixing Capacity

This characteristic is a major limitation. It results in low efficiency in the use of P fertilizers, especially for annual crops. It can be overcome in part by placement of fertilizer to reduce soil-fertilizer contact. Examples include banding of fertilizer at planting and surface application of fertilizer in established pastures and other perennial crops.

Low Water-holding Capacity

Another very important disadvantage of LAC soils is their low water-holding capacity. Most annual crops are relatively limited in their capacity to penetrate into the deep subsoil and are very susceptible to relatively short periods of drought even during the rainy season when the subsoil is always moist.

Lack of Primary Minerals

Most LAC soils are highly weathered to considerable depth; therefore, they contain few primary minerals and limited reserves of nutrients.

Predominance of 1:1 Clay Minerals

This characteristic generally results in soils that are friable and easily tilled over a wide range of moisture content. However, due to the absence of 2:1 (swelling) clays, they lack an important mechanism for the recovery of structure, once it is destroyed.

High Sesquioxide Content

Sesquioxide cementation results in very stable microstructure and good internal drainage and aeration. On the other hand, it generally leads to weak macrostructure and soils that are quite susceptible to erosion. Because of their good internal drainage, they are susceptible to leaching losses. Both of these limitations can be offset by maintaining a growing plant cover on the soil as continuously as possible, and through the use of deep rooting perennial species capable of efficiently recycling nutrients from the subsoil.

Relatively Smooth Topography

Most Oxisols and Ultisols landscapes are smooth to gently rolling and lend themselves to efficient mechanization and modern farming systems.

Deep Profiles

On smooth landscapes, most LAC soils are characterized by deep profiles free of obstacles to root penetration, thus permitting deep rooting of adapted, acid soil-tolerant perennial species. This results in good subsoil moisture reserve and efficient recovery and recycling of nutrients which leach down the profile.

Presence of Laterite

There is a widely held belief that great danger exists in the opening up of rainy tropical areas to more intensive land use. The literature on tropical ecology and soils continues to propagate the myth of the widespread threat of laterization; the fear that most tropical soils when cleared of rain forests or savannas will dry up and harden into brick-like surfaces through the process of laterization. Laterization takes place where plinthite (firm, iron-rich soil nodules) and other iron-rich soil materials occurring in the upper part of the soil profile are exposed to drying and subsequently harden irreversibly into laterite nodules or massive laterite ironstone. Plinthite generally occurs only in soils which are subjected to a fluctuating water table in the upper part of the profile. Alternating oxidation and reduction result in the precipitation of iron as it is oxidized near the soil surface during the dry season. Moormann and Van Wambeke (1978) estimate the extent of such active plinthite formation to be less than 2% of all tropical lands and it is rare that even on these soils the plinthite would be exposed in such a way that it would harden irreversibly when put into agricultural use. Buol and Sanchez (1978) estimate that plinthite exists in the upper 1.25 m in 7% of the soils in the Oxisol-Ultisol regions of South America and that the same percentage holds for the Ultisols in Southeastern United States.

Kellogg (1975) points out the great usefulness of laterite as a building material in the tropics. The author has observed plinthite-laterite

blocks used in ancient Malaysian temples that were apparently cut from the subsoil while still relatively soft and hardened irreversibly once exposed to the atmosphere. Laterite gravel is used extensively for road building in the Colombian Llanos and many other savanna regions.

THE SPECIAL ROLE OF FORAGE-BASED AGRICULTURE IN AREAS OF LOW ACTIVITY CLAY SOILS

Soil fertility is a relative matter and depends on the scale used to measure it. If the fertility of Oxisols in the Colombian Llanos is measured with maize, the soils are as infertile as can be found. However, when their fertility is measured with *Stylosanthes capitata* or *Brachiaria decumbens* an entirely different answer results (CIAT, 1977). The soil "looks" quite fertile and in fact is, in terms of productivity for those particular species. Obviously, the more acid the soil and the more limited the availability of the essential plant nutrients the more restricted the range of plants that can be grown with minimum inputs.

Fortunately, many tropical forage grasses and legumes are very tolerant of soil acidity and low fertility. They have evolved in savanna regions characterized by these conditions. Many of them have excellent potential for the production of grazing animals with minimal inputs required. The recycling of nutrients on well-managed pastures is efficient and nutrient removal (export) in the harvested product (meat) is very low.

Forage-based livestock systems can be quite stable and represent relatively low risks to the ecosystem while providing a means of building capital during the initial phases of development of new areas. In many cases, the production of beef and milk from predominantly beef herds is a step in the direction of much more intensive development and land utilization, especially on soils with more favorable physical conditions and topography. Some soils which will never be suitable for cropping are used successfully for very intensive high input livestock production with extremely high yields (Vicente-Chandler et al., 1974).

The use of grazing animals also overcomes some of the disadvantages of low fertility in other ways; they can be used to concentrate fertility

from large to small areas in and around corrals, which then can be used for food crop production, primarily for direct on-farm consumption.

CONCLUSION

The major limitations to greater production on the low activity clay soils of the humid tropics can be readily removed by careful and judicious management and with the application of fertilizer and/or lime. When these restraints are removed, many LAC soils become highly productive. The inputs required vary from soil to soil and crop to crop but always cost money. That money will be spent when tropical farmers and ranchers have access to markets and are assured a fair return on their investment.

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DISCUSSION

Q. A.M. Bunyolo: In view of conflicting statements regarding the liming of acid tropical soils, what would you say is the most realistic depth to which these soils should be limed? Some experiments in tropical areas have shown that liming the soil to 30 cm depth has the most beneficial effect while others have not. By beneficial effects I mean an immediate response in the first season due to increased nutrient and moisture availability as the rooting depth is extended by liming.

A. J.M. Spain: If moisture is limiting during the growing season and if one works with Al-susceptible species, deep incorporation of lime should result in better crop performance unless deep plowing results in adverse changes in surface physical and/or chemical conditions which may often be the case, especially in soils with shallow A horizons. Best incorporation of lime can be accomplished by first applying about 50% of the lime required to achieve the degree of Al neutralization desired (to the depth to be plowed), followed by disking to about ½ the depth to be plowed, followed by plowing and then applying the remaining 50% of lime and disking again. If all of the lime is applied before plowing and the soil is strongly acid at the depth to be plowed, most of the lime will be layered near the bottom

of the plow layer and conditions may well be worse than they were before liming and plowing. It is usually not practical to plow to depth greater than 30 cm and it is often difficult.

Q. V. Ndoreyaho: In the literature it is recommended that one should not lime tropical soils above pH 6.5. Why this restriction and what happens in the soil?

A. J.M. Spain: Many perennial and some annual species grow very well in soils with a high Al saturation (80-90%) without lime. They may need Ca and/or Mg as nutrients but are not (or only slightly) affected by Al. Liming of LAC soils may induce serious micronutrient deficiencies (Zn, Mn, B) and result in nutrient imbalance, especially Ca vs Mg (when calcite lime is used) and Ca vs K.

A. B.T. Kang: We recommend the use of minimum Al saturation percentage requirement for liming. This will depend on the crops grown and on the farming systems.

Q. P. Pietrowicz: 1. Regarding the Brachiaria root system and especially the mycorrhiza, what is known about mycorrhiza development and plant ability of P uptake, also from the P fraction fixed in acid soils? 2. Does liming limit the rooting depth, caused by a sudden change in the pH and correspondingly in the amount of free Al in the soil?

A. J.M. Spain: 1. *B. humidicola* and *B. decumbens* along with most grasses in the savanna region of Colombia are mycorrhizal. *B. humidicola* is one of the most efficient P feeders and is also a very productive and good quality grass. It has a very fine root system in our conditions. 2. I do not know from experience. I don't think liming would limit rooting depth. It often induces micronutrient deficiencies which may reduce general plant vigor, in some cases very drastically, e.g., Zn deficiency in cassava and probably cashew.

Q. J. Bennema: What kind of salts do you give to the cattle in your improved system for savanna regions?

A. J.M. Spain: The management practice which has given the greatest response (in reproductive performance) in breeding cattle on native savanna is the supplying of a complete mineral mix (ad lib) with main effects apparently from Ca and P. We also give complete mineral mix to animals on introduced (planted) pastures in our research in the Colombian Llanos.

Q. E. Schlichting: Lime requirement should not be connected with pH but with the amount of exchangeable Al or Mn or the possible fixation of P. Even in temperate regions there are soils which can easily be overlimed already at pH 6.

A. J.M. Spain: I agree with Dr. Schlichting. The most important criterion in liming tropical soils is exchangeable Al. Acceptable Al saturation percentage and thus lime requirement depends on the cropping system and/or species included in the rotation. Economic consideration (cost/benefit ratios) will often dictate the species which are viable in a given ecosystem.

Q. A.J. Herbillon: Would it be possible to translate the amount of Al in solution (given in ppm) into meq of Al per 100 g of soil or clay?

A. J.M. Spain: It is difficult to equate the Al concentration in solution culture trials to meq exchangeable Al in the soil because the effect of Al concentration in solutions depends very much on the P and Ca concentration in the solution. Also, the effect of exchangeable Al in soils is conditioned by P and Ca availability in soils. Disregarding this problem, it would probably be easier to correlate ppm Al in solution with % Al saturation in soils.

Q. J. Bennema: Related to the question of % base saturation, do the allic characteristics as used in Brazil serve your purpose?

A. J.M. Spain: I find the term "allic" as defined in the Brazilian taxonomy very useful. It says in one word what otherwise takes several words or phrases to say, i.e., that the soil or horizon in question is extremely acid, high in % Al saturation, low in % base saturation and, therefore, relatively infertile for most annual crop species.

Q. H. Eswaran: Could you indicate some properties of Oxisols that are important to soil management?

A. J.M. Spain: I will only comment on the distinction between eutrophic and dystrophic. I believe it is misleading to use NH_4OAc CEC as a basis for calculating % base saturation. From a management point of view, it would be better to use permanent charge (sum of bases plus Al). In many soils we have studied, % base saturation of ECEC has been high (more than 90%) and yet they have been called dystrophic be-

cause % base saturation of CEC at pH 7 was less than 50% and low base and nutrient status have been cited as limiting factors. In part, I see this as a result of the present definition of dystrophic and eutrophic.

MANAGEMENT OF LOW ACTIVITY CLAY SOILS IN TROPICAL AFRICA FOR FOOD CROP PRODUCTION

B.T. Kang and A.S.R. Juo

INTRODUCTION

Low activity clay (LAC) soils are the most abundant soils in tropical Africa. For much of this region, the bush fallow system of cultivation (Ruthenberg, 1976) is still the dominant practice of food crop production. Though subsistence, the traditional bush fallow system is an effective method for managing the LAC soils when land is in abundance. However, this system, which relies heavily on a long fallow period (i.e. 7 to 15 years) for regenerating soil fertility, is gradually reaching its limit in certain areas due to rapid increase in population and land use, which no longer allow a sufficient fallow period.

The development of improved crop production systems on LAC soils is to be based on two prerequisites, namely, the inherent soil fertility limitations and the socio-economic constraints of the small-holder farmers. This paper reviews recent research on the management of LAC soils in tropical Africa.

MAJOR LAC SOILS IN TROPICAL AFRICA AND THEIR MANAGEMENT LIMITATIONS

Low clay activity (LAC) soils are soils with an effective CEC of less than 14 meq/100 g of clay in the diagnostic horizon where the influence of soil organic matter is minimal. According to their mineralogical and surface charge characteristics, they may be further divided into three groups: (1) the kaolinitic LAC soils, (2) the oxidic LAC soils, and (3) the siliceous LAC soils. Definition and criteria for such groupings

have been described by Juo (1980, 1981). It is important to point out that soils under such groupings often have distinctive differences in terms of their fertility capability and limitations.

Kaolinitic Soils

The kaolinitic soils occur widely in the humid and subhumid regions of tropical Africa. These soils are mainly Paleustalfs and Plinthustalfs in the sub-humid region and Paleudults and Plinthudults in the humid region. Such soils generally have a coarse to medium-textured surface horizon and a more clayey B horizon with clay content greater than 35%.

The kaolinitic soils in West and Central Africa are commonly associated with a rolling topography with an average slope often exceeding 5%. Thus, in areas with high rainfall intensity and erratic rainfall distribution (i.e. the humid/subhumid transition zone of southwestern Nigeria), soil erosion is a critical factor limiting large-scale and mechanized systems of food crop cultivation.

Oxidic Soils

The oxidic LAC soils are the fine-textured soils with a low effective CEC but a large pH-dependent CEC (or variable charge) due to the presence of substantial amounts of free Fe oxides with a very large specific surface area (i.e. greater than 150 m^2/g of Fe_2O_3). Such types of LAC soils are generally derived from volcanic rocks, such as basalts, or from other ferromagnesian rocks low in quartz. The oxidic LAC soils are found in the East African highlands (i.e. Eutric Nitosols, FAO/UNESCO) and in some restricted areas in other parts of tropical Africa. Such soils have excellent physical properties and are less susceptible to erosion and mechanical compaction. Thus, large-scale commercial food and cash crop farming are commonly found on such soils.

Soil Taxonomy classification draws little distinction between the kaolinitic and oxidic LAC soils. The present Soil Taxonomy criteria which differentiates the oxidic and kaolinitic families is based on the ratio of oxide to clay content by weight; whereas the surface and charge characteristics and the differences in soil physical properties are not taken

into consideration. In general, most fine-textured Ustox, Humox, and Humults fall within the oxidic LAC soil category.

Siliceous Soils

This group of LAC soils are soils with a sandy to loamy sand surface layer and a diagnostic subsoil horizon which contains less than 35% clay but more than 55% quartz sand or other durable minerals. In West Africa, such soils are generally derived from Pleistocene coastal sandy sediments and from Cretaceous sandstones. Because of the predominance of quartz sand, the influence of soil mineralogy and surface charge characteristics on soil behavior becomes less important. Multiple nutrient deficiencies and imbalance are important limiting factors when such soils are used for more permanent food crop production.

In the subhumid or savanna region (mainly Paleustalfs and Paleustults), low available soil moisture reserve is a major constraint limiting the cultivation of crops such as upland rice and soybeans with high moisture and nutrient demands.

In the humid forest region, however, the siliceous LAC soils beneath the lush green forest are often extremely infertile and acidic. Mechanized forest clearing for extensive food crop cultivation may be prohibitive unless essential inputs, such as lime, multinutrient fertilizers and pesticides are readily available. The common siliceous LAC soils in the humid region are Paleudults and Haplorthox, coarse-loamy, siliceous, isohyperthermic family. An approximate correlation of the three groups of LAC soils with Soil Taxonomy classification is given in Table 1, and some properties of selected LAC soils are given in Table 2.

MANAGEMENT OF LAC SOILS

Humid and Per-humid Regions

The humid and per-humid regions are defined as Precipitation, P-Potential Evapotranspiration, ET for period of between 6 to 8 months, or more than 8 months per year, respectively (Lawson and Juo, 1979). Ultisols and Oxisols belonging to the kaolinitic and siliceous groupings are the domi-

Table 1. An approximate correlation of the four mineralogical soil with Soil Taxonomy classification at the great group level 1981).

Mineralogical groupings	Chemical class[a]	Soil Taxonomy correlation (Great Group)
Kaolinitic	Eutric	Paleustalfs, Plinthustalfs, Tropuda linitic family)
	Dystric	Paleustults, Plinthustults, Paleudu Plinthudults, Tropaquults, Haplorth (Kaolinitic family)
Oxidic	Eutric	Eutrustox, Eutrorthox, Haplorthox, stalfs, Tropohumults, Humox (Oxidic or Kaolinitic family)
	Dystric	Acrustox, Acrorthox, Haplorthox, Pa Tropohumults, Humox, Paleustults, P mults (Oxidic or Kaolinitic family)
Siliceous	Eutric	Psamments, Paleustalfs, Aquepts, Aq (Siliceous family)
	Dystric	Psamments, Paleustults, Paleudults, thox, Aquepts, Aquents (Siliceous family)

[a]Eutric (high base status); Dystric (low base status).

nant soils in these regions. The present agricultural land use c soils involved mainly tree crop farming (rubber, oil palm) and trad: bush fallow system where cassava is the major food crop.

Nutrient management. The inherently low nutrient status and hig ching losses are among the main soil constraints for establish'ng mor manent cropping systems on LAC soils in the humid and per-humid re Deficiencies of N, P, K, Ca and Mg are common under continuous culti of high yielding food crops (Bapat, 1974; Fore and Okogbo, 1974; J Uzu, 1977; Kang, 1967; Kang, 1978). Application of high lime rat induce imbalance and deficiencies of Mg, Zn and Mn on these poorly bu soils (Edwards and Kang, 1978; Friessen et al., 1980). However, as strated by Fore and Okigbo (1974), high maize yields can be obtaine applications of farmyard manure, N, P, K, Mg fertilizers and lime.

Soil acidity and liming. For continuous crop production on st

Table 2. Some properties of selected LAC soils from tropical Africa.

Horizon	pH H_2O	Clay (%)	Sand (%)	Total Free Fe_2O_3 (%)	Bulk Density (g/cm^3)	Clay Activity meq/100 g	BET-N_2 Surface Area m^2/g Clay	Exch Cations meq/100 g Soil		
								Ca	Mg	K
Kaolinitic Soil (Paleustalf, Ibadan, Nigeria)										
A1	6.2	16	66	3.8	1.35	67.4	47	6.19	3.37	0.41
B2t	6.0	54	37	7.2	1.49	9.2	44	3.29	1.20	0.16
Siliceous Soil (Paleustult, Nsukka, Nigeria)										
A1	4.6	26	67	3.2	1.21	7.1	24	0.25	0.04	0.05
B21t	4.7	29	64	3.6	1.49	6.6	39	0.20	0.04	0.05
Oxidic Soil (Eutrustox, Embu, Kenya)										
A1	6.0	64	24	-	1.09	15.6	-	6.39	2.53	0.72
B21	5.5	64	28	8.9	1.04	6.4	102	2.20	0.99	0.34

acidic Ultisols and Oxisols, liming is often needed in order to neutralize toxic levels of Al (and/or Mn) and to supply Ca and Mg as plant nutrients.

Results of a five years' liming experiment on a siliceous soil (Typic Paleudult) at IITA high rainfall sub-station at Onne in southeastern Nigeria showed that sustained crop yield of maize-cowpea grown in annual rotation can be obtained with relatively low lime rates and balanced (N, P, K, Mg, Zn) fertilization (IITA, 1978; 1979; 1980). Lime at a rate of 0.5 t/ha maintained maize yield near maximum for two years after application. Moreover, Ca applied as lime leached readily from the surface layers in the form of neutral salts which had little effect in ameliorating subsoil acidity (Fig. 1). Therefore, lime requirement on such soils should be based on the critical exchangeable Al level for the crop to be grown (Kamprath, 1970). For similar soils annual lime rates of 200 to 500 kg/ha will suffice to maintain reasonable maize and cowpea yields. The critical levels of exchangeable Al saturation (i.e. for 90% maximum yield) are 35% and 50% for maize (Cv. TZPB) and cowpea (Vita 1 and Vita 4) cultivars, respectively.

Effect of residue burning. Earlier reports indicated the beneficial effect of burning in the traditional system of cultivation through its liming effect and the quick release of nutrients contained in the ash (Nye and Greenland, 1965; Brinkmann and Nascemento, 1973; and Suebert, 1975). A recent study (Okoro, 1981) on residue burning and mulching conducted on a siliceous soil (Typic Paleudult, coarse loamy, siliceous isohyperthermic) at IITA high rainfall sub-station at Onne near Port Harcourt, Nigeria, showed no significant difference between burning and residue mulching in terms of the growth and yield of maize (Cv. TZPB) while weed growth was effectively controlled by herbicide application (Table 3). Results from this study suggest that in the humid tropical regions where the exchangeable Al in soils is below the critical level of the crop to be grown, burning may not give any additional benefit over residue mulching. It appears that the need for burning in the traditional system of cultivation is to facilitate seedbed preparation.

Role of trees in developing viable cropping systems. Farmers have for generations exploited the nutrient recycling ability of trees and shrubs in the natural fallow to regenerate soil fertility. However, the

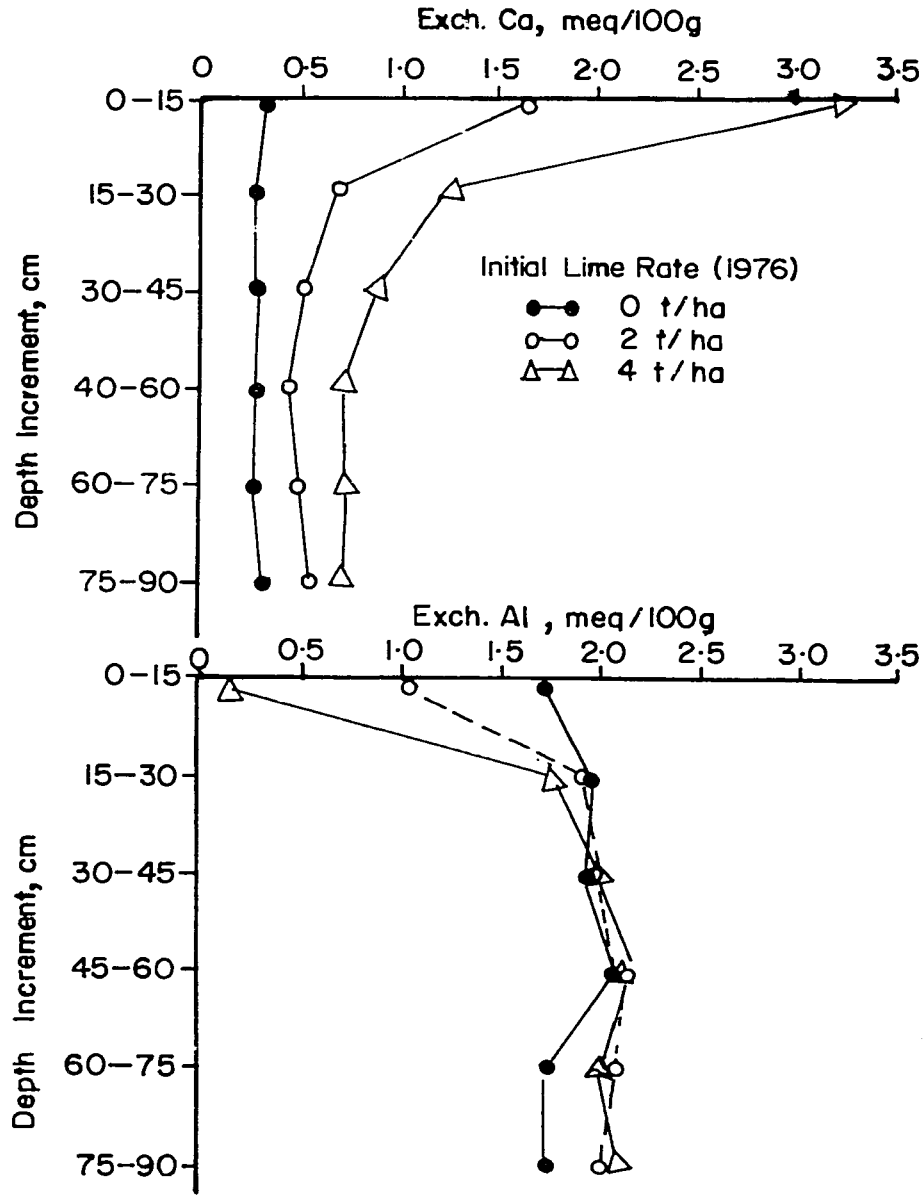

Fig. 1. Vertical distributions of exchangeable Ca and Al in a Typic Paleudult at Onne three years after lime application. (D.K. Friesen, A.S.R. Juo and M.H. Miller, unpublished)

Table 3. Effect of residue management, fertilizer application and liming on yield of maize grown on Typic Paleudult in Eastern Nigeria (Okoro, 1981).

Residue--Fertilizer Treatment	YEAR 1978	1979	1980
	Kg/Ha		
A Residue Burnt			
Control	1190	595	1391
NPK MG ZN	2302	2233	3587
NPK MG ZN + Lime[a]	3008	2355	3702
B Residue Mulched			
Control	1140	556	1493
NPK MG ZN	2878	1682	3137
NPK MG ZN + Lime[a]	3495	1799	3377
L.S.D. (0.05)	679	746	981

[a]Lime at rate of 1 ton/ha applied in 1978 and 1980.

traditional bush fallow/food crop rotation systems are undergoing significant changes as a consequence of increasing land use pressure and overexploitation of forest resources. The result is generally a steady decrease in number of trees and shrubs in fallows and a steady increase in grasses and weed flora. However, farmers in certain populated areas, such as in southern Nigeria, recognize the usefulness of certain fallow species in restoring soil fertility. Fallow plots with an almost pure stand of *Acioa baterii*, *Anthonata macrophylla* and *Alchornea cordifolia* are common (Obi and Tuley, 1973; Okigbo and Lal, 1979). A recent survey in southeastern Nigeria indicates that farmers used a fallow period of 2 to 4 years with selected species but allowed 6 to 8 years with uncontrolled fallow regeneration (Amare et al., 1981). Recognizing the many limitations for utilizing the strongly leached siliceous soils for continuous cropping, more research effort is needed to improve and to integrate the fallow phase in a viable low-input land management system for the strongly acidic soils in the high rainfall tropics.

Humid/Subhumid Transitional Region

In the humid/subhumid transitional zone of West Africa ($P \geq ET$ for a period of 5-6 months), the less leached Alfisols (i.e. Oxic Paleustalfs, clayey, kaolinitic, isohyperthermic family) are the major soils under the predominant secondary forest vegetation. Tree crop farming (cocoa, kola, rubber, oil palm) and bush fallow/food crop rotation are the dominant types of agricultural land use. Because of the poor soil physical properties and the high intensity of rains, soil erosion on sloping land is a major limitation for extensive food crop cultivation using conventional tillage systems (Lal, 1976; Wilkinson, 1975). However, long-term experiments of maize-cowpea rotation on a small field with manual operation, show that sustained high crop yields have been obtained for over ten years with judicious fertilizer use (Kang et al., 1977b; IITA, 1979, 1980).

Nutrient management. The major fertility problems of the LAC soils in this region were recently reviewed by Kang and Fox (1980). Deficiencies of N, P and K are common. Deficiencies of Mg, S, Zn and Fe have been reported for crops such as maize, cowpea and upland rice.

On land newly cleared from secondary forest, nitrogen response is influenced by soil texture, organic matter content, and plant residue conservation. Phosphorus fertilizer requirements of the LAC Alfisols in this region are generally low and the residual effects are high (Juo and Fox, 1977; Kang and Osiname, 1980). Requirements for K are generally low. Soils from the siliceous group respond more to K than those from the kaolinitic group. Deficiency in Mg has been reported on maize grown on continuously cropped and eroded land (IITA, 1978, 1979).

Though the LAC soils in this region contain a high level of total Mn, the level of extractable Mn in the soil under natural conditions is low (Cottenie et al., 1980). However, soil acidification due to acidifying fertilizers may mobilize soil Mn to phytotoxic levels (IITA, 1978).

No-tillage system. On the highly erosive Alfisols, the no-tillage production systems with crop residue mulching on newly cleared forest land have shown distinct advantages over conventional tillage (Lal, 1976). For effective soil and water conservation, the no-till system requires adequate crop residue mulch (4-6 tons/ha) and land carefully cleared from bush or forest fallow (5 years or more).

Experiments conducted at IITA for the past six years have shown that on a kaolinitic Alfisol with slopes up to 15%, mechanized, continuous no-till maize production can be practiced without serious erosion (Couper et al., 1979). Maize yield under the no-till residue mulch system was consistently higher than that of conventional tillage (Fig. 2), but because of a variety of factors, such as soil compaction, soil solidification, and failure to adjust fertilizer requirement, yield declined after the fourth year (IITA, 1979, 1980). These results indicate the inherent limitation for utilizing the highly erosive, kaolinitic LAC soils for mechanized continuous food crop production. Alternate tillage and fallow systems are being tested to overcome the compaction problems.

Alley cropping and live-mulch. Recognizing the limitations for utilizing kaolinitic LAC soils for extensive and mechanized crop production, efforts are being made at IITA to develop a low input system, such as "alley cropping," which can be easily adopted by the small farmers. Alley cropping is a system where food crops are grown in spaces between rows of planted woody shrubs or tree fallows. The fallow species is periodically pruned during the cropping season to prevent shading and provide green manure for the accompanying food crop (Wilson and Kang, 1980). Promising results were obtained from alley-cropping trials using a maize and *Leucaena Leucocephala* combination. Leucaena trees which were planted in 4 m rows gave substantial nitrogen yield from the pruned dry matter. Reasonable maize yield was obtained without additional nitrogen application (Kang et al., 1981). Such a low input system offers an attractive alternative to bush fallow for the small farmers in the region. Further trials are being conducted to study the suitability of the system in the subhumid and perhumid regions. Additional indigenous fallow species such as *Acioa baterii, Alchornea cordifolia, Anthonata macrophylla, Glyricidia sepium, Sesbania grandiflora, Tephrosia candida* are being evaluated.

The live-mulch system could be another alternative to bush fallow. It involves planting a food crop, such as maize, directly in a living cover of a low-growing plant with minimum soil disturbance. This system incorporates the soil conservation features of organic mulch and no-tillage, but has an additional advantage of controlling weeds. The legume live mulch also has the advantage of contributing nitrogen to the system. Pro-

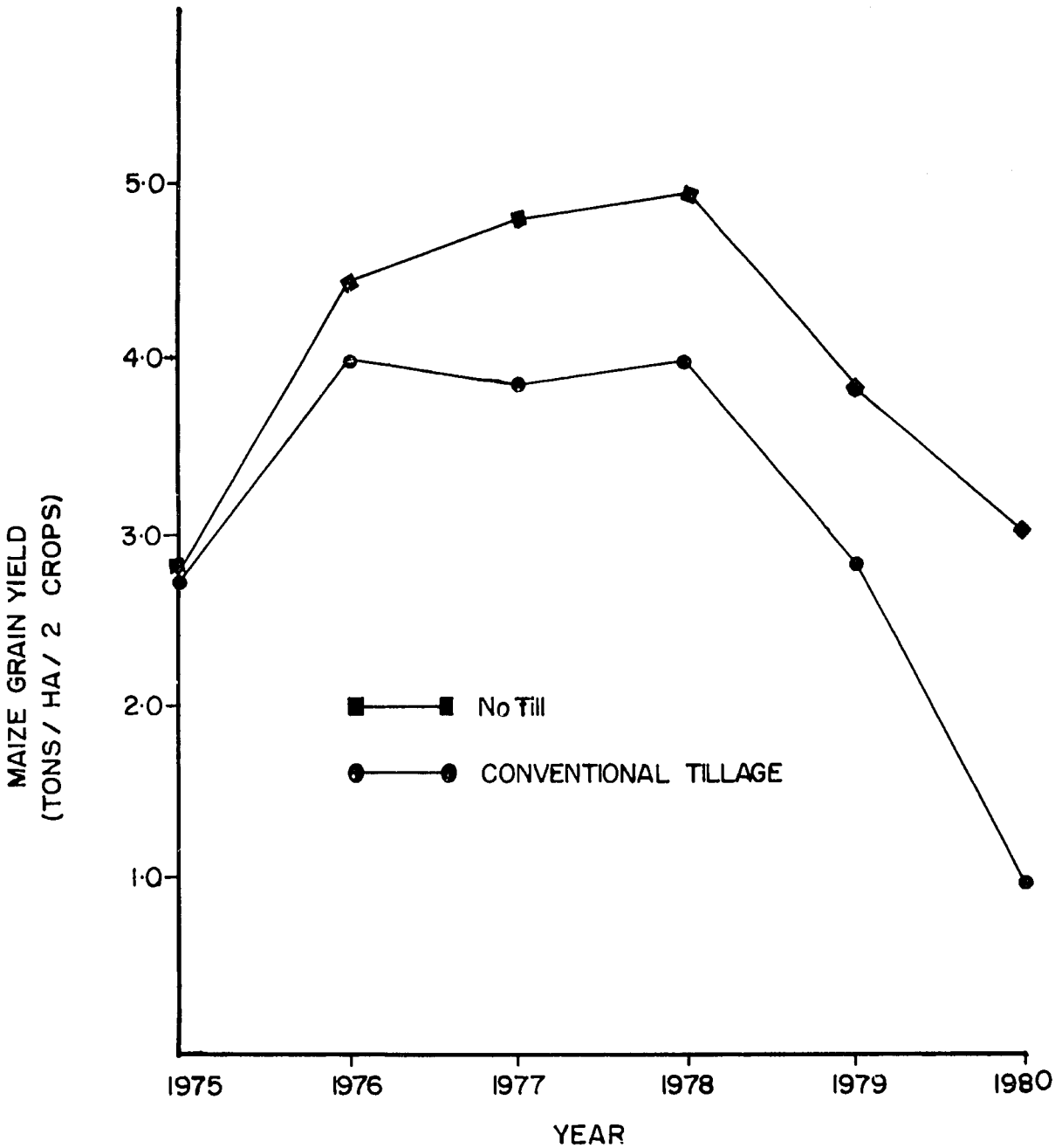

Fig. 2. Long-term effects of two tillage systems on maize grown on a kaolinitic Alfisol manually cleared from secondary forest at Ibadan, Nigeria.
(R. Lal, D.C. Couper and S.L. Claasen; quoted by E.H. Hartmans, 1981)

mising results have been obtained at IITA for systems of growing maize in a live mulch cover of *Psophocarpus palustris* and *Centrosema pubescens* (Akobundu, 1980).

Subhumid and Semi-arid Regions

In the subhumid and semi-arid regions ($P \geq ET$ for periods of 4-6 and 2-4 months of the year, respectively), the upland is generally dominated by kaolinitic Alfisols and siliceous Inceptisols. Natural grass and shrub fallow are still common, but the tree component is fast disappearing because of higher intensity of cropping as well as the increasing need for fuel wood. Areas with reliable rainfall or with supplementary irrigation are often intensively cropped.

Charreau (1974), Jones and Wild (1975), and Lawson and Juo (1979) reviewed the climatic constraints and soil management problems of these regions. Erratic rainfall, low soil organic matter, low available soil moisture reserve, and soil compaction are the major constraints for crop production.

Nutrient management. Deficiencies of N, P and K are common and observed on a wide variety of food crops (Charreau, 1974; Jones and Wild, 1975). Nitrogen is the most limiting nutrient for cereal crops. Phosphate deficiency is widespread (Mokwunye, 1979; Pichot and Roche, 1972); but the requirement is generally low with a high residual effect of applied P. Crop response to K varies, depending upon soil parent material and soil texture (Wild, 1971). With the exception of sandy soils, response to K application was only observed after several years of intensive cropping (Anderson, 1973; IITA, 1980).

Sulphur, Zn and B deficiencies are common, particularly on groundnut and cotton grown on sandy or siliceous soils (Bolle-Jones, 1964; Bromfield, 1972; Kang and Osiname, 1972). Because of the low CEC and low organic matter content in most savanna soils, continued application of acidifying fertilizers may easily induce nutrient imbalances and soil acidity problems (Bache and Heathcote, 1969). This problem can however be amended by applying adequate amounts of farmyard manure and crop residue (Jones, 1971).

Appropriate tillage systems. A substantial amount of research on soil tillage has been conducted in the subhumid and semi-arid regions of West

Africa (Charreau and Nicou, 1971). Because of the abundance of naturally compacted soils in the subhumid and semi-arid regions, tillage has been shown to be necessary for the following reasons: (i) increasing soil porosity, (ii) improving crop root development, (iii) conserving subsoil moisture, (iv) better seedbed preparation, and (v) better weed control (Charreau and Nicou, 1971; Kowal, 1968; Poulain and Tourte, 1970; Nicou, 1979; and Nicou and Charreau, 1980). In general, the appropriate tillage practice recommended by IRAT (Institut de Recherches Agronomiques Tropicales) researchers for highly compacted LAC soils involve deep plowing at the end of the rainy season, followed by chisel plowing before planting to facilitate seedbed preparation.

The applicability of no-tillage systems for crop production in the subhumid and semi-arid regions has not been extensively studied. Unpublished results from several field trials conducted by IITA and other research institutions indicated plowing was superior to no-tillage. The key problem limiting the practice of no-till farming in the drier regions is availability of abundant mulch materials. Recent tillage studies on maize cropping conducted in Upper Volta (Rodriquez, 1981) showed that in the absence of a sufficient amount of mulch, no-tillage was no better than the traditional "daba" (hand-hoeing) method of seedbed preparation (Table 4). With an adequate amount of maize residue used as surface mulch (approximately 4-6 t/ha), maize yield was significantly higher than the no-till plots with a lower rate of mulch (Table 5). In the unmulched no-tillage plots, surface crusting severely affected seed emergence and crop establishment.

Table 4. Effect of tillage methods on maize yield at Saria, Upper Volta (Rodriquez, 1981).

Tillage Treatment	Grain Yield (at 0% Moisture) (Kg/ha)
No-till with Paraquat	1530
Conventional Tractor Plowing	2010
Chisel Plowing	1860
Bullock Plowing	2080
Traditional Hand Hoeing	1400
L.S.D. (0.05)	473
C.V. (%)	17.4

Table 5. Effect of crop residue mulch and fertilizer application on maize yield (Kg/ha at zero percent moisture) under no-tillage at Kamboinse, Upper Volta (Rodriquez, 1981).

Fertilizer, Kg/ha ($N-P_2O_5-K_2O$)	Crop Residue Mulch		
	No Residue	In Situ Maize Residue	In Situ Maize Residue x 2
40-23-14	1000	970	1470
120-69-42	910	1920	2060
Residue Treatment:	Significant at 1% level.		
Residue x Fertilizer:	Significant at 5% level.		
C.V. (%):	12.9		

Tropical Highlands

The fine-textured, oxidic soils with both high and low status of clay activity comprise significant area in the highlands of East Africa. In West and Central Africa, such soils are of limited distribution in western Cameroon and southeastern Zaire. In densely populated areas such as Rwanda, Burundi and western Cameroon, such soils are being intensively cropped.

Commercial food and cash crop farming on the high base status oxidic soils, i.e. Tropodalfs, Eutrustalfs, and Eutrustox (Soil Taxonomy classification) or Eutric Nitosols (FAO/UNESCO) have long been proven successful in Kenya and Cameroon (Keya, 1977 and van Barneveld, 1979).

On the other hand, in areas such as the highlands of Rwanda, where high costs of imported inputs become a major constraint, the development of improved agroforestry systems that can utilize local resources for the maintenance of soil productivity has been suggested (Behmel and Neumann, 1981).

The Institute des Sciences Agronomiques (ISAR) has conducted research on management of acid soils in the subhumid highland of Rwanda. Results from these studies were compiled by Neel (1974) and Rutunga and Neel (1980). Major constraints for intensive utilization of these oxidic LAC soils for crop production were given as follows: (1) Acidity (Al and Mn toxicities): Liming at the rather high rate of 4 tons/ha is needed for optimum crop (wheat, bean) growth (Table 6). (2) High P fixation: Rela-

Table 6. Effect of N, P and K and liming on yields of wheat and bean grown in 1973 on Oxic Humitropept in subhumid high altitude of Rwanda (after Neel, 1974).

Lime Rate Ton/Ha	Fertilizer Treatment	Wheat Yield	Bean Yield
		- - - - - - - - Kg/Ha	- - - - - - -
1.0	NK	203	202
	NPK	1337	574
4.5	NK	574	634
	NPK	1767	973
8.0	NK	472	544
	NPK	1655	1096

Fertilizer Rate $N-P_2O_5-K_2O$ in Kg/Ha.

Wheat 100-200-200

Bean 30-200-50

tively high P rates (100-200 kg P_2O_5 /ha) are required for optimal crop growth. Moreover, low soil temperature can be a limiting factor in the highland (Law and Cooper, 1976). Significant reduction in maize yield with delayed planting (about 0.6 tons/ha/week) was attributed to the decrease of soil temperature which follows the onset of the rainy season.

In spite of low soil temperature and high phosphate requirement, the fine-textured oxidic soils in the tropical highlands of Africa, given necessary inputs, may prove to be the most productive soils for food crop cultivation.

SUMMARY AND CONCLUSIONS

The low activity clay soils are the most abundant soils in the humid and subhumid regions of tropical Africa. According to their mineralogical and surface charge characteristics, they may be further divided into: kaolinitic, oxidic and siliceous groups. These groupings also reflect distinctive differences in terms of their fertility capability and responses to different management practices.

Because of the low CEC and low buffering capacity of the LAC soils,

multiple nutrient deficiencies imbalance are common in the region. Major soil management constraints may be summarized as follows: (i) humid and per-humid regions: soil acidity, (ii) humid/subhumid transitional zone: soil erosion, (iii) subhumid and semi-arid regions: soil compaction, and (iv) tropical highland: high P fixation. No-till system with crop residue mulching, alley cropping and live-mulch systems are promising food crop production systems that require extensive on-farm testing.

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DISCUSSION

Q. A.M. Bunyolo: Could you please give the critical levels of Al saturation for the following crops: maize, soybeans, groundnuts, cotton, and sunflower? A large part of my country, Zambia, is covered by acid soils (pH 3.9 to 4.3) but unfortunately we do not have data on critical levels of Al for most of our crops. If there is a paper summarizing the results of your experiments, I would be very happy to have a copy.

A. B.T. Kang: Critical Al saturation for maize is 30%. We don't have figures for soybeans, groundnuts, cotton, and sunflower.

Q. C. Sys: We believe that management problems such as Al status and P-fixation capacity are related more to soil characteristics than to the agroecological zones described. In West Africa, the sub-humid zone has a relatively high base saturation (Ustalfs) and no major problems due to Al arise. In the sub-humid savannas of Southern Zaire, the soils are highly weathered acid Oxisols (Haplustox) that have a high P-fixation capacity and need correction of the Al status for crops sensitive to Al toxicity. I should also like to know if you see any advantage or disadvantage in the unusually high Ca/Mg ratio in the savanna soils of West Africa.

A. B.T. Kang: I agree that the degree of P-fixation is related to soil characteristics. In general, however, there is a tendency for higher P-fixation in soils of high altitudes and Al toxicity problems are more common in the humid and perhumid region. The abnormally high Ca/Mg ratio may probably induce Mg deficiency.

Q. M.L. Leamy: I am very pleased that agronomists and soil taxonomists are in dialogue at this meeting. My question is, are the agronomic

limitations described (e.g., high P-fixation in tropical highlands) truly characteristic of the climatic zone or do they depend more on the soil properties within that zone? For example, most tropical Andisols occur in the highlands and have high P-fixing properties.

A. B.T. Kang: There is, in general, a higher tendency for P-fixation in the highlands of tropical Africa, even where the soils are not Andisols.

FERTILITY AND MANAGEMENT OF ANDEPTS OF RWANDA

P. Vander Zaag and R.L. Fox

ABSTRACT

The Andepts of Rwanda constitute approximately 50,000 hectares of fertile cultivated soils. Mean values of some properties of soils of the Karisimbi volcano area, which covers 50% of the area, are pH:5.5; total N:1.55%; P in solution:0.038 μg/ml; SO_4-S:62 μg/g soil; exchangeable Ca, K and Mg:12, 0.35 and 1.6 meq/100 g respectively. Soils developed on Sabyinyo, the oldest volcano covering 30% of the area, have lower total N (0.33%), lower SO_4-S (10 μg/g) and lower Mg (1.3 meq/100 g). Three other volcanos, Bisoke, Gahinga and Muhabura, were not sampled since they cover only 20% of the area.

Small areas on the higher slopes of Sabyinyo are high in exchangeable Al. Up to 60% of the exchange complex is Al saturated. These are non-productive for most crops.

These Andepts have relatively low P requirements (mean = 370 μg P/g soil to obtain 0.2 μg P/ml in solution) in comparison to volcanic soils from Kenya, the Cameroons and Hawaii.

The consequences for Rwanda if these soils are allowed to erode will be severe because in many areas soil depth is shallow and subsurface materials are relatively less fertile than surface soil materials.

The traditional low input farming system returns little fertility to the land. This raises the question of how long these soils can continue to nourish the highest population density in Africa and still export food.

INTRODUCTION

The volcanos which line the border between Rwanda, Uganda and Zaire are intensively farmed. The five volcanos: Muhabura (3900 m), Gahinga (3747 m), Sabyinyo (3674 m), Bisoke (3711 m) and Karisimbi (4507 m) probbaly belong to the late tertiary and early quaternary era. Sabyinyo is believed to be the oldest and Bisoke the youngest.

Volcanic deposits cover approximately 700 sq. km in Rwanda. Pyroclastic materials cover an equal area in Uganda and Zaire. Nearly 50,000 ha in Rwanda have been cleared and cultivated within the last 80 years. Topography is moderately sloping in the lower regions (1800-2300 m), increasing to 45 degrees with increasing elevation.

The cultivated crops are maize, sorghum, potatoes, pyrethrum and peas along with bamboo and eucalyptus. In the forest zone, as elevation increases, bamboo is replaced by *Hagenia abyssimica,* mosses and lichens.

The purpose of this paper is to present results of a survey of the major plant nutrients in some representative soils and some implications for the management and potential of these soils.

MATERIALS AND METHODS

Soil Sampling

Soil samples were collected along three transects (Fig. 1). Transect 1 ascends Sabyinyo Volcano from Ruhengeri to the forest. Transect 2 runs from Ruhengeri along the lower limits of Karisimbi Volcano to Gisenyi. Transect 3 ascends Karisimbi into the forest. Sample sites were in fields away from homes and were spaced 1 to 4 km apart. Three subsamples were collected, mixed and composited from each site. There were two depth increments from each site: 0 to 15 cm and 30 to 45 cm.

Laboratory Analysis

Silicon and phosphorus in saturation extracts. Soil samples (>50 g) were placed in leaching tubes; water was added until the soils were saturated. After 3 days one ml aliquots of water were added to the columns until

the soils were saturated. After 3 days one ml aliquots of water were added to the columns until about 12 ml of solution was displaced; this was clarified and P and Si were determined in the extract.

P sorption curves. Data for constructing P sorption curves was obtained by equilibrating 3 gm samples of soil for 6 days at 25 degrees C in 30 ml of 0.01 M $CaCl_2$ containing various amounts of $Ca(H_2PO_4)_2$ (Fox and Kamprath, 1970). Shaking was for 2 one-half hour periods each day. P required to obtain 0.02 and 0.2 μg P/ml in solution was determined by interpolation from the P sorption curve.

Extractable P. The polyacrylamide method of Banderis et al. (1976) was used to determine $NaHCO_3$-extractable P. Bray and Kurtz No. 1 P (0.025 N HCl + 0.03 NH_4F) was determined using a soil:solution ratio of 1:7.

Adsorbed sulfate. Sulfate was extracted with a $Ca(H_2PO_4)_2$ solution containing 500 ppm P. The extraction was repeated 4 times. The soil:solution ratio for each extraction was 1:5 (Fox et al., 1964). The extracts were digested with nitric-perchloric acid before they were analyzed for sulfate using the method of Tabatabai (1974) modified to include an addition of solid $BaCl_2$ into each sample.

Exchangeable aluminum. Aluminum was extracted with 1 N KCl using a soil:solution ratio of 1:25. Shaking was for 30 minutes followed by centrifugation. There was no washing with KCl.

Nitrogen mineralization. Soil samples were incubated for 14 days at 30 degrees C using the method of Stanford and Hanway (1955) except that the soil materials were mixed with crushed sponge rock. Following incubation, nitrate and ammonium were extracted with 1 M KCl. Separate samples were used to determine initial MH_4^+ in the soils. Ammonium was determined by steam distillation and acid titration.

RESULTS AND DISCUSSION

Soil Chemical Analysis

Chemical analyses of the three transects generally indicate good fertility status of the surface soil materials (Table 1). Karisimbi, which is one of the youngest volcanos, generally has higher nutrient levels than

Table 1. Summary of some soil chemical properties of Andisols of Rwanda (mean values).

Chemical Property	Cultivated			Forest	
	Sabyinyo Transect 1 (6)[a]	Karisimbi Transect 3 (6)	Lower Limit Karisimbi Transect 2 (11)	Sabyinyo (1)	Karisimbi (1)
Soil pH	6.2	5.5	6.3	4.4	5.5
Si in Saturation ext. (μg/ml)	16.4	12.8	15.5	16.3	9.5
Total Nitrogen (%)	.33	1.49	1.01	2.0	2.07
NH_4 after 14 days incubation (μg NH_4-N/g)	11.6	3.0	36.0	14.0	4.0
Nitrification rate (μg NO_3-N/g/day)	5.7	7.0	4.7	6.4	12.5
NH_4/NO_3	.13	.03	.61	.16	.02
Sodium Bicarbonate P (μg p/g)	95.0	19.0	27.0	163.0	9.0
Bray No. 1 P (μg P/g)	18.3	1.0	1.8	3.4	1.0
P in saturation extract (μg P/ml)	.017	.038	.008	.015	.048
P required for:					
.02 μg P/ml (μg P/g)	10	< .0	70	20	0
.2 μg P/ml (μg P/g)	175	260	400	430	900
SO_4-S extractable (μg S/g)	10.0	62.0	29.0	84.0	40.0
Ca meq/100 g	11.8	11.8	12.4	2.3	6.6
Mg meq/100 g	1.3	1.6	4.1	.7	.7
K meq/100 g	.32	.35	1.2	.65	3.5
Na meq/100 g	.14	.14	.22	.21	.19
Al meq/100 g	.0	.7	.09	5.86	.0
ECEC meq/100 g	13.6	14.6	17.9	9.7	7.8
Al saturation (%)	.0	5.0	.0	60.0	.0

[a]Number of samples taken.

Sabyinyo. Sulfur levels are probably low on the lower slopes of Sabyinyo near Ruhengeri (Table 2). Total N was also lower on Sabyinyo. Magnesium levels appear to be low along the transects that ascend Sabyinyo and Karisimbi. Potassium levels are marginal and P levels, by the bicarbonate method at least, are adequate to perhaps excessive.

The bamboo forest soil sampled on Sabyinyo was very acid, pH 4.4, and exchangeable Al comprised 60% of the effective cation exchange capacity (Table 1). This is believed to be a result of Si removal with the bamboo trunks whereas the leaves which are high in Al are recycled, causing an Al build-up. Perhaps as a result of extreme acidity, organic matter had accumulated until soil N was 2%. Magnesium was also low in this soil. Neel and Prins (1973) analyzed some "infertile soils" on Sabyinyo and obtained similar levels of Al ranging from 3.22-5.77 meq/100 g which equals 30-62% Al saturation. From pot experiments they determined that P, Mg and K were limiting on these soils even though they obtained 0.6-.87 meq Mg/100 g and .48-.75 meq K/100 g, values that are similar to our results (Table 1). It should be noted however that the close confines of pots tends to exaggerate deficiencies because roots tend to pile up against the sides and bottoms of the pots where they can accomplish little by way of nutrient extraction.

The forest soil of Karisimbi was similar in analysis to the cultivated part of the same volcano, except that the level of Ca was lower.

Comparison of the Andepts to Other Soils

In comparison to three representative soils from other areas of Rwanda the Andepts appear well supplied with nutrients (Table 3). The Gitarama and Gikongoro samples are from the eastern slopes of the Congo-Nile ridge. Soils from that area have low Si, N and P levels and high Al. The Akagera region is drier and under pasture, giving it a fertility level similar to the Andept except for P (Fig. 2).

A P map was constructed giving the P requirements to obtain 0.2 g P/ml in soil solutions for various areas of Rwanda. Andepts require high quantities of P although actual P is high in the Andept regions (Fig. 3). To obtain the standard P requirement of 0.2 μg P/ml over 300 μg P/g of soil is required (Fig. 3).

LIST OF FIGURES

Fig. 1. Map of the Andept region of Rwanda showing 5 volcanos which border on Uganda and Zaire (1 cm: 2.5 km).

Fig. 2. P sorption curves for 4 representative soils of Rwanda. Soil 1 is an Andept; Soil 2 (Ultisol) comes from Gikongoro; Soil 3 (Ultisol) is from the central plateau near Gitarama; and Soil 4 (Inceptisol) comes from the eastern Savanna of Akagera. Note the steep slope of the sorption curve for the Andept which has a relatively high P status of 0.02 μg P/ml. Soil 2 has a low P status and medium P requirements, whereas Soils 3 and 4 have low P requirements.

Fig. 3. A map of standard P requirements for Rwanda. The legend refers to the estimated quantity of P required as μg P/g of soil to provide 0.2 μg P/ml in soil solution. Only the Andept region requires more than 300 μg P/g of soil.

Fig. 1.

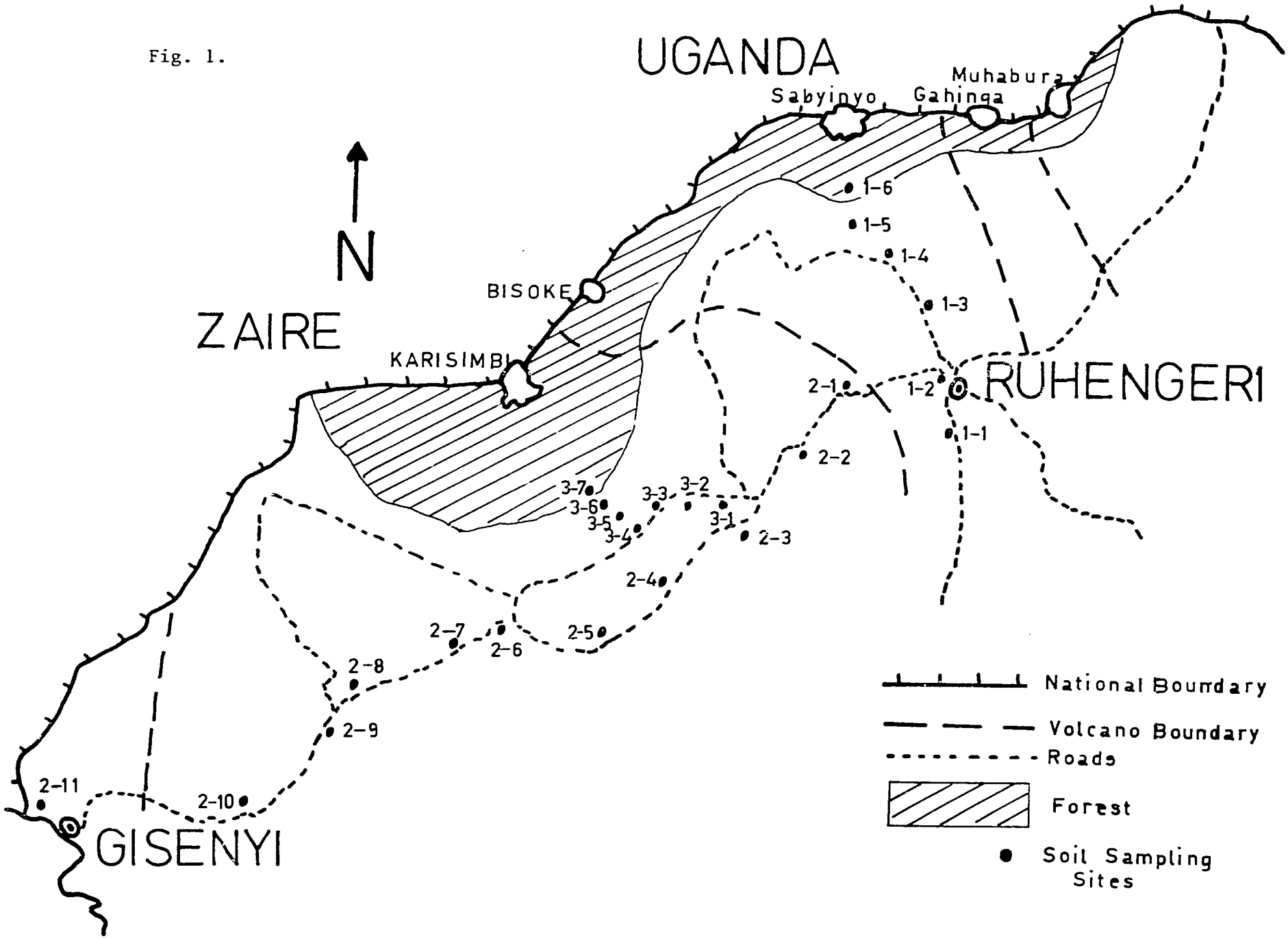
UGANDA
ZAIRE
N
Sabyinyo
Gahinga
Muhabura
BISOKE
KARISIMBI
RUHENGERI
GISENYI
1-1
1-2
1-3
1-4
1-5
1-6
2-1
2-2
2-3
2-4
2-5
2-6
2-7
2-8
2-9
2-10
2-11
3-1
3-2
3-3
3-4
3-5
3-6
3-7
National Boundary
Volcano Boundary
Roads
Forest
Soil Sampling Sites

Fig. 2.

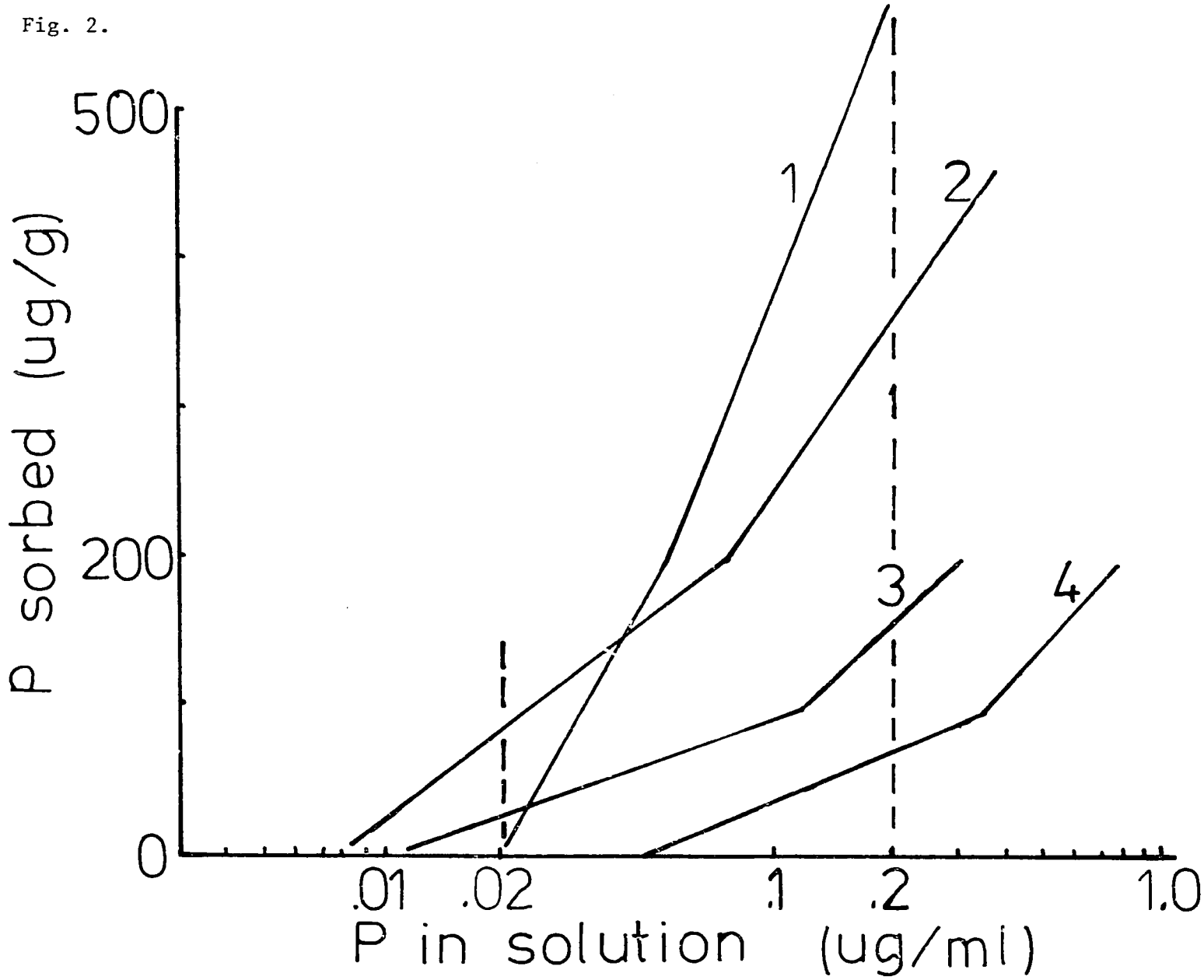

Fig. 3.

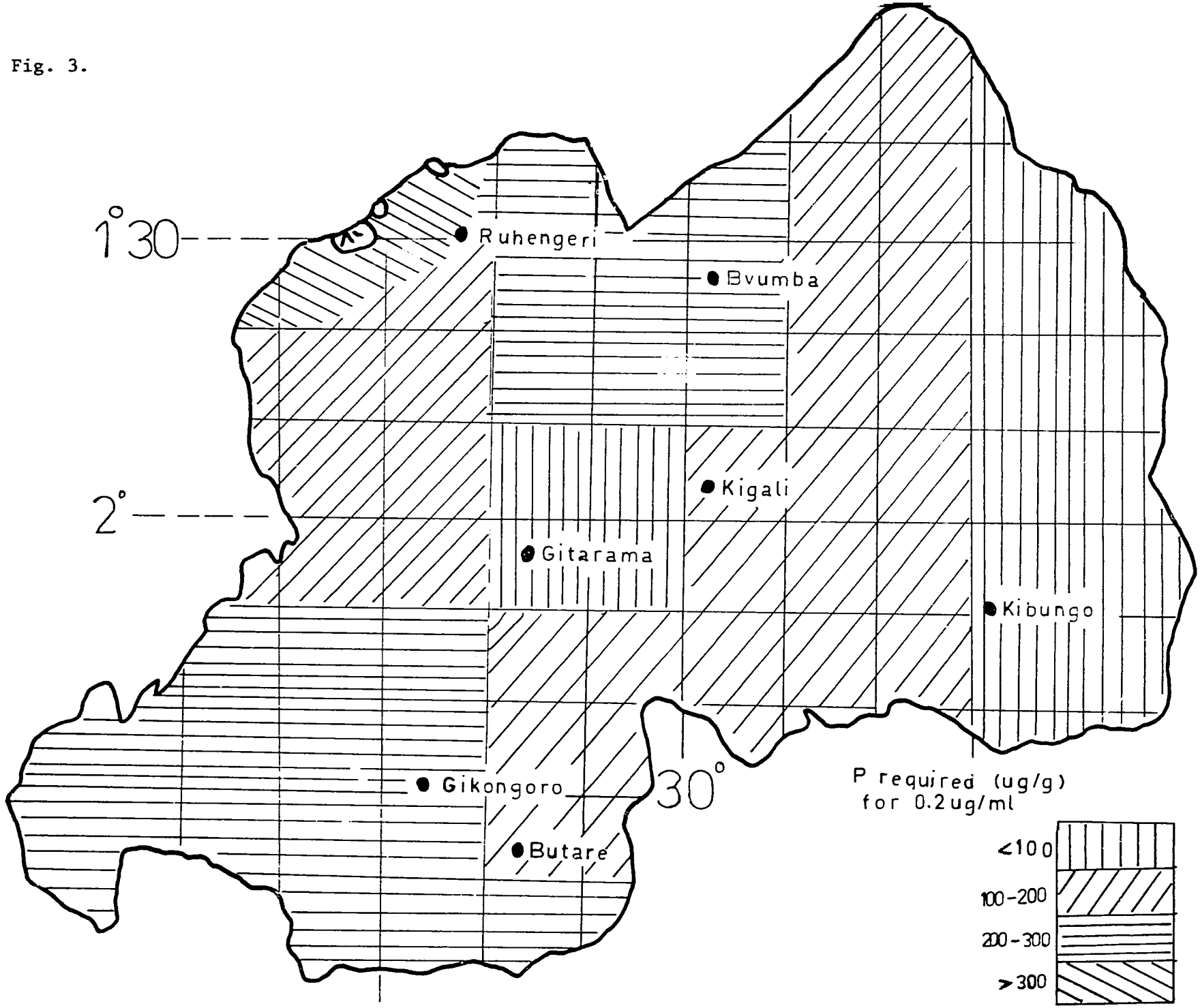
1°30
2°
30°
Ruhengeri
Bvumba
Kigali
Gitarama
Kibungo
Gikongoro
Butare
P required (ug/g)
for 0.2ug/ml
<100
100-200
200-300
>300

Table 2. The inverse trend between P and S in the Sabyinyo surface soils.

Site	pH	Sodium Bicarbonate P μg/g	SO_4-S μg/g
1-1	6.3	73	16
1-2	6.3	250	2
1-3	6.1	118	2
1-4	5.7	300	4
1-5	6.5	50	50
1-6	4.4	163	84

An Andept of Rwanda is compared with Andepts from three other locations in Table 4. The P sorption levels are intermediate between the Eutrandept and Dystrandept of Hawaii but lower than the other soils presented (Table 4). P sorption by these soils is strongly influenced by weathering, which is primarily a function of rainfall (Fox and Searle, 1978).

Management Practices Recommended

Loss of the surface soil by erosion will result in a generally lower fertility (Table 5) of the soils investigated. In particular, total N will drop significantly and the P fertilizer requirement will greatly increase. Exchangeable bases will remain relatively constant.

Areas high on the volcanos are steep. In many places soil depth is only 40 cm and a large percentage of the soil volume is rock. Erosion control is imperative in such areas. Contour farming using the existing mound system is probably the most appropriate method of erosion control. These mounds are generally in bands about 2 meters wide and 0.5 to 1 meter high. However, farmers frequently do not place them perpendicular to the slope. Upper slopes are frequently more than 45 degrees. These must remain in forest; denuded areas should be reforested.

Acid spots that have high exchangeable Al should be limed. Neel and Prins (1973) recommended 5.5 T/ha of lime along with 10 kg MgO and some P and K fertilizers.

In the past, fertilizer experiments have usually given little or no yield response from N, P, or K applications. However, in a recent P ferti-

Table 3. A comparison of some chemical properties of an Andept with 3 representative soils from other areas of Rwanda.

Site	Soil	Chemical property determined										
		pH	Si	Total N	P required .02	P required .2 µg P/ml	SO_4S	Ca	Mg	K	Al	ECEC
			µg/ml	%	(µg P/g)		(µg P/g)	- - - - - -meq/100 g- - - - - - - -				
Karisimbi	Andept	6.0	13	.5	0	500	6	11.8	1.3	.26	.0	13.5
Gikingoro	Ultisol(?)	4.5	7	.3	70	370	80	2.5	.4	.28	5.3	8.9
Gitarama	Ultisol(?)	5.3	8	.1	30	150	18	5.8	1.6	.19	1.3	9.1
Akagera	Inceptisol	5.5	15	.4	0	70	120	8.7	3.0	1.24	.8	14.7

Table 4. P sorption at 0.2 μ g P/ml in solution by volcanic soils from various locations.

Location	P sorbed μ g/g	No. of Samples	Rainfall mm
Cameroon (Mt. Cameroon)	1300	1	?
Kenya (Mt. Kenya)	800	6	?
Rwanda	370	24	1500
Hawaii Typic Hydrandept-Honokaa	2900	1	3000
Hydric Dystrandept-Maile	1200	1	2000
Typic Eutrandept-Waimea	200	1	700

Table 5. Anticipated influence of erosion on soil chemical properties as indicated by an Erosion Hazard Index.[a]

Chemical property	Sabyinyo (transect 1) 0-15	30-45	Erosion Hazard Index	Karisimbi (transect 3) 0-15	30-45	Erosion Hazard Index
Total N (%)	.33	.23	1.4	1.49	1.05	1.4
P required for:						
.02 μg/ml (μg/g)	10	20	2.0	0	50	---
.2 μg/ml (μg/g)	175	190	1.1	260	800	3.1
SO_4-S (μg/g)	10	12	.8	62	47	1.3
Ca (meq/100 g)	11.8	11.5	1.0	11.8	9.3	1.3
Mg (meq/100 g)	1.3	1.2	1.1	1.6	1.3	1.2
K (meq/100 g)	.32	.25	1.3	.35	.21	1.7
Na (meq/100 g)	.14	.98	.15	.14	.66	.21

[a]The Erosion Hazard Index is the ratio of some critical factor of soil fertility (soil N, P requirement, etc.) in the top soil to the subsurface soil material.

lizer experiment on the slopes of Sabyinyo at Kinigi, potato yields were increased from 33 tons/ha to 48 tons by an application of 560 kg P/ha. Potatoes required 400 μg P/g of soil (560 kgs P/ha) to attain a yield that was 95% of the maximum attained, 50 T/ha. A P sorption curve for the site indicated that P in solution should have been 0.1 μ g/ml after fertiliza-

tion. This is slightly lower than the requirement for potatoes obtained by Van der Zaag et al. (1979). The P levels reported for these Andepts are approximately adequate for most agronomic crops in the tropics. Moreover, the fact that potatoes perform well on these soils emphasize that these are unusual Andepts and suggest one good reason why the population density is so high. P deficiency on maize and sorghum is frequently observed in the area, presumably on soils with P concentrations of .02 to .04 μg/ml. Soil temperatures less than 20 degrees C (isomesic and isothermic) lower the rate of P desorption and diffusion which necessitates higher P levels than usual to satisfy plant needs (Gardner and Jones, 1973).

Experiments need to be done in areas of indicated deficiency to determine whether Mg and S are limiting.

The Andept region of Rwanda is the "bread Basket" for the country. Population density is high and yet this area is an exporter of food. This is being done with no fertilizer inputs. Such exploitation of soils cannot continue indefinitely. Composting residues, green manuring and importation of chemical fertilizers must be undertaken if this region is to support an ever-increasing population.

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DISCUSSION

Q. M.L. Leamy: What is the important management difference between isomesic and isothermic Andisols in Rwanda?

A. P. Vander Zaag: When we get into isomesic temperatures, P deficiencies become more pronounced even though P levels are considered to be adequate. Thus timely planting dates are essential and planting should not be done during the rainy season when temperatures are lower.

Q. B.T. Kang: The effect of low temperature on P deficiency in maize may not only be an effect of lower P diffusivity but probably also due to poor maize growth at lower temperatures.

A. P. Vander Zaag: Yes, in particular poor root development which is strongly influenced by P.

STRATEGY FOR UPDATING SOIL TAXONOMY

R.W. Arnold, J.E. Witty and H. Eswaran

ABSTRACT

Since its publication in 1975, suggestions are being received for changes in definition of criteria, proposals for new taxa and other kinds of amendments to Soil Taxonomy. Procedures for receiving, testing, and approving these amendments are discussed. With the momentum generated through the work of the international committees, a new edition of Soil Taxonomy is envisaged by the end of the decade.

INTRODUCTION

In developing the basic principles of classification, Cline (1949) states, "the purpose of any classification is to organize our knowledge so that the properties of the objects may be remembered and their relationship may be understood most easily for a specific objective. The process involves formation of classes by grouping the objects on the basis of their common properties. In any system of classification, groups about which the greatest number, most precise and most important statements can be made for the objective, serve the purpose best. As the things important for one objective are seldom important for another, a single system will rarely serve two objectives equally well."

There are two important concepts in the statements of Cline; first is that the classification is made for a purpose and if the purpose is not served then the classification must be modified. Secondly, the classification is a reflection of the state of knowledge at the time it was made and as new knowledge accumulates, the classification must be refined to accommodate it.

Classifications have been made, used, and discarded or further developed from the time of the antiquities to modern day. It is interesting to note that the early Greek philosophers such as Cato (234-149 BC) grouped soils according to the kinds of crops they were best suited for. Later, crop performance was related to physical properties--stony, loose, coherent--and as a result these properties became the basis for the grouping. Roots for modern soil classifications did not develop until the related sciences--geology, petrography, botany, chemistry, physics--became established. Later, with the emergence of the concepts of soil fertility and genetic theories of soils, the stage was set for the development of Soil Taxonomy.

Cline (1979) has recently reviewed the developments of soil classification in the United States, particularly developments related to Soil Taxonomy. The decision to work on a new classification system was taken in 1950 by the Soil Conservation Service and it was 25 years later, in 1975, when Soil Taxonomy was finally published (Soil Survey Staff, 1975).

The publication of Soil Taxonomy in 1975 did not mark the end of an exercise for several reasons. It was the work of over 200 soil scientists from the U.S. and many others abroad, under the able leadership of Dr. Guy D. Smith. In finalizing the system, compromises had to be made from the many divergent opinions that were received. Several criteria that were included could not be adequately tested or no criticisms were received at the time of the proposals. Although testing of the system continued during its developmental phases, certain parts could not be tested until the whole system was published. Further, due to a lack of data, the classification of soils in the intertropical areas was weak and could not receive the kind of testing that their counterparts in the U.S. received.

The publication of Soil Taxonomy in 1975 marked a phase whereby all users could critically examine the system as a whole. Those who were involved in developing the system had a sense of relief and satisfaction on its completion while others, particularly the newer generation, look upon it as a challenge for improvement. An elaborate review process was set up by the Soil Conservation Service (SCS) after publication of Soil Taxonomy. The purpose was to receive suggestions for modifications, have a mechanism to test the suggestions, and finally to approve the changes.

The review process as initially envisaged in 1976 proved to be too cumbersome and, due also to understaffing, was not very effective. People who made suggestions were not sure of the status of their suggestions and with time there was a decline in the interest.

In 1976, the first International Soil Classification Workshop was organized by the University of Puerto Rico (UPR) with funding from the Agency for International Development (AID), in Brazil. The Workshop was organized to address the mandate of a committee formed earlier under the initiative of Dr. Frank Moormann, This committee, today referred to as the International Committee on the Classification of Alfisols and Ultisols with Low Activity Clays (ICOMLAC) was organized to reexamine the classification of such soils in intertropical areas. The formation of the Committee and organization of the Workshop aided in awakening the review process of SCS. The success of ICOMLAC resulted in other committees; today there are seven ICOM's. UPR has now organized four Workshops, each one of them a resounding success and each generating a number of proposals for changes in Soil Taxonomy.

The staffing problem in SCS still remained the bottleneck in acting on the proposals. In the last year, two events have significantly improved the situation. The first is the creation of a position in SCS for Soil Classification. Dr. Richard Guthrie is now the Staff Leader and has the responsibility for receiving and acting on proposals to modify Soil Taxonomy. The second event, probably more important on the international scene, was the establishment of the Soil Management Support Services (SMSS). SMSS, as you all know, is a program of international technical assistance of SCS, funded by AID. A major component of the activities of SMSS is to coordinate the refinement of Soil Taxonomy on the international front.

ACTIVITIES TO REFINE SOIL TAXONOMY

There have been two divergent views with respect to amending Soil Taxonomy. The first group prefers to allow Soil Taxonomy to rest for some time. They envisage a maturation period during which people can use it,

become familiar with it and at some, later, unspecified period, begin the exercise of revising it. There is ample justification for this view, one being to avoid the impression that the system is in a state of flux. The second view is that it should be revised immediately, that we need to maintain the momentum or people will lose interest.

We, in the SCS, prefer to chart a medial course. For all practical purposes, the 1975 publication is final and all users are required to refer to it and use it. However, we do appreciate that there are weaknesses in the system; there are mistakes, and there are points which need immediate rectification to prevent misinterpretations. In the course of soil survey activities, some are brought to our attention; suggestions also appear in scientific journals. When we consider them significant and requiring immediate attention, the changes are approved and circulated as National Handbook Notices. Until now, most of such changes have dealt with omissions, typographical errors, and some inconsistencies.

Our present strategy is to develop a second edition by the end of this decade. A major change in the second edition will be the classification of the soils in the intertropical areas. We expect to modify some existing definitions, add taxa, and even identify new diagnostic horizons or material. A proposal is already underway in the International Committee on Andisols (ICOMMAND) to create a new order of Andisols. The Committee on Oxisols (ICOMOX) is also discussing some major changes in the definition of the order and lower categories. The new committee on wet soils (ICOMAQ) will attempt to find a better classification for the padi soils.

The international committees (ICOM's) have all been charged with the classification of the soils in the intertropical areas. This does not imply that the classification of the other soils is perfect. We are constantly testing this in the U.S., but we would probably also have to look for some mechanism to provoke interest in the international sphere. The recent interviews of Dr. Guy Smith with scientists from all over the world will show the reasons for many of the decisions made while developing Soil Taxonomy. Two remarks made by Dr. Smith make it clear that there are certain aspects which could be reevaluated: (a) that there was insufficient data even within the U.S. for a more critical appraisal of criteria, and

(b) as criteria was submitted for criticism and if none were received, the original proposal was included in Soil Taxonomy. The monograph on these interviews will highlight these and could be acted upon.

PROCEDURE FOR AMENDING SOIL TAXONOMY

The official procedure for making amendments will be published in the National Soils Handbook of the SCS; an initial draft is included in Appendix I.

Current Procedure

1. We act on new proposals first and those for which we receive a follow-up letter requesting early acceptance.
2. We evaluate the proposal and determine the amount of review it has received.
3. If the amount of prior review is minimal but we believe the proposal should be accepted, we send it out to the Head, National Soil Survey Laboratory (NSSL), and the Heads, Soils Staffs, at the four Technical Service Centers (TSC's) for their recommendations. The four Heads, Soils Staffs, are chairmen of the respective regional Soil Taxonomy Committees and as chairmen they have the option to send the proposal to committee members for their review. If we receive no objections, the amendment is approved by the Director, Soils. The Head, NSSL, and the four TSC Soil Staff Heads are notified with a request that they notify soil scientists within their area and the cooperators.
4. If the amount of prior review appears adequate and no objections were received, the amendment is approved by the Director of Soils. Again the approval notice is sent to the NSSL and TSC's.
5. A few months after an amendment has been approved, a NSH notice is prepared. Each notice will include: (a) a brief statement describing the amendment and date approved, (b) justification for the amendment, and (c) required changes in Soil Taxonomy to accommodate the amendment. The main reason for not publishing immediately in the NSH is to give a few others a limited amount of time to evaluate all the changes required.

Approved Amendments

We believe the document titled "Soil Taxonomy--Approved Amendments and Clarification of Definitions" dated May 5, 1978, should receive special attention. Even though the document, which received wide distribution, was labeled "approved," it never really received official sanction. We are reviewing this document. Those proposed "approved amendments" that we can identify as not being too controversial and that are adequately documented and justified will be published in the NSH first. Most of these have been identified and a few have been written up as a notice in draft form. The notice will be referenced back to the 1978 document.

The "approved amendments" that were controversial will require additional research before a decision is made as to which ones should be approved and published in the NSH. Others that include subject matter involving international committees will be deferred until we receive the committees' recommendations.

Most other proposals that we have on hand were published in the document "Proposed Amendments to Soil Taxonomy" dated May 1978. During the last 1½ years, very little time has been spent reviewing these proposals.

OTHER PLANS

1. A computer program for recording the status of Soil Taxonomy proposals has been developed. So far, however, we have not inputted any of the proposals and a real plan for doing so has not been developed. At this time, we do not have a good record of the status of proposals and if somebody inquires about a particular proposal it takes some searching to determine its status.

2. We hope to computerize Soil Taxonomy to assist in keeping track of changes required as a result of approving amendments and to test proposed amendments. Such a computerized system is needed because changing one part often has implications in many other places. It is very easy to overlook a needed change if the operation is done manually. At this time, we have approval to develop a contract with New Zealand and we believe the contract

will be approved for funding mostly through SMSS. New Zealand has already done considerable work needed for a program as a result of their flow diagrams.

3. Sometime in the late 1980's we plan to produce an updated edition of Soil Taxonomy that incorporates all the changes that we expect to be making within the next few years. There will be numerous changes and some of them will be major, especially as a result of incorporating recommendations from the International Soil Taxonomy Committees. We expect, however, that within the U.S. the impact of these major changes will be relatively small in that probably only a few families and very few series will be split. In other words the classification of a series may change but its ranges of characteristics likely will be unchanged.

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DISCUSSION

Q. J. Bennema: Many soil survey institutions outside the U.S. do not use soil series but, for example, phases of subgroups. They may also have their own classification system which might be the best for their objectives and of which they are the boss. Soil Taxonomy may be used as a reference system. Could you please comment on this?

A. R.W. Arnold: Soil Taxonomy is useful to provide a worldwide perspective of soils and locally classified soils should, therefore, be placed in the system to better understand the relationship among well known soils locally and similar soils that occur elsewhere. In coun-

tries which have their own classifications we only ask for cross references to Soil Taxonomy so we can improve definitions and placements of soils in appropriate taxa.

Deficiencies are noted when you place soils (even phases of subgroups have adequate descriptions of profiles) into the taxa of Soil Taxonomy, and then can be tested further and improved for the world community of soil scientists.

Q. R. Frankart: Which procedures must be followed if we wish to modify the criteria for diagnostic horizons, e.g. the sombric horizon?

A. R.W. Arnold: Definitions of diagnostic horizons or features are central to the application of criteria in Soil Taxonomy. Because each diagnostic feature has a range of properties, it is important to define quantitatively the minimum set of properties for its consistent recognition and identification. Also, the limits of a diagnostic horizon or feature must be compared with competing horizons or features. Then the priority of significance within taxa can be proposed and evaluated to determine the categorical level and classes (taxa) that seem to be important. For example, if a sombric horizon has also argillic features, can we make them mutually exclusive or is one part of the sombric horizon a special kind of an argillic horizon. If a sombric horizon is also spodic, is it a special case of a spodic horizon? Hopefully the important studies in Central Africa will provide definitions of a sombric horizon for testing and also suggestions for ways to place soils with sombric horizons in Soil Taxonomy.

Q. M.L. Leamy: I applaud the requirement for documentation, e.g. 10 pedons for a new family. However, what are the implications for the ICOMs? ICOMAND, for instance, has 94 proposed new subgroups. The collecting and compiling of up to 1,000 pedons is a little daunting.

A. R.W. Arnold: As Soil Taxonomy was developed subgroups and families were only provided for those soils that were known to exist. One or more soil descriptions and some supporting data should be required to propose a taxon for further testing. We would appreciate knowledge about whether the soil covers enough land area to be considered at lower categories or handled as phases for recognition locally. Once an ICOMAND proposal is tested and approved, more restrictive documen-

tation is required for further modification. As more information becomes available, the testing must be more rigorous because of the consequences. This is usually more difficult at higher categorical levels than at lower categorical levels.

APPENDIX I

Amendments to the National Soil Classification System in Categories Above The Series

The national soil classification system is dynamic and as a new knowledge is gained and soils are examined and described in new places, amendments to the system are required to accommodate the new information. Soil Taxonomy expresses in print knowledge of the system and understanding of soil science up to the time it was published.

(1) Kinds of Amendments. The kinds of amendments that may be expected are as follows:

- Addition of Taxa.
- Deletion of taxa.
- Changes in definitions of taxa.
- Changes in definitions of diagnostic criteria.
- Additions of diagnostic criteria.
- Clarification of the text not related to any of the above.

(2) Origin of Suggestions for Amendments. Suggestions for amendments to the soil classification system may originate from any individual or group participating in the National Cooperative Soil Survey or from outside the United States. Others must obtain a sponsor from within the National Cooperative Soil Survey.

(3) Supporting Evidence for Amendments. The amount and kind of evidence required to accompany recommendations for amendments to the soil classification system varies, depending on the nature of the proposed changes. For example, a description of a proposed soil series with interpretations and laboratory data is acceptable evidence to support a new class in the family category.

To add classes above the family level, minimum supporting evidence must include a description of at least one pedon, laboratory data on at least the critical parts of the diagnostic horizons that are used to propose the new class, a statement of the significance of the separation relative to interpretation, and an estimate of the extent.

Appendix I (cont'd)

Definitions of some taxa may need to be revised to provide more suitable groupings. For these minimum supporting evidence must describe the impact of each proposed change on definitions of all taxa that will be affected, including all changes required in Soil Taxonomy to accommodate the amendments.

(4) Procedures for Proposing and Reviewing Amendments.

(i) Regional Soil Taxonomy Committees. Four Soil Taxonomy Committees, one for each of the group of states served by a technical service center, consider proposed amendments referred to them by the committee chairmen. Members are:

- The principal soil correlator, serving as chairman.
- Six additional members, three from state agencies and three from Federal agencies.
- Members from Federal and state agencies are selected by the Federal and state members respectively of the Regional Work Planning Conference of the National Cooperative Soil Survey.
- Members serve 3-year terms except for the initial period, one state and one Federal member retiring each year.
- Additional soil scientists, depending on the nature of the recommended changes and the expertise needed, may be asked to consult with the committee at the discretion of the chairmen.

(ii) National Ad Hoc Work Groups. Such work groups are appointed by the Director of Soils as needed. These ad hoc work groups review reports from regional Soil Taxonomy committees and recommend additional study or implementation of proposed amendments. Membership includes representatives of state and Federal agencies, and may include international representatives. They are composed of:

- A chairman,usually a member of the National Office Soil Staff, and
- Additional members depending upon the nature of the recommended changes and the expertise needed.

(iii) Procedures for Amendments--Lower Categories.

(A) Soil Series. Soil series is the most common taxonomic refer-

Appendix I (cont'd)

ence for naming soil map units in the United States. Changes in the classification of soil series are made through the correlation process. When about 800 ha of a unique new kind of soil are recognized, using descriptions obtained for at least 10 pedons, necessary laboratory data obtained, and interpretations developed, a new series can be proposed and established as outlined in Section 301.1(c)(5) of the National Soils Handbook.

(B) Adding New Families. Proposals to establish new families that lack soil series are submitted to the Principal Soil Correlator for concurrence. Supporting documents should include descriptions or notes for about 10 pedons, laboratory data if limits between other recognized classes are such that adequate identification cannot be based on field criteria alone, and interpretations for the intended uses. Extent should be at least 800 ha. Proposals to add new family criteria to the system of soil classification follow the procedure for changes in the system outlined in Sections 301.1(d)(4)(iii)(D) and 301.1(d)(4)(iv) of the NSH.

(C) Implied Subgroups. The classification of some soils at the subgroup level was not provided in the soil classification system because of limited knowledge or small extent. These soils can be classified in a great group, but by definition are excluded from all recognized subgroups. For example, some soils, such as Grossarenic Hapludults, are excluded from the typic and other subgroup definitions of the great group. They are excluded because they have not been located and studied, but are "implied" because there is a reasonable assumption that they occur. The following procedure is used for soils that are outside the range of any defined subgroup:

- Determine if an existing subgroup can be modified to accommodate the new soil without changing the intent or value for reasonable grouping of similar soils. If the new soil would be placed in a family not presently recognized in the most similar existing subgroup and has interpretations unlike those of series in that subgroup, a new subgroup may be proposed. If a new subgroup is proposed then:

- The proposal and supporting documentation are sent to the Director of Soils. The Director reviews the proposal, determines if additional action is necessary, and notifies the proposing individual within

Appendix I (cont'd)

30 days.

(iv) Procedures for Amendments--Higher Categories

Proposals for changes or additions to higher categories are submitted to the Director of Soils. Proposals originating in the United States are submitted through a Principal Soil Correlator who is chairman of a regional Soil Taxonomy Committee. Proposals originating outside of the United States may be submitted to an appropriate international committee or to the Director of Soils, Soil Conservation Service, U.S. Department of Agriculture, Washington, D.C. 20013. Only those proposals that are well documented will be evaluated.

The Director of Soils and Staff Leader for Soil Classification and Program Leader for International Soils Program evaluate the proposals; if approved, amendments are issued by the Director. If further study is needed, proposals are referred to Principal Soil Correlators, to International Committees, or to other special work groups. Finalized proposals are submitted to the Director for approval or disapproval.

(5) Notification of Amendments

(i) Decisions on proposed amendments will be sent by the Director of Soils to the originators and reviewers of the proposed amendments as soon as the review procedure is completed.

(ii) Approved amendments will be published in the National Soils Handbook of USDA-SCS.

(iii) Amendments are filed in Section 301.1 of the National Soils Handbook of the Soil Conservation Service. Amendments can be transferred to working copies of Soil Taxonomy by individual soil scientists.

(iv) Each amendment will be printed on a separate sheet so that it can be properly filed. Exceptions are changes which involve only correction of spelling or punctuation or minor word changes for clarification, several of which can be printed on a single sheet.

(v) Copies of the amendments will be sent to all soil scientists of the NCSS and to other interested soil scientists (both national and international). They will also be sent to domestic and some international journals of soil science and to libraries known to hold copies of Soil Taxonomy.

PROGRESS REPORT ON THE ISM LABORATORY METHODS AND DATA EXCHANGE PROGRAMME

L.P. van Reeuwijk and W.G. Sombroek

INTRODUCTION

One of the recommendations of the 2nd International Soil Classification Workshop held in Malaysia and Thailand in August 1978 sponsored by U.S.A.I.D. reads as follows:

> "MT 9. The laboratory methods for soil characterization in various parts of the world be cross-checked, correlated and, if possible, standardized, and that the International Soil Museum in Wageningen, The Netherlands assume an active role in this matter."

Complying with this recommendation, the International Soil Museum (ISM) has made a start with such a programme after obtaining agreement of its Advisory Bodies. A circular letter was sent to 19 major soil laboratories, many of them working in or for developing countries (see list attached) inviting them to join in an exchange programme of laboratory procedures and data. All of them enthusiastically accepted the invitation.

The programme consists of two parts:

(1) All participants are supplied with subsamples of 10 bulk reference samples prepared by ISM with the kind cooperation of the Kenya Soil Survey. All participants analyze these samples according to their standard procedures and send the results to ISM, which acts as the Programme Secretariat.

(2) Each participant sends ten different soil samples to ISM which will all be analyzed according to "standard procedures" as indicated in the FAO Soils Bulletin No. 10 (1970) and the USDA-SCS Soil Survey Investigations Report No. 1 (1972), or the new edition which is currently in preparation. The results can be compared with participant's own results. This work will largely be done by the Soil Laboratory of the Royal Tropical Institute (KIT) at Amsterdam following a generous offer from that side. Intensive contacts have developed between

ISM (Dr. L.P. van Reeuwijk) and KIT (Dr. J.P. Andriesse and Dr. F. van der Pol) on the one hand and the USDA/SCS Lincoln National Laboratory (Dr. S.C. Holzhey and Dr. J.M. Kimble) on the other to ensure full agreement on the details of the procedures to be adopted for this central analysis. For the time being it will concentrate on charge characteristics (CEC, base saturation) and particle size analysis.

The data will be compared, evaluated and distributed among all participants, very much along the lines of ICOMLAC, ICOMOX, etc.

Depending on the results achieved with this scheme, and on international funding possibilities, the project may in due course be extended to include more than the initial laboratories (say 50 or 100) and the scope may be widened to encompass other analyses such as carbon, pH, exchangeable Al, water dispersable clay, etc.

Part 1 of the programme is well under way and some of the initial results are presented here with a brief discussion.

Thus far, the results of 13 participating laboratories have been received and some preliminary conclusions seem to be justified. As yet, no in-depth analysis of the data has been made. Therefore, the methods used by the different laboratories are not reported here, let alone the detailed procedures. This will be done as soon as all contributions have been received. The data have been obtained by routine methods employed by the respective laboratories and, in general, such data are used locally for soil interpretation purposes.

Tables 1, 2, 3 and 4 give the data on CEC determination and particle size analysis as they have been produced by the participants (second decimals were rounded off) whereas Tables 5, 6, 7 and 8 give some derived figures calculated by the Programme Secretariat. In the tables, the maximum and minimum values for each sample have been underlined by a full and an interrupted line respectively. The following (most striking) features can be observed:

There is an unexpected wide variation in results, both for CEC and particle size analysis. For most soils, Andosols excepted (they are a special case), the CEC differences between the lowest and the highest figures range roughly from 60% (sample 5) to over 320% (sample 10) relative to the lowest figure. For the clay contents these differences range from 45% (sample 5) to 270% (sample 10) respectively.

Apparently, of these soils, sample 5 gives the least rise to controversy, whereas sample 10 causes difficulties in some laboratories. Thus, the character of the soil material may be of strong influence on the success of an analysis ('easy' and 'difficult' soils). This is further illustrated by the Andosol (samples 8 and 9), a notoriously 'difficult' soil, where the extreme values are dramatically further apart. On the other hand, however, quite a number of data appear to be reasonably close or even identical. This may give some confidence that eventually a standardization of procedures will be successful.

The silt data tables (3, 4 and 5, 6) indicate that particle size analysis largely depends on the effect of the dispersion procedure.

The CEC-clay data (Table 7) may, in principle, obscure errors when both clay content and CEC are either too high or too low. However, when this is not the case, the lever effect may yield such extreme values that errors are showing up clearly. For instance, sample 4 seems to have reasonable values in virtually all cases, whereas for samples 8 and 9 impossible high values have been obtained (next to reasonable ones).

The variation in particle size analysis is further expressed in Table 8, giving the clay content ratio of the B and A subhorizons analysed. Dispersion difficulties may not be the same in the A and B horizon (different content in organic matter and other cementing agents) and thus influence this ratio. The increase in clay content down the profile is being used as an important criterion for soil taxonomic purposes. The present data may illustrate the degree of reliability of the criteria.

CONCLUSION

Some variations in the data may be ascribed to sample differences, but the thorough preparation of the subsamples distributed to the participants should have reduced this to a relatively insignificant contribution to the overall variation. Therefore, the differences in results reported here must be largely ascribed to differences in methods and the execution of the procedures. The present results strongly indicate that standardization of methods and procedures is needed for good soil correlation over

the world. The results also indicate that such a standardization is feasible.

REFERENCE SAMPLES

Laboratory Method and Data Exchange Programme

No.	Location	Horizon	Depth (cm)	Classification
1 2	Busia, Kenya	Ap Bt2	0 - 15 50 - 70	Oxic Pale (?) udult/Ferric Acrisol, petric phase
3 4	Magarini, Kenya	A[a] B[a]	0 - 22 80 - 120	Typic Eutrostox/Rhodic Ferralsol
5	Bura-east, Kenya	A[a]	0 - 20	Typic Natrargid/Orthic Solonetz
6 7	Nairobi, Kenya	Ap Bt2	0 - 18 65 - 115	Orthoxic Palehumult/Humic Nitosol
8 9	Kijabe, Kenya	Ah B[a]	0 - 17 75 - 105	Udic Eutrandept/Mollic Andosol
10	Randwijk, Netherlands	C[a]	60 - 110	Typic Fluvaquent/Calcaric Fluvisol

[a]Unspecified

DISCUSSION

Q. R.W. Arnold: Do the laboratories run and report duplicates or more replicates to estimate the analytical error for the laboratory and each determination? It may assist in tracing problems that may exist in particular analyses.

A. W.G. Sombroek: One or two laboratories sent duplicate data. We don't know if the other labs did their analyses in duplicate or triplicate; they only provided single values.

Q. S.W. Buol: Did the samples have to be subjected to any plant quarantine treatment at international boundaries?

A. W.G. Sombroek: No.

Comment. F.R. Moormann: Although the divergence between results is great, the picture becomes better if the values are related to diagnostic limits as used in Soil Taxonomy; as an example, the B/A clay ratio of the Ferralsol (samples 3 and 4) can be cited.

APPENDIX

Table 1 Clay content (< 2 µm, wt %)

	Acrisol		Ferralsol		Solonetz	Nitosol		Andosol		Fluvisol
Lab. \ Sample	1	2	3	4	5	6	7	8	9	10
1	13.9	13.3	6.8	23.8	27.5	33.6	46.6	4.4	9.6	15.2
2	14.3	25.3	16.7	36.2	26.3	75.8	85.3	27.4	9.7	16.1
3	20	30	14	38	36	74	84	16	24	24
4	16	28	16	37	29	74	85	16	31	18
5	21	31	17	37	32	81	90	39	36	26
6	14	25.5	15	36	29	71.5	81.5	20	7	17
7	15.6	27.7	17.0	39.7	30.7	78.6	87.5	26.0	12.9	17.8
8	16.8	26.7	17.4	39.0	31.4	65.8	82.2	16.1	1.7	15.3
9	14	26	14	34	30	62	76	6	8	18
10	13	23	10	33.5	25	54.5	70	11	14	15
11	14.1	25.4	16.5	38.8	28.0	72.0	84.6	15.7	7.1	16.4
12	19.1	29.9	18.5	39.5	30.7	80.3	88.6	54.8	58.7	19.5
13	12.2	24.8	14.8	36.3	28.3	29.4	63.1	8.3	2.5	7.1

Table 2 CEC*(meq/100g)

Lab. \ Sample	1	2	3	4	5	6	7	8	9	10
1	4.9	6.5	2.1	2.8	20.1	17.3	13.0	44.3	20.3	6.4
2	3.4	3.4	1.3	2.1	18.9	8.9	8.3	13.7	9.5	7.0
3	2.9	7.2	2.2	2.8	17.2	23.2	12.5	49.5	26.0	11.4
4	5.6	6.5	3.0	3.0	25.3	18.3	12.4	43.3	25.1	12.5
5	4.9	6.6	2.5	3.1	22.3	19.7	13.5	70.5	28.9	9.0
6	4.7	6.3	2.0	2.4	22.5	18.4	12.3	63.4	25.9	8.0
7	2.8	4.4	1.1	1.3	15.5	16.1	11.6	57.1	27.1	6.5
8	4.5	5.7	2.0	2.4	20.7	17.8	12.1	55.5	25.2	7.8
9	3.4	4.9	1.8	2.0	24.7	9.6	8.1	12.2	14.4	27.1
10	6.0	7.0	3.0	3.0	24.0	22.6	13.0	62.0	31.0	12.0
11	4.9	6.9	2.3	2.8	22.7	20.3	13.7	65.6	29.8	9.5
12	5.4	7.6	2.7	4.9	23.2	25.6	22.4	62.0	44.8	11.4
13	7.2	8.4	3.7	3.9	22.0	24.3	19.7	72.9	41.1	10.4

*1 N NH_4OAc (pH 7) for laboratories no. 1, 5, 6, 7, 8, 10, 12 and 13.

Table 3 Silt I content (2-20 μm, wt %)

	Acrisol		Ferralsol		Solonetz	Nitosol		Andosol		Fluvisol
Sample / Lab.	1	2	3	4	5	6	7	8	9	10
1	19.1	28.0	5.0	7.4	11.4	28.7	23.7	31.2	32.7	20.9
2	16.9	17.3	0.9	1.3	9.2	11.9	6.8	34.0	33.0	21.4
3										
4										
5	16	16	1	1	9	9	4	38	50	23
6	19	19.5	2	2.5	12.5	17.5	12	48	49	22
7	18.5	18.7	0.7	0.7	11.0	1[illegible].2	5.9	44.7	52.1	23.4
8	17.1	16.2	0.1	0.3	10.9	20.0	11.3	49.9	31.0	23.6
9										
10	17.5	18.0	6.5	3.5	12.5	26.0	14.5	39.5	39.0	21.0
11	18.0	18.4	0.4	1.2	11.1	15.6	8.1	46.7	40.7	21.5
12	15.4	16.0	1.3	1.4	12.0	8.8	5.1	24.7	27.0	22.3
13	19.8	19.3	2.6	1.8	11.8	51.8	25.6	64.3	73.2	29.8

Table 4 Silt II content (2-50 μm, wt %)

Sample / Lab.	1	2	3	4	5	6	7	8	9	10
1										
2										
3	24	24	2	2	4	12	8	40	36	28
4	33	31	3	1	14	20	11	71	57	51
5	26	23	1	2	10	12	6	49	56	42
6	32	30	3	3	14	21.5	14.5	61.5	75	48
7	31.7	28.8	0.9	0.9	12.9	14.6	8.8	57.0	78.0	46.3
8										
9	30	22	2	4	8	16	8	40	40	42
10	34.0	28.5	7.0	4.3	14.0	30.3	16.5	49.5	55.5	44.5
11	30.1	28.0	0.8	2.0	13.4	19.8	11.1	60.7	53.8	44.0
12	29.9	28.8	2.2	2.1	15.6	13.3	8.2	35.7	33.8	48.7
13	33.4	29.6	3.4	2.6	13.3	63.0	35.5	78.2	88.1	52.9

Table 5 Silt I/Clay Ratio

	Acrisol		Ferralsol		Solonetz	Nitosol		Andosol		Fluvisol
Lab. \ Sample	1	2	3	4	5	6	7	8	9	10
1	1.4	2.1	0.7	0.3	0.4	0.9	0.5	7.1	3.4	1.4
2	1.9	0.7	0.1	0.04	0.4	0.2	0.1	1.2	3.4	1.3
3	–	–	–	–	–	–	–	–	–	–
4	–	–	–	–	–	–	–	–	–	–
5	0.8	0.5	0.1	0.03	0.3	0.1	0.04	0.1	1.4	0.9
6	1.4	0.8	0.1	0.1	0.4	0.2	0.2	2.4	7.0	1.3
7	1.2	0.7	0.04	0.02	0.4	0.1	0.07	1.7	4.0	1.3
8	1.02	0.6	0.006	0.008	0.4	0.3	0.1	3.1	18.2	1.6
9	–	–	–	–	–	–	–	–	–	–
10	1.4	0.8	0.7	0.1	0.5	0.5	0.2	3.6	2.8	1.4
11	1.3	0.7	0.02	0.03	0.4	0.2	0.1	3.0	5.7	1.3
12	0.8	0.5	0.07	0.04	0.4	0.1	0.06	0.5	0.5	1.1
13	1.6	0.8	0.2	0.05	0.4	1.8	0.4	7.8	29	4.2

Table 6 Silt II/Clay Ratio

Lab. \ Sample	1	2	3	4	5	6	7	8	9	10
1										
2										
3	1.2	0.8	0.1	0.05	0.1	0.2	0.1	2.5	1.5	1.2
4	2.1	1.1	0.2	0.03	0.5	0.3	0.1	4.4	1.8	2.8
5	1.2	0.7	0.06	0.05	0.3	0.2	0.1	1.3	1.6	1.6
6	2.3	1.2	0.2	0.1	0.5	0.3	0.2	3.1	10.8	2.8
7	2.0	1.0	0.05	0.02	0.4	0.2	0.1	2.2	6.1	2.7
8	–	–	–	–	–	–	–	–	–	–
9	2.1	0.9	0.1	0.1	0.3	0.3	0.1	6.7	5.0	2.3
10	2.6	1.2	0.7	0.1	0.6	0.6	0.2	4.5	4.0	3.0
11	2.1	1.1	0.05	0.05	0.5	0.3	0.1	3.9	7.6	2.7
12	1.6	1.0	0.1	0.05	0.5	0.2	0.1	0.7	0.6	2.5
13	2.7	1.2	0.2	0.07	0.5	2.1	1.8	9.4	35.2	7.5

Table 7 CEC-clay (meq/100 g) (not corrected for org. matter)

	Acrisol		Ferralsol		Solonetz	Nitosol		Andosol		Fluvisol
Lab. \ Sample	1	2	3	4	5	6	7	8	9	10
1	36	49	31	12	73	52	26	1007	211	42
2	24	13	8	6	72	12	10	50	98	44
3	15	24	16	7	48	31	15	309	108	48
4	35	23	19	8	87	25	15	270	81	69
5	23	21	15	8	70	24	15	181	80	35
6	34	25	13	7	78	26	15	315	370	47
7	18	16	7	3	51	21	13	219	210	37
8	27	22	11	6	66	27	15	344	1479	51
9	24	19	13	6	82	16	11	204	181	151
10	46	30	30	9	96	41	19	564	221	80
11	35	27	14	7	81	28	16	414	419	58
12	28	25	14	12	75	32	25	113	76	58
13	59	34	25	11	78	83	31	878	1644	164

Table 8 Clay Ratio B/A

Lab. \ Sample	1/2	3/4		6/7	8/9	
1	0.96	3.50		1.39	2.18	
2	1.77	2.17		1.13	0.35	
3	1.50	2.71		1.14	1.50	
4	1.75	2.31		1.15	1.93	
5	1.48	2.47		1.11	0.92	
6	1.82	2.40		1.14	0.35	
7	1.78	2.34		1.11	0.50	
8	1.60	2.24		1.25	0.11	
9	1.86	2.43		1.23	1.33	
10	1.77	3.35		1.28	1.27	
11	1.80	2.35		1.18	0.45	
12	1.57	2.14		1.10	1.07	
13	2.03	2.45		2.15	0.30	

THE WORKSHOP IN RETROSPECT

A. Osman

This assessment was to have been given by Dr. R. Dudal, Director of the Land and Water Development Division of FAO, and I do not pretend that I can match his eloquence or wit. I will, however, try to make a summary of the major events and achievements. Unlike most of you, I had a bad start at this workshop. Until today I have not received my luggage and so if I make any stinking comments you will appreciate the reason. Nevertheless, I must add that this was the only flaw in this workshop which has otherwise been so perfect that as the organizer of the previous, 3rd International Soil Classification Workshop, it has made me extremely jealous. With all my resources of ACSAD, I thought I had organized an excellent workshop in Syria and Lebanon in 1980. Here in Rwanda, with their minimum resources, our Rwandese colleagues under the able leadership of Mr. Henry Neel and with the support of ABOS (Belgian technical assistance program) have excelled all expectations. The high technical quality of the workshop was ensured by the selection of scientists by the Soil Management Support Services (Dr. H. Eswaran) and the University of Puerto Rico (Dr. F.H. Beinroth).

The theme of the workshop is the classification and management of tropical mountain soils and as indicated in the speech of the Secretary General of Rwanda, this is one of the areas of tropical soils which has received least attention in the recent years. The Secretary General also indicated that Rwanda has a very high density of population and particularly when one considers the amount of available arable land and population growth, the situation is of some concern. These remarks add a new dimension to this workshop as it is probably one of the first international meetings to discuss such kinds of soils. Mr. Iyamuremye, Director General of the Institut de Science Agronomique, Rwanda, also alluded to the uniqueness of this meeting in his opening address. He looked upon this workshop as a forum whereby the scientists from the Less Developed Countries (LDC's)

could meet and discuss with their counterparts from the western world. When I look back at the discussions we had in the last 2 weeks, I can confidently say that we have certainly utilized this forum very effectively. The very frank exchange of ideas, concepts, and theories, the disagreements that were voiced, the satisfaction expressed by some and the frustrations as shown by others, and finally the spirit of compromise are all marks of an exciting workshop and you will agree that we had our share of this during this workshop.

We have here amongst us some of the top talents in the field of classification and management of tropical soils. The steering committee must be congratulated for not only assembling this panel of specialists but also arranging a technical program that extracts the best from them. The first technical session set the scene for the workshop. Dr. Van Wambeke focused on the purpose of the workshop and dwelled briefly on the logic of Soil Taxonomy. Professor Tavernier presented one of the best speeches that I have heard when he traced the developments in soil classification and I will only hope that he will put these ideas on paper. Dr. Pécrot proceeded to link the workshop to the role soil resource inventories play in agricultural development. Finally Dr. Beinroth, with his excellent array of diapositives, showed very convincingly, the role of Soil Taxonomy in agrotechnology transfer.

I must congratulate the Rwandese colleagues for the excellent series of papers which informed us on the soils and agriculture in Rwanda. These papers and the documentation in the Tour Guide made the field trips more meaningful.

Though I would like to go at length for each of the papers presented, this is clearly impossible in the short time allotted for me. Basically, the technical sessions were centered on five major topics--Oxisols, low activity clay soils, Andisols, soil moisture and temperature regimes, and soil management. I would like to draw your attention to the papers by the soil management specialist. It is probably the first time that I have seen such excellent rapport between the soil management people and the classificationists. I doubt if any classification system other than Soil Taxonomy can generate such a rapport.

The highlights of the technical sessions were the discussion sessions of the international committees. This is the backbone of the workshop and

despite the fact that several night sessions were organized, I must confess that personally I felt that this was insufficient. You would all agree with me that these discussion sessions are as fruitful and important as the paper sessions. I am not lodging a complaint, but I strongly feel that more time could be set aside for discussions. Although Hari got us together for four nights and even though everybody participated enthusiastically, I could sense workshop fatigue setting in.

Like the technical sessions, the field trips were meticulously arranged and profiles carefully selected in accordance with the purpose of the workshop. I was amazed to note that the time of arrival and departure from a soil inspection site was carefully calculated, and I was further amazed when I found that the organizers stuck to the schedule with clockwork precision. This is really organization at its best. However, the regimental approach adopted at the beginning of the tour might have dampened the discussion. Later, I am sure all of us were pleased when discussions became more informal. Again, I would like to make one remark which could improve future workshops. The time allocated for discussion at the soil sites could be extended. This might mean, in some instances, seeing fewer soils. The organizers were apparently aware of this and in order to arrive at a compromise, have included forms to be filled up by each participant. This innovation is useful for each participant to express his personal views which he may not have the opportunity to do at the pit. I wish to commend the organizers for providing this facility and urge everyone to use it.

In retrospect, it is always easy to be clever or critical as I have been. However, one has to be honest, and without any doubt, I can add to what Dr. Van Wambeke already expressed at the last profile site yesterday; indeed this has been an exceptionally good workshop. The technical papers have provided much basic information on such soils. The discussions, both in this room and at the soil sites, have clarified several issues, provided food for thought, provoked new ideas, and crystallized others. The workshop will not solve immediately any of the problems faced by the developing countries. It will, however, create an awareness and generate new research which is lacking in these areas.

Before I close, Mr. Chairman, may I add my personal gratitude and congratulations to the organizers to that which Dr. Sombroek is going to ex-express, for a job well done.

VOTE OF THANKS

Dr. W.G. Sombroek

It is my privilege and pleasure to say a few words of thanks. I shall do it partly in French, partly in English, and slowly.

Nous remercions avant tout le Gouvernement de la République du Rwanda, plus spécialement le Ministère de l'Agriculture et de l'Elevage et l'Institut des Sciences Agronomiques du Rwanda (ISAR). Monsieur le Directeur-Général, nous sommes très reconnaissants d'avoir pu tenir ce "workshop" ici, grâce à votre coopération effective, et votre hospitalité.

J'espère que, soit directement soit indirectement, cette réunion servira à valoriser votre patrimoine, plus spécialement le développement agronomique et la mise en valeur de vos terres, grâce à une cartographie des sols adéquate et une corrélation exacte avec les systèmes internationaux de classification des sols.

Ensuite, je veux remercier l'ABOS, l'Algemeen Bestuur voor Ontwikkelingssamenwerking de la Belgique. Ce sont des mots de ma langue maternelle, alors permettez que je continue pour quelques secondes dans cette langue :

Mijnheer Neel, wilt onze dank overbrengen aan de vertegenwoordigers van ABO voor haar moeite en financiele ondersteuning van deze Workshop.
Ik hoop dat dit een voorbeeld en precedent zal zijn voor andere Europese Ontwikkelingshulpinstanties tot het ondersteunen van dit soort bodemclassifikatieaktiviteiten in de toekomst.

Gentlemen, I have just been expressing the hope that the support of ABOS for this workshop will be an example, a precedent for other European bilateral technical assistance organizations to join in supporting the development of international soil classification.

Next, I should like to thank, on behalf of all participants, the officials of USAID for their continued support of the organization of these workshops to refine and improve the "Soil Taxonomy" system of soil classification, and to promote its use in developing countries. Please be as-

sured that this support constitutes a great stimulus, directly and indirectly, for the development of our knowledge of tropical and subtropical soils, and its application to rural development and agrotechnology transfer. As to the technical organization of this meeting, I should like to thank first of all the Soil Management Support Services program of the U.S. Soil Conservation Service, through its Program Leader Dr. Hari Eswaran, for its thorough preparations. I would like to make a special compliment to Dr. John Kimble of the SCS Lincoln Laboratory for the very comprehensive laboratory data on the soil profiles studied during this workshop.

Next, I wish to thank the University of Puerto Rico, in the person of Prof. Dr. Fred Beinroth for its excellent organization, on behalf of SMSS, of the workshop program.

I also commend the Geological Institute of the University of Ghent, in the person of Prof. R. Tavernier, for its confirmed support to certain scientific aspects of these workshops.

Enfin, je vais remercier, au nom de tous les participants de l'étranger, les pédologues rwandais et leurs associés belges et autres qui travaillent ici, de leurs efforts intensifs et efficaces pour l'organisation technique de ce workshop, y compris toutes les tournées sur le terrain. Je répète quelques noms, déjà cités par le Professeur Van Wambeke hier lors du dernier sol étudié : Messieurs Rutunga, Birasa et Ndoreyaho, Messieurs Vander Zaag, Marijnissen, et Vercruysse. Je suis bien sûr que j'oublie quelqu'un, mais certainement je n'oublie pas M. Henri Neel, le pédologue belge devenu diplomate, qui avec son énergie et son enthousiasme a assuré pour une grande part le succès de ce séminaire.

Messieurs les participants, je vous prie de vous joindre à moi par un applaudissement ardent pour remercier nos hôtes de ce beau pays des mille collines. Gentlemen, please join me in a big show of hands in thanking our hosts.

APPENDIX

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