PROCEEDINGS OF THE

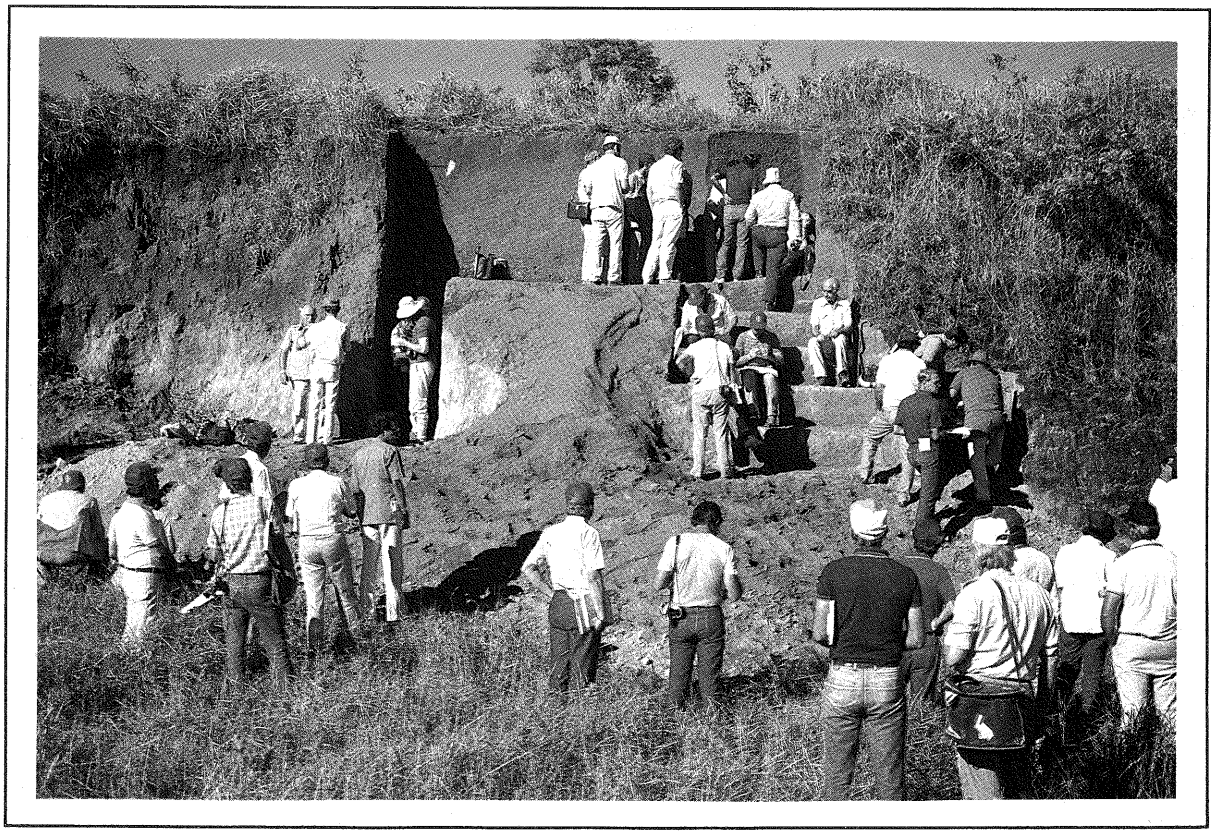
EIGHTH INTERNATIONAL SOIL CLASSIFICATION WORKSHOP

Classification, Characterization and Utilization of Oxisols

BRAZIL

12 to 23 May 1986

Part 1: Papers



EMBRAPA SMSS AID UPR

Rio de Janeiro

1988

CLAS 18

PROCEEDINGS OF THE

EIGHTH INTERNATIONAL SOIL CLASSIFICATION WORKSHOP

Classification, Characterization and Utilization of Oxisols

Scanned from original by ISRIC – World Soil Information, as ICSU World Data Centre for Soils. The purpose is to make a safe depository for endangered documents and to make the accrued information available for consultation, following Fair Use Guidelines. Every effort is taken to respect Copyright of the materials within the archives where the identification of the Copyright holder is clear and, where feasible, to contact the originators. For questions please contact soil.isric@wur.nl indicating the item reference number concerned.

BRAZIL
12 to 23 May 1986

Part 1: Papers

Workshop Co-Sponsors

Serviço Nacional de Levantamento e Conservação de Solos,
Empresa Brasileira de Pesquisa Agropecuária

Soil Management Support Services, Soil Conservation Service
United States Department of Agriculture

University of Puerto Rico

Editors: F. H. Beinroth, M. N. Camargo and H. Eswaran
Copy Editor: Norma Gorst
Production: Victoria Pecsok and Jeffrey Uehara

ISN 9278

WORKSHOP COMMITTEES

Advisory Committee

R. L. Duesterhaus, USDA/SCS
T. S. Gill, AID/S&T/AGR
O. F. Rivaldo, MINAGRI/EMBRAPA

Steering Committee

F. H. Beinroth, UPR, Chairman
S. W. Buol, ICOMOX
I. A. Gomes, EMBRAPA/SNLCS
H. Eswaran, SMSS
M. N. Camargo, EMBRAPA/SNLCS

Organizing Committee

M. N. Camargo, EMBRAPA/SNLCS
P. K. T. Jacomine, EMBRAPA/SNLCS
J. Olmos I. L., EMBRAPA/SNLCS
F. H. Beinroth, UPR
C. S. Holzhey, USDA/SCS
H. Eswaran, SMSS

CONTENTS

Foreword v

Preface ix

PERSPECTIVES AND BACKGROUND

Refining *Soil Taxonomy, R.W. Arnold* 3

IMPLICATIONS OF THE ICOMOX PROPOSAL

Implications of the ICOMOX Proposal Relative to the Classification of Andisols, *R.L. Parfitt, A.E. Hewitt, and M.L. Leamy* 9

Implications of the ICOMOX Proposal Regarding the Mandate of ICOMAQ, *J. Bouma* 13

PROPERTIES OF OXISOLS

Acric Properties and Their Significance to Soil Classification, *G. Uehara* 19

Constraints to the Analytical Characterization of Oxisols, *C.S. Holzhey and J.M. Kimble* 23

Families in the Oxisol Order, *B.F. Hajek and R.L. Guthrie* 32

Chemical Estimation of Weatherable Minerals Present in the Diagnostic Horizons of Low Activity Clay Soils, *A.J. Herbillon* 39

Apparent ECEC in Some Brazilian Soils with Variable Charges Determined Using Three Different Extractors, *M.A.M. Duriez, M.E.C.C.M. Melo, R.A.L. Johas, and W.S. Araujo* 49

Phosphorus Adsorption Characteristics of Brazilian Oxisols, *N. Curi and O.A. de Camargo* 56

Contribution of Organic Matter to Exchange Properties of Oxisols, *E. Klamt and W.G. Sombroek* 64

Iron Oxides in Brazilian Oxisols, *N. Kämpf, M. Resende, and N. Curi* 71

Magnetic Properties of Brazilian Oxisols , *M. Resende, D.P. Santana, D.P. Franzmeier, and J.M.D. Coey* 78

Mineralogy of the Deferrified Clay Fraction in B horizon of Pedons of the VIIIth International Soil Classification Workshop, *L.L. Antonello* 109

X-Ray Diffraction of Iron Oxides of Selected Samples from the VIIIth International Soil Classification Workshop Pedons, *N. Kämpf* 139

Comparison of Gravimetric Water Retention at Different Tensions,
L.B. Oliveira, J.C. Almeida, and J.L. Paula 145

Water Retention in B Subhorizons of Some Oxisols, *L.B. Oliveira,*
J.C. Almeida, and J.L. Paula 147

The Relationships of Specific Surface Area of Soil with Some Physical Parameters in Subhorizons
of Brazilian Oxisols and Other Orders, *J.L. Paula, L.B. Oliveira, and J.C. Almeida* 150

OXISOLS OF DIFFERENT REGIONS

Impact of the ICOMOX Proposal on the Classification of Soils of the United States and Puerto Rico,
the Trust Territory, and Guam, *J.E. Witty, F.H. Beinroth, and H. Ikawa* 155

Evaluation of the ICOMOX Proposal in the Venezuelan Context, *R. Schargel and J.A. Comerma* 158

Evaluation of the ICOMOX Proposal in the Southeast Asian Context,
S. Paramanathan, L. Moncharoen, and M. Recel 164

Oxisols in Zambia, *C. Kalima and O. Spaargaren* 167

Oxisol-Landscape Relationships in Brazil, *I.F. Lepsch and S.W. Buol* 174

The Brazilian Classification of Latosols, *M.N. Camargo, P.K.T. Jacomine,*
A.P. Carvalho and J. Olmos I.L. 190

AGRONOMIC AND ENGINEERING ASPECTS OF OXISOLS

Agronomic Considerations of Modern Agriculture on Oxisols, *W.J. Goedert and E. Lobato* 203

Oxisols Acidity and Fertility Evaluation: A Need for Suitable
Management, *A.S. Lopes and N. Curi* 211

Critical Evaluation of Different Phosphorus Extractions on Oxisols, *B. van Raij* 225

Difficulties in the Application of *Soil Taxonomy* in Brazil and the Brazilian Experience with
Building Up Oxisols' Fertility, *N. Curi and A.S. Lopes* 231

Geotechnical Characteristics of Oxisol B Horizons, *L.M.G. Motta,*
J. Medina, J.L.R. Souza, and J. Olmos I.L. 236

The Assessment of Cement Requirement of Oxisols by a Physico-Chemical Method,
F.J. Casanova and J.A. Ceratti 243

APPENDIX

Oxisol Amendment 259

Workshop Program 275

List of Non-Brazilian Participants 278

List of Brazilian Participants 280

FOREWORD

The Serviço Nacional de Levantamento e Conservação de Solos (SNLCS) of Empresa Brasileira de Pesquisa Agropecuária (EMBRAPA) was the institution responsible for the organization of the First and Eighth International Soil Classification Workshops (I and VIII ISCW) in Brazil, host country of both events.

The organization of the VIII ISCW was co-sponsored by the University of Puerto Rico (URP), Soil Management Support Services (SMSS), and also with the cooperation of the Centro de Pesquisa Agropecuária dos Cerrados (CPAC) of EMBRAPA and the Instituto Agronômico de Campinas (IAC) of São Paulo.

As in the I ISCW, the decision of SNLCS to co-sponsor the VIII ISCW was also directed by the objectives of the event which indoubtelly are of great significance for Brazil and to give our cooperation in the refinement of the taxonomy of the soils more characteristic of the humid tropic, the Oxisols.

Brazil has vast regions occupied by Oxisols which, as well known, present good physical conditions, allied to a relief favorable to mechanization, to an availability of luminous and thermic energy favorable to plant growth, to an hydric condition related to regional variation in rain distribution which determine a high productivity potential, as long as the deficiency of natural fertility is corrected and the vegetative cycle of crops is adapted to the hydric conditions.

Meetings which make possible the interchange of information between soil pedologists and discussion of problems related to these soils are very relevant, since they can contribute for a more adequate utilization of their potential, but it is still necessary to intensify researches regarding mainly soil management aiming at a high productivity and the transference of technologies developed.

In spite of the ardous work held to overcome the difficulties imposed by the nature of an event of such magnitude, we are highly gratified by the success obtained and with great satisfaction present this publication.

IDARÊ A. GOMES
Serviço Nacional de Levantamento e Conservação de Solos (SNLCS)
Empresa Brasileira de Pesquisa Agropecuária (EMBRAPA)

DEDICATION

This publication is dedicated to the memory of Prof. Dr.Ir. J.Bennema (1920-1985), who for many years was a leading and enthusiastic participant in soil survey and classification activities in Brazil.

Jacob Bennema was a native of Holland. He graduated at Wageningen University as an M.Sc. in Tropical Forestry, with soil science as a major subject. After graduation he worked for a ten-year period with the Soil Survey Organization of the Netherlands (Stiboka). Based on his studies on soil development and sea-level changes in Holland he obtained his Ph.D., also at Wageningen University, in 1954.

From 1956 until 1964, as a Soil Survey Expert of the Food and Agricultural Organization of the United Nations (FAO), he was assigned to the Government of Brazil in advancing soil survey and developing improved methods of land classification for agricultural purpose. That undertaking was effected through actual field work, serving as an advisor to the then Soil Survey Division ("Comissão de Solos"), renamed in 1975 into "Serviço Nacional de Levantamento e Conservação de Solos" (SNLCS) of the Brazilian Agricultural Research Corporation (EMBRAPA), attached to the Ministry of Agriculture.

Dr. Bennema worked very closely with leading Brazilian soil scientists, building up a soil survey staff needed in the country, advancing knowledge on the soils, promoting a beneficial interchange with national institutions, and developing contacts with foreign countries.

During those years of direct association with the Brazilian Soil Survey Staff, he was a most active partaker in soil correlation, travelling widely in all regions of Brazil on soil expeditions and regular reconnaissance soil surveys. This resulted in a "system of soil classification for use in Brazilian soil surveys". The structure of that system and the criteria employed were not conceived beforehand or simply copied from North-American or European systems. Instead, they were developed gradually, on the basis of the geography and properties of the Brazilian soils as they became known through the painstaking field and laboratory work of SNLCS, of universities and of research stations in may parts of the country - with its large variations in climatic, lithologic and geomorphologic conditions.

Bennema was a prime promotor of this practical and authentically national approach to a classification system in support of soil mapping legends, while keeping contact with soil geographers and soil classification specialists in other parts of the world. He also led the production of a system of interpretative classification of agricultural land suitability, arising from the need of transforming the soil survey information into agricultural use directives, according to the reality prevailing in the country.

After 1966 Bennema returned to Holland as professor in tropical soil science. He maintained however close contact with his

erstwhile Brazilian colleagues through correspondence and occasional visits until his untimely death. His dedication to the knowledge of the soils in his second patria and to the field training of a Brazilian cadre of soil scientists was acknowledge through his election as Honorary Member of the Brazilian Society of Soil Science in 1973.

WIM SOMBROEK
Secretary-General
International
Society of Soil
Science

PREFACE

Since 1975 the Soil Conservation Service of the U.S. Department of Agriculture has been engaged in a concerted effort to adapt Soil Taxonomy, a basic system of soil classification for making and interpreting soil survey, to the edaphic conditions of the lower latitudes. To this effect, it established eight international committees for the purpose of critically evaluating the definitions of respective taxa and the selection of differentiating criteria.

In order to provide fora for discussion of the issues studied by the various committees and to allow examination of key examples of the soils under consideration in the field, the University of Puerto Rico initiated and helped organize a series of international soil classification workshops. In close cooperation with host country institutions, workshops were held in Brazil in 1977, Malaysia and Thailand in 1978, Syria and Lebanon in 1980, in Rwanda in 1981, in the Sudan in 1982, in Chile and Ecuador in 1984, and in the Philipines also in 1984. These workshops dealt with the taxonomy and management of Alfisols and Ultisols with low activity clays, Oxisols, Aridisols, high-altitude soils of the tropics, vertisols and soils derived from volcanic Andisols, and wetland soils, 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 U.S. Department of Agriculture Soil Conservation Service, the Soil Managenment Support Services (SMSS), provided most of the funds, in part through grants to the University of Puerto Rico, which continues to be centrally involved in the organization of the workshops.

The VIII International Soil Classification Workshop held in Brazil from 12 to 23 May 1986 thus formed part of a comprehensive transnational effort to improve the classification of the soils of the tropics and subtropics. It addressed the taxonomy, properties and utilization of Oxisols in general, and the mandate of the International Committee on the Classification of Oxisols (ICOMOX) in particular.

The second Brazil workshop was co-sponsored by the Serviço Nacional de Levantamento e Conservação de Solos (SNLCS) of the Empresa Brasileira de Pesquisa Agropecuária (EMBRAPA), the Soil Management Support Services of the Soil Conservation Service (SCS), U.S. Department of Agriculture, the University of Puerto Rico (UPR), and the U.S. Agency for International Development. Major funding for the workshop was provided by AID and EMBRAPA.

The chairman of the Host Organization Committee, Marcelo Camargo of the SNLCS, and the committee members deserve high commendations for the excellent logistic and technical preparation of the workshop. Without their inputs and contributions the promise of a scientifically successful and socially enjoyable workshop could not have been realized. Special credit in this regard must be accorded to Dr. Camargo.

The compilation of the proceedings was a joint effort of the University of Puerto Rico, SNLCS, and SMSS. The staff of the International Benchmark Sites Network for Agrotechnology Transfer (IBSNAT) Project performed the complex task of editing the technical papers with diligence and competence.

Part I of the proceedings includes the technical papers presented at the workshop. Part II provides reference background on the field excursions and includes complete descriptive and analytical data for the study pedons supplied by the SNLCS and the National Soil Survey Laboratory of the USDA Soil Conservation Service.

We consider the proceedings an up-to-date reference publication on the classification and characteristics of Oxisols and their management for various uses.

F.H. BEINROTH
Department of Agronomy and Soils
College of Agricultural Sciences
University of Puerto Rico

H. ESWARAN
Soil Management Support Services
Soil Conservation Service
U.S. Department of Agriculture

PERSPECTIVES AND BACKGROUND

REFINING *SOIL TAXONOMY*

R. W. Arnold[1]

Soil Taxonomy: A Classification Scheme

An important function of a classification is to organize the available information in such a way that the properties of the objects and the relationships among those can be perceived or recalled readily. A classification reflects our knowledge and concepts at a specific time and is a capsule of our understanding of the complexities of the population (Cline 1963).

Soil Taxonomy was developed to serve soil surveys, which are made for practical uses (Soil Survey Staff 1975). The taxonomic classes, however, do not have to serve directly as technical interpretive units. By reasoning, soil properties can be interpreted as soil qualities and related to behavioral responses for specific uses. In a similar manner, soil properties can be associated with processes of soil formation.

Soil surveys serve many facets of agriculture, engineering, forestry, and recreation commonly to determine land suitabilities. No single set of properties is equally pertinent to different objectives, consequently no set of classes, or basis for grouping, or basis for subdivision can provide homogeneous units for direct application to multiple objective (Smith 1963).

To help make and interpret soil surveys, soil bodies of interest must be large enough and orderly enough to consistently locate and identify soil patterns on maps. The classes in *Soil Taxonomy* must have real counterparts in mappable bodies. This means polypedons are the basic bodies to be classified rather than pedons whose expression of some properties is rather limited. We often forget or overlook the importance of including geographic attributes, such as size and shape, in the criteria of classes. In addition we should take care not to apply criteria independently of the values and variability that exist within natural landscapes.

Because of the way we describe and sample soils, it is difficult to obtain mutually exclusive classes that include geographic attributes of the bodies we want to map and interpret. It is a continuing challenge to pedologists everywhere.

Soils differ throughout the world, thus we need good working concepts of how a soil or group of soils fits into a global spectrum. These relationships are sometimes difficult to achieve because soils are scale-dependent and extend over very limited areas of the earth's surface, consequently there are hundreds of thousands of different kinds of soils. No one can readily comprehend or remember the vast accumulation of soils information that exists; however, soil classification is one way of abstracting such information. The model of soils portrayed by *Soil Taxonomy* is, therefore, a collection of the ideas, concepts, data sets, and interpretations of the world of pedology captured at this time.

Soil Taxonomy was not the product of any one person or even small group of persons. It is a monument to the skills and persistence of pedologists everywhere who share the responsibility for improved understanding of the relationships among the myriad of soils.

The logic and structure of the hierarchy are major strengths of *Soil Taxonomy*, yet the rigid class limits belie the dynamic nature of soils in the field. The efficiency with which accessory characteristics are carried along with the differentiating ones is very powerful indeed. On the other hand, the uncertainty of the correlation of accessory properties with differentiating properties and the rigid class structure of the system limit the precision of statements that can be made for soils as they are observed in the field.

The utility of soil surveys relies on the correctness of mapping and the relevance of interpretations. Accurate mapping depends upon understanding the spatial correlations of soils with recognizable elements of landscapes. The real foundations of a soil survey program are, therefore, the initiative and capacity of its personnel to understand soils. Without such curiosity and comprehension a survey program takes on the guise of technology by technicians rather than science by scientists. *Soil Taxonomy* is a marker of the progress of our science.

Rationale for Change

The immediate objectives of *Soil Taxonomy* are to provide service:

[1]Director, Soil Survey Division, Soil Conservation Service, U.S. Department of Agriculture, Washington, D.C.

- by identifying soil bodies so that we can communicate, interpret, and make applications and
- by organizing soil bodies in a framework designed to reveal understanding of soils as natural bodies (Smith 1963).

The objectives of *Soil Taxonomy* are themselves the reasons for refining the system. There is a continuing opportunity to improve our understanding of soil properties, their development, and effects on behavior. This is possible because of the collection, testing, and evaluation of additional soil information as it becomes available to the pedological community.

Yes, we know more today than we did yesterday; we believe we understand better today than we did yesterday. We can provide a more meaningful identity to some soil bodies today than we could yesterday. Thus, we find improvements in our communications, in our interpretations, in our applications of information, and also in our understanding of the relationships among soil bodies in nature. You are an important part of that collection of individuals who care enough to devote time and energy and brain power to improve, to update, to refine, and to provide future flexibility to pedological thought and understanding.

Soil Taxonomy has the flexibility to add, remove, or modify criteria or classes with each change that may be tried, or adapted, without destroying the overall system. Refinement is a never-ending process. New knowledge obtained through research comes mainly from the perspective of soils portrayed by *Soil Taxonomy* and the concepts and theories it inspires. This new knowledge contributes to the precision of quantified definitions of classes, of soil properties, and of correlations. These quantitative aspects encourage us to adjust our models and theories, our classifications, and our definitions to fit new facts as they are discovered.

Understanding largely consists of explanations; explanations of the unfamiliar in terms of the familiar. Such explanations usually are correlations with the commonplace, often as empirical relationships, thus we come to know the new by extending from the old. New or improved concepts of weathering build upon our current ideas of weathering.

Soil Taxonomy carries with it some stated and some implied rules of operation. The definitions of categories, orders through series, are intended to guide the selection and testing of properties and features used to characterize and classify soils. Soil properties that are thought to reflect major soil-forming processes (orders) and those that are major controls of current processes (suborders) are of great importance in this system. Although the processes of soil formation are influential in the selection of properties, the properties themselves are used to determine the placement of soils into respective classes. Thus, theory guides selection of soil properties that are thought to be significant to soil-forming processes. The applications of quantified definitions and observations are the tests of adequacy of the theories behind our model of soil.

We plan to change *Soil Taxonomy* to accommodate improved understanding and to identify more precisely the soil bodies of interest. It is far easier to change the wording and arrangement of the classification keys which identify soil bodies than it is to adequately test and evaluate the philosophical basis and appropriateness of definitions as criteria are proposed to increase understanding.

Activities to Refine *Soil Taxonomy*

Soil Taxonomy was published in late 1975. After a few years a computer file was set up by the Soil Conservation Service (SCS) to monitor proposals to modify the system. STIPA, the Soil Taxonomy Index for Proposed Amendments, has now been cleaned up to reduce overlap and redundant entries, and to return incomplete proposals to the originators for further action.

In 1979 George Bailey of SCS began a computer retrieval and bibliography of published articles that referred to *Soil Taxonomy*. The volume for 1966-1979 will soon be published by the Commonwealth Agricultural Bureaux. A follow-on edition is planned for the period 1980-1987 or thereabouts.

While studying New Zealand Andisols, Guy Smith commented on many of the decisions that influenced the development of *Soil Taxonomy*. His explanations of diagnostic horizons, features, and selection of criteria were published by the New Zealand Soil Bureau and were reprinted in *Soil Horizons* in the United States. Somewhat later Smith was interviewed by soil scientists in Belgium and at several U.S. locations. Tapes of these discussions have been computerized at Cornell University and, after being reviewed and edited, will be published as background material to help explain part of the rationale of *Soil Taxonomy*.

A symposium describing the impact of *Soil Taxonomy* on soil science was presented at the Soil Science Society of America annual meeting in Los Angeles in 1981 (Kral 1984). The symposium proceedings represent a status report, pointing out some strengths and shortcomings of the system. *Soil Taxonomy* is a good example of quantified soil properties and classes but there are many soils, particularly in the subtropics, which are not adequately described and defined in the system. Other symposia have described classification and use of Vertisols, soils with low activity clays, and micromorphology (Douglas and Thompson 1985).

In the early 1980s scientists from around the world collaborated to write *Pedogenesis and Soil Taxonomy*. Their two-volume publication (Wilding, Smeck, and Hall 1983) describes the concepts and interactions that represent the current model of soils and details the soils that are recognized in each of the ten orders of *Soil Taxonomy*.

In 1976, Frank Moormann, then at the International Institute of Tropical Agriculture, convinced William Johnson, SCS, that Alfisols and Ultisols dominated by low-activity clays should be recognized above the subgroup level of classification. Moormann chaired the first of the international committees that study parts of *Soil Taxonomy* and recommend changes for its refinement. The recommendations of ICOMLAC (International Committee for Low Activity Clays), which include a kandic diagnostic horizon and modification of existing great groups and subgroups in Ultisols and Alfisols, have been approved recently as modifications of the classification system.

Seven other committees are studying aspects of *Soil Taxonomy*, including the definitions and keys for Oxisols, Aridisols, Spodosols, Verisols, and Andisols. In addition, criteria for moisture and temperature regimes of the tropics and the aquic

moisture regime are being evaluated.

The work of these committees is done primarily through an exchange of information in circulars from the chairmen of the international committees. Soil classification workshops, such as this one in Brazil, have been convened to let scientists examine soils, concepts, and definitions together. Useful data bases of lab and field information are accumulating as products of the workshops on classification sponsored by USAID (Agency for International Development) through the Soil Management Support Services (SMSS) program administered by the Soil Conservation Service, USDA (U.S. Department of Agriculture). Reports of numerous activities of SMSS have been aired in the widely distributed *Soil Taxonomy Newsletter*.

Interpretive statements and results of the groupings of *Soil Taxonomy* classes are examined at the International Training Forums cosponsored by SMSS and institutions in the host countries. Sets of data on soils, sites, and land use are being assembled from the 13 forums held to date.

Parts of *Soil Taxonomy* have been translated into Italian, Spanish, Arabic, French, Chinese, and Japanese. The English version has been stored in computer form to facilitate revision and cross-checking for consistency and completeness.

A short version key to *Soil Taxonomy* was prepared by ISRIC (International Soil Reference and Information Center) and fuller versions were published by SMSS and Cornell University in 1983 and 1985. Each version for the keys contains the latest approved changes in definitions and organization of *Soil Taxonomy*.

Formats for keying out soils in *Soil Taxonomy* were prepared by the Soil Bureau in New Zealand. Some of the international committees developed software programs to key out selected soils. Recently, all of the higher categories keys have been computerized under the guidance of S.W. Buol at North Carolina State University.

The official record of refinements to *Soil Taxonomy* is maintained by the Soil Survey Division of the SCS, USDA. SCS has issued seven amendments since the publication of *Soil Taxonomy*. The first two issues covered the early changes proposed mainly by Guy Smith and John McClelland, a former SCS director of soil classification. The emphasis was on diagnostic horizon wording and on correcting typographic errors in the text. Issue number three described the procedures for proposing, documenting, testing, and approving refinements of *Soil Taxonomy*. Issue four revised subgroups, changed several families, and provided the horizon designation changes accepted by the National Cooperative Soil Survey of the United States. Issue five covered more implied subgroups, issue six again spelled out changes mainly related to horizon designations, and issue seven mainly involved refinements of subgroups. The eighth amendment will give the approved changes associated with the addition of a kandic horizon.

Conclusions

As of 1986 there have been about two hundred modifications, corrections, additions, and deletions to *Soil Taxonomy*. Although some of the changes only correct minor word placement, most refinements result in clearer definitions of soil bodies, or in better expressed concepts of soil properties and their development. These refinements reflect the interest, the dedication, and the willingness of hundreds of scientists in many organizations to share the responsibility of maintaining *Soil Taxonomy* as a model of soil that we can be proud of.

We know that models are abstractions of reality. We know that models distill the essence of our knowledge and portray in an imperfect way those things we want to portray. But models also permit us to share—to share in a rich and noble past, to share in the urgency of today, and to share in a pathway that leads to new knowledge and improved understanding.

For more than a hundred years soil science has dealt with soils as natural individual bodies. The current paradigm attempts to blend theories of genesis and the rigidity of classification with the field observed variability. Theories and concepts of soils as members of continua with fuzzy set properties and variable boundary conditions may guide our way on new pathways. We are very possibly on a bridge between paradigms in pedology. I can think of no better rationale for continuing our activities in refining *Soil Taxonomy*.

References

Beinroth, F.H., G. Uehara, J.A. Silva, R.W. Arnold, and F.B. Cady. 1980. Agrotechnology transfer in the tropics based on *Soil Taxonomy*. *Adv. Agron.* 33:303-339.

Cline, M.G. 1963. Logic of the new system of soil classification. *Soil Sci.* 96:17-22.

_____. 1980. Experience with Soil Taxonomy of the United States. *Adv. Agron.* 33:193-226.

Douglas, L.A., and M.L. Thompson. 1985. Soil micromorphology and soil classification. SSSA Special Publ. no. 15, SSSA, Madison, WI.

Kral, David (ed.). 1984. Soil taxonomy: Achievements and challenges. SSSA Special Publ. no. 14. SSSA, Madison, WI.

Smith, G.D. 1963. Objectives and basic assumptions of the new soil classification system. *Soil Sci.* 96:6-16.

Soil Survey Staff, SCS, USDA. 1975. Soil taxonomy: A basic system of soil classification for making and interpreting soil surveys. USDA Agric. Handb., no. 436. U.S. Govt. Printing Office, Washington, D.C.

Wilding, L.P., N.E. Smeck, and G.H. Hall (eds.). 1983. Pedogenesis and soil taxonomy. I. Concepts and interactions. II. The soil orders. Elsevier, Amsterdam.

IMPLICATIONS OF THE ICOMOX PROPOSAL

IMPLICATIONS OF THE ICOMOX PROPOSAL RELATIVE TO THE CLASSIFICATION OF ANDISOLS

R.L. Parfitt,[1] A.E. Hewitt,[2] and M.L. Leamy[3]

Abstract

Following a brief review of the Andisol definition, the distinction between Andisols and Oxisols is discussed. The boundary depends in many cases upon acid oxalate extractable Al or the thickness of andic soil material. Acid oxalate extractable Fe is proposed as an additional limit for Andisols, intended for the recognition of ferrihydritic soils. Intergrading subgroups are discussed with examples including oxic and thapto-oxic subgroups of Andisols, and andic subgroups of Oxisols. One example demonstrates that kandic horizons with significant weatherable minerals occur in the Andisols. Allic great groups of Andisols are described. There is evidence that KCl Al may be overestimated in some soils. Allic family mineralogy classes of Oxisols are commented on. ICOMAND (International Committee on Andisols) proposes to avoid clay measurements where possible as criteria in the Andisols. The formamide test is advocated as a quick and simple means of measuring total halloysite content for the family mineralogy class.

The ICOMOX (International Committee on Oxisols) proposal has implications for the definition of the proposed new order of Andisols, and for intergrading subgroups between the Oxisols and Andisols. The Oxisol-to-Andisol boundary occurs in two ways: first, where younger volcanic ash overlies an older soil with an oxic horizon, and second, where weathering of volcanic ejecta has reached the stage that the soil has some Oxisol characteristics. In this paper we present pedons that illustrate these boundary conditions and explain the relevant differentia at order and subgroup levels. Additional comments are made on the use of Al toxicity, clay criteria, and the halloysitic family mineralogy class.

Reference in this paper to the current Andisol proposal means the proposal outlined in ICOMAND circular letters 6 and 7. Circular letter 8 is at present in preparation.

[1]Soil Scientist, N.Z. Soil Bureau, DSIR, Lower Hutt, New Zealand.
[2]Soil Scientist, N.Z. Soil Bureau, DSIR, Dunedin, New Zealand.
[3]Director, N.Z. Soil Bureau, DSIR, Lower Hutt, New Zealand.

Brief Review of the Andisols

Central Concept

It is the intention of the Andisol order to group together soils in volcanic ejecta which either have a matrix dominated by glass with some evidence of weathering or an exchange complex dominated by the short-range order materials: allophane, imogolite, ferrihydrite, or Al-humus complexes.

Andisols have several important properties in common. The exchange complex has low permanent charge and high pH-dependent charge. Aluminum toxicity is rare. Phosphate fixation and water retention are high relative to most other soils of comparable texture. Bulk density is low and percentage carbon tends to be high relative to other mineral soils. Saturated hydraulic conductivity and porosity are high. Andisols pose unique engineering problems particularly because of the fragility of pumice, very high plastic and liquid limits, and high sensitivity.

Distribution

Andisols occur primarily in the udic moisture regime but may occur in any other moisture regime or any temperature regime. They are widely distributed, associated with areas of Holocene or late Pleistocene volcanism. They are associated with Entisols on younger volcanic parent materials and with Spodosols, Mollisols, Ultisols, or Oxisols on volcanic parent materials with more advanced soil development.

Definition

Essentially, Andisols are mineral soils which have *andic soil properties* throughout a continuous thickness of 35 cm or more, beginning at or within 25 cm of the surface. They do not have an argillic, natric, spodic, or oxic horizon unless it is a buried genetic horizon with its upper boundary at a depth of 50 cm[4] or more.

[4]There is a suggesion that this limit be reduced to 35 cm.

Andic soil material, as defined in circular letter 6 (April 1984), must meet one or more of the following three requirements:

1. a. Acid oxalate extractable Al(Alo) ≥ 2 percent,
   b. Bulk density < 0.9 g/cm³, and
   c. Phosphate retention > 85 percent,

or 2. a. Alo ≥ 0.4 percent, and
   b. (1)sand > 30 percent by weight of the fine earth and glass >30 percent by weight of the sand, or
   (2)volcani-clastic material coarser than 2 mm is > 60 percent by volume of the whole soil,

or 3. a. Alo between 0.4 and 2 percent,
   b. sand > 30 percent by weight of the fine earth,
   c. enough glass in the sand according to a graphical sliding scale.

Requirement 1 covers ash soils dominated by short-range order compounds, requirement 2 covers pumice soils with a matrix dominated by glass, and requirement 3 covers soils intergrading between 1 and 2.

Boundary of Oxisol to Andisols

pH in NaF

Initially, pH in NaF was suggested as a measurement which could be used to separate Andisols and Oxisols. This has now been dropped from the Andisol definition, and some explanation is appropriate.

It was thought that Oxisols would have lower pH(NaF) values (less than 9.4) than Andisols. However, this limit proved to be a poor discriminant as some oxic horizons have values as high as 9.9. Furthermore, a number of problems with the pH(NaF) measurement have emerged. First, the purity of the NaF reagent is often suspect; second, there has been poor agreement in pH(NaF) values between laboratories; third, there is poor correlation between pH(NaF) values and acid-oxalate extractable Al values; and fourth, some gibbsites have been found to react to NaF. Acid oxalate Al is the discriminant now preferred by ICOMAND.

Acid Oxalate Al (Alo)

Some Oxisols have P retention > 85 percent bulk density < 0.9 and so meet some of the requirements of Andisols. In such soils Alo is the discriminant with a value of 2 percent or more required for Andisols.

An example is the Pamfuetle soil (Table 1A). The data indicate that it is not an Andisol because the Alo values are too low throughout any 35 cm thickness.

The significance of the Alo measurement is that it provides an estimate of the amount of allophane or Al-humus complexes which are present, because they are readily soluble in acid-oxalate. On the other hand, gibbsite, goethite, hematite, and kaolin (usually present in Oxisols) are relatively insoluble in acid oxalate.

Use of Acid Oxalate Fe (Feo)

Some Kenyan soils adjacent to the Rift Valley (Wielemaker and Wakatsuki 1984) have the morphology of Andisols, but they do not meet the Alo requirements. The parent material is peralkaline. Very little allophane is present in these soils, but the dominant short-range order mineral is ferrihydrite ($Fe_2O_3$²FeOOH.2.6 H_20). Ferrihydrite can be thought of as the iron analogue of allophane, but the two minerals are not entirely similar. Nevertheless, ferrihydrite does seem to confer andic properties on soils and ferrihydrite must be considered in the Andisol proposal. Ferrihydrite dissolves in acid oxalate and Feo can be used in the criteria for andic soil properties. ICOMAND is suggesting that part 1a for andic soil properties (Alo ≥ 2 percent) be replaced by Alo + 1/2 Feo ≥ 2.5 percent.

This criterion will place the Kenyan soils as well as Hawaiian soils in ustic moisture regimes with the Andisols. From available data, it seems that Feo values for oxic and kandic horizons are low (<0.7 percent), and the use of Feo in the Andisol proposal should not affect the classification of Oxisols.

ECEC

Some strongly leached allophanic Andisols can have very low ECEC values in the B horizons. The Patua soil from New Zealand is an example, where ECEC is 0.6 me/100 g soil with 30 percent clay. This horizon meets the requirements of a kandic horizon, but the presence of weatherable minerals, and priority of the Andisols in the key to orders, ensures that it is assigned to the Andisols.

Intergrading Subgroups

Andic Subgroups of Oxisols

In the ICOMOX proposal, andic subgroups must have

> an 18 cm or thicker layer in the upper 75 cm with a bulk density less than 1 g/cm³ and either an acid oxalate Al content more than 1.0% or 4 m KOH extractable Al of 0.75% or more.

In ICOMAND circular letter 8, presently being prepared, it is proposed that the 4 m KOH extractable Al criterion be abandoned. Also it is proposed that the criterion Alo + 1/2 Feo ≥ 1.3 be added to include soils with significant ferrihydrite.

Examples of andic subgroups of Oxisols are included in Table 1. The Los Ulmos pedon (Chile) has 66 cm of low bulk density soil material overlying a kandic horizon. It fails Andisols, however, because the Alo value is only 1.2 percent. It is assigned to the Andic Hapludoxs.

The Pamfuetle pedon (Table 1) from Cameroon has been an important example used in fixing the current Oxisol, Andisol boundary. It was determined that the soil better fitted the Oxisol rather than the Andisol concept. Andisols should have an exchange complex dominated by short-range order material. The Pamfuetle has, in fact, the exchange complex dominated by small crystalline Fe oxides (A. Herbillon, pers. comm.). By the current definition the Pamfuetle fails Andisols because Alo values exceed 2 percent through a thickness of only 15 cm. It, however, is assigned to the Andic Akrudoxs.

The Kenyan pedon (Table 1) has a layer in the topsoil which fails to meet the requirements of the Andisols because it is too thin, the bulk density is too high, and Alo is too low. It, however, meets the requirements of the Andic Hapludoxs.

In the Pamfuetle, Kenyan, and Los Ulmos pedons the andic material occurs in the surface horizons, overlying Oxisol soil

Table 1. Pedons Illustrating the Oxisol, Andisol Boundary

Horizon	Depth (cm)	Phosphate retention (%)	Bulk density (g/cm^2)	Alo (%)	Sio (%)	Feo (%)
1A. Pamfuetle Pedon (Cameroon)						
A11[a]	0-10	97	0.74	1.7	0.20	0.5
A12[a]	10-26	96	0.75	2.2	0.24	0.5
IIB1	26-40	91	0.85	0.8	0.07	0.5
IIB21	40-81	91	0.87	0.8	0.07	0.5
IIB22	81-140	90		0.37	0.03	0.5
1B. Kenyan Pedon (Wielemaker and Wakatsuki 1984, profile 6)						
A[a]	0-25		0.9	1.2		4.0
B	25+		1.1	1.3		4.6
1C. Los Ulmos pedon (Chile)						
A[a]	0-66	94	0.9	1.2	0.20	0.9
B	66-200	91	1.0	0.6	0.20	0.7
1D. Patumahoe pedon (New Zealand)						
Ap	0-26	65	1.0[b]	0.4	0.03	0.6
Bt	26-58	89	0.9[b]	0.7	0.07	0.3
Bt+Bg	58-134	99	0.8[b]	3.8	1.16	0.7

[a]Horizon with andic soil material recogized at subgroup level.
[b]These figures require replication.

material. However, the Patumahoe pedon (New Zealand) is curious in that a kandic horizon overlies andic soil material. The soil is in layered tephra and tephric loesses which have undergone varying amounts of preweathering. The soil is marginal to Oxisols, as would be expected in a landscape younger than 100,000 years. It is assigned to the Andic Kurudoxs.

Oxic Subgroups of Andisols

In the original Andisol proposal of 1978, provision was made for an oxic subgroup of the now abandoned Haplotropands. In the current ICOMAND proposal oxic subgroups must have:

1. > 30 percent 15 bar water content of air-dried soil;
2. sum of bases + KCl extractable Al > 2.5 me percent per 100 g fine earth;
3. less than 10 percent weatherable minerals in the 0.2 to 0.02 mm fraction.

It is not certain yet in which great groups oxic subgroups will be used, but the Haplotropands will now mostly be included in the Hapludands.

Provision was also made in the 1978 Andisol proposal for "acric" subgroups. Acric subgroups are defined similarly to the Akric great groups of the Oxisols. The status of the acric subgroup in relation to oxic subgroups needs to be critically evaluated.

Thapto-oxic Subgroups of Andisols

Andisols on the flanks of some volcanoes grade with distance from the volcano into Oxisols, as the depth of andic soil material over an oxic horizon thins. The Andisol definition allows for the presence of an oxic horizon if it is a "buried genetic horizon having its upper boundary at a depth of 50 cm or more." Where volcanic ash accumulates in small increments over a long period of time, there are obvious problems in determining whether or not an oxic horizon might be considered a buried genetic horizon. It is better, therefore, to rule that in all cases where oxic horizons are overlain by andic soil material, the oxic horizons are considered to be buried. Given this understanding, in a continuum of progressively thinning overburden of andic soil material overlying an oxic horizon, the following soils will occur.

Thickness of andic soil material overburden (cm)	Subgroups	Order
0- 17	"Typic"	Oxisol
18 - 49	Andic	Oxisol
50 - 99	Thapto-oxic	Andisol
100+	"Typic"	Andisol

ACRIC PROPERTIES AND THEIR SIGNIFICANCE TO SOIL CLASSIFICATION[1]

G. Uehara[2]

The word *acric* comes from the Greek *akros* which means "at the end." In *Soil Taxonomy* (1975), acric is used as a prefix to convey an image of a soil near the end of its development cycle, and, therefore, a soil of extreme weathering. Mohr, a Dutch pedologist working in Indonesia during the colonial period, categorized the soils he encountered there as being either juvenile, mature, or senile. Mohr's senile soils are clearly the analogues of *Soil Taxonomy's* acric soils. In *Soil Taxonomy*, acric soil materials must, by definition, have an effective cation exchange capacity (ECEC) of less than 1.5 cmole/kg in the clay fraction.

What is the process that leads to this state, and what is the significance of acric conditions to soil behavior and performance and, therefore, to soil classification? The purpose of this paper is to answer these questions so that readers may understand the weathering process that leads to the acric state and use this understanding to classify acric soils in ways that permit the user of the classification system to predict and control the behavior and performance of acric and related soils.

Acric Soil Formation

The single most important process in acric soil formation is desilication and the resultant accumulation of an insoluble sesquioxide residue. This does not mean, however, that acric soils are low in silica. Silica in the form of quartz is frequently the most abundant oxide in acric soils. An acric soil, therefore, may have a high total silica content but requires low silica in the clay fraction. A soil rich in quartz in the silt and sand fractions can have an ECEC of less than 1.5 cmole/kg in the clay fraction. Thus, acric soil formation is essentially a process that results in a clay fraction that has a low silica-sesquioxide (SiO_2/R_2O_3) ratio. The two most important and common sesquioxides in acric clays are the oxides and hydrous oxides of iron and aluminum. The oxides of titanium, manganese, chromium, zinc, nickel, and cobalt accumulate to a lesser degree only because they are not as abundant in the earth's crust as aluminum and iron. After prolonged weathering under warm and humid conditions, what remains on the landscape is an insoluble residue of highly weathered materials we now call acric.

Frequency of Occurrence

The occurrence of acric soil materials increases with increasing proximity to the equator. In the higher latitudes, low temperatures and the rejuvenating action of pleistocene glaciation diminishes the opportunity of a soil to attain the acric state. Acric soils are rare even in the tropics and are found mostly on the ancient landscapes of Africa, Asia, Australia, and South America. They also occur on younger landscapes consisting of easily weatherable, basic rocks. In view of their rarity, one can rightfully ask about the need to give acric materials so much attention. The significance of acric materials lies not in their abundance but in the position they hold taxonomically.

The Four Taxonomic Benchmarks

The acric material holds one of four key taxonomic positions. The other three positions are held by the histic, andic, and vertic materials. These four materials can be considered end-members of a three dimensional phase diagram represented by a tetrahedron as shown in Figure 1. Soils dominated by one of these materials and whose behavior and performance are largely influenced by it, fall in clearly defined taxa at the order level. The acric, andic, histic, and vertic materials correspond respectively to the soil orders Oxisol, Andisol, Histosol, and Vertisol. If only the inorganic mineral soils are considered (see Fig. 2) one can readily see how the other soil orders fit in the scheme. Three soil orders, however, do not fit in the tetrahedron. They are the Aridisols, Entisols, and Alfisols. The Aridisols do not fit because they are classified on the basis of aridity, and the Entisols do not fit because they are classified on the basis of their lack of pedological organization. The third order, Alfisol, is a different matter. As

[1] Contribution of the IBSNAT Project (Contract No. AID/DAN 4054-C-00-2071-00).

[2] Professor of Soil Science, Department of Agronomy and Soil Science, University of Hawaii, Honolulu, HI 96822.

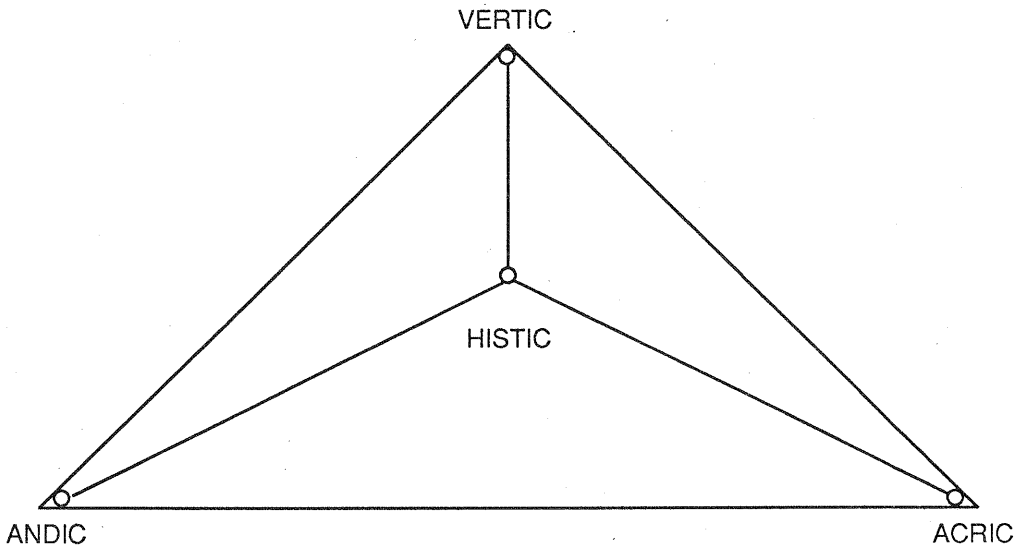


Fig. 1. The acric, andic, histic, and vertic soil materials are used as benchmarks for soil classification.

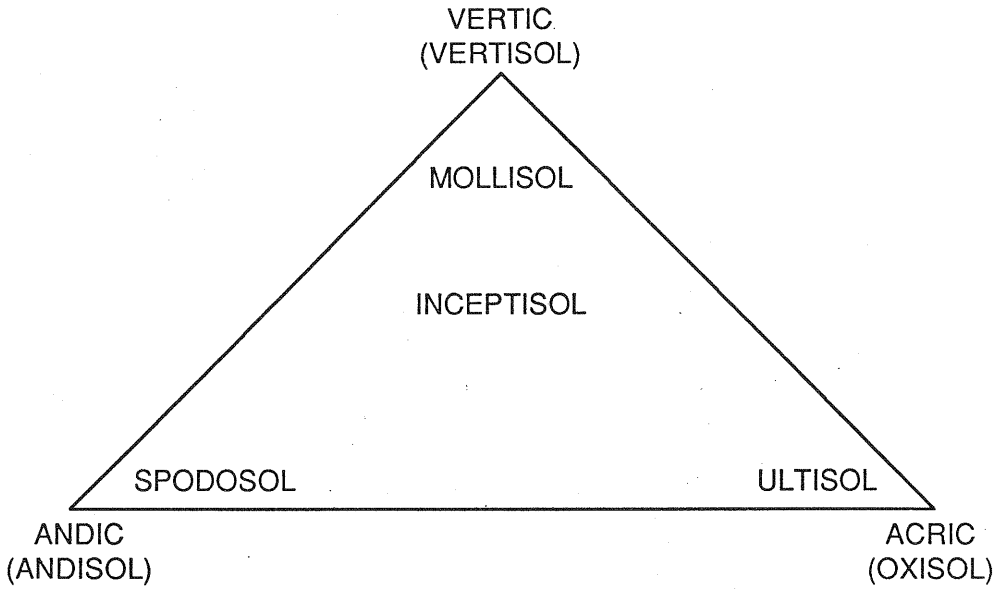


Fig. 2. Compositional relationship among soil orders (Uehara and Gillman 1981).

it now stands, Alfisols (and to a large degree, Ultisols) can range from near the vertic to as far as the acric in behavior and classification. This may indicate a flaw in the way Alfisols and Ultisols are now classified. I will return to this point later.

The Chemistry of Acric Materials

The feature that renders acric materials unique is their variable surface charge characteristic and their low ECEC. There are many variable charge soils but only a few of them are acric. This statement can be explained by the equation that describes the surface charge characteristics of variable charge materials. The equation is (Uehara and Gillman 1981):

$$\sigma_v = \left(\frac{2C\varepsilon RT}{\pi}\right)^{1/2} \sinh z(1.15)(\text{pHo} - \text{pH}), \quad (1)$$

where:

σ_v = surface charge density
C = electrolyte concentration
ε = dielectric constant
R = gas constant
T = absolute temperature
z = counter ion valence
pHo = zero point of charge

Acric soil materials are variable charge clays for which the quantity (pHo - pH) is near zero or positive. We can visualize this more readily if the relationship between ECEC and equation 1 is written in full. The relationship is:

$$\text{ECEC} = S\sigma_v \quad (2)$$

$$\text{ECEC} = S \left(\frac{2C\,\varepsilon RT}{\pi}\right) \sinh z(1.15)(\text{pHo} - \text{pH}) \quad (3)$$

where: ECEC = effective cation exchange capacity
S = specific surface.

Note that in equation 3, ECEC decreases as (pHo - pH) approaches zero. In fact, the soil material is a net cation exchanger only when (pHo - pH) is negative, that is, pH is greater than pHo. Most acric materials are not cation exchangers but anion exchangers, that is, the soil pH is below pHo, and the net charge on the clay surface is positive. For this reason the Typic subgroups of acric Oxisols by definition require a positive delta pH, that is, the pH measured in 1N KCl is higher than the pH measured in water. A net positively charged acric material can still be a cation exchanger because σ_v refers not to absolute charge, but to net charge. This means that even when an acric material is an anion exchanger (pHo > pH), some cations can be adsorbed. However, when pHo > pH, the anion exchange capacity is higher than the cation exchange capacity.

Equation 3 also tells us that even when pHo ≥ pH, the ECEC can be made large (larger than 1.5 cmole/kg) simply by increasing the electrolyte concentration in the soil solution. This tells us that the acric state requires a soil in which pH is near or below pHo and a soil solution very low in electrolyte concentration. Acric soils are therefore highly leached soils.

Another interesting feature of acric materials is that the more they are leached the higher their pHs become. This occurs because leaching removes silica (desilication) and results in a lower silica-sesquioxide ratio. Soil scientists have known for more than 50 years that pHo, sometimes known as the isoelectric point, increases as the silica-sesquioxide ratio decreases. In fact, the pHo of pure iron and aluminum oxide is between 8 and 9. In variable charge materials, solution pH tends to follow pHo. Mattson (1932) called this phenomenon isoelectric weathering. For this reason acric soils, rich in sesquioxide, highly leached, and low in ECEC, have pHs, measured in water, of 6.0 or more. More commonly, the pH in water is low in the surface horizon and higher in the subsoil, but the increase in pH with depth is generally associated with a decrease in bases.

In highly leached acric soils, soil pH increases with depth when pHo increases with depth. The pHo of acric soils is largely controlled by organic matter and is inversely related to it. A soil that clearly illustrates the above points is the Nipe series of Puerto Rico and Cuba (see Table 1). In this soil pHo and pH increase and bases and carbon decrease with depth.

The Zero Point of Charge and Soil pH

As illustrated in Table 1, soil pH of acric materials is largely controlled by the position of the zero point of charge of pHo, and pHo is in turn controlled by the silica-sesquioxide ratio and the organic matter content. In the Nipe soil, the silica-sesquioxide ratio is nearly the same throughout the first two meters and pHo is largely determined by organic carbon.

Organic matter has a zero point of charge near pH 2.0. In the Nipe soils and most soils in general, a small amount of organic matter goes a long way toward lowering the pHo of sesquioxide because the organic matter coats the oxide particles. As more and more organic matter is added, the materials in that horizon take on the characteristic of organic matter.

The principle of isoelectric weathering applies to all variable charge soil materials. An organic soil or Histosol with a low isoelectric point or pHo will, upon prolonged leaching, approach the pH of its isoelectric point. This is why organic soils tend to be acid. On the other hand, high oxide, acric soils with high isoelectric points tend toward higher pH. We see this in the high pH of the Nipe subsoil.

By the same token, silica and quartz, like organic matter, have low isoelectric points. A highly leached quartzitic soil will be acid for the same reason that a highly leached organic soil is acid.

Were it not for organic matter, the pH of the surface horizons of our most highly leached acric soils would be near neutral. The fact that they are not neutral can be attributed to the lowering of the material's isoelectric point by organic matter. In the final analysis, the chemistry of acric soils is controlled not only by its silica-sesquioxide ratio, but by the carbon-sesquioxide ratio as well.

Table 1. Selected Chemical Data of the Nipe series, a Typic Acrorthox

Depth (cm)	Clay (%)	Carbon (%)	Bases (me/100g)	pH			
				H_2O	1N KCl	pH	pHo[a]
0-28	56	6.0	1.4	5.1	4.3	-0.8	3.5
28-46	58	2.0	0.9	5.0	4.4	-0.6	3.8
46-71	60	1.3	trace	5.0	4.7	-0.3	4.4
71-97	56	0.9	trace	5.2	5.7	+0.5	6.2
97-122	60	0.7	trace	5.5	6.1	+0.6	6.7
122-157	54	0.6	trace	5.7	6.4	+0.7	7.1
157-178	38	0.2	trace	5.8	6.7	+0.9	7.6

[a] Computed from equation $pHo = 2pH_{KCl} - pH_{H_2O} = pH_{KCl} + \Delta pH$.
Source: Soil Survey Staff 1967.

Significance to Soil Classification

Acric soils are important only insofar as they help us to understand the behavior and performance of related variable charge soils. In this regard it is interesting to note that of the four benchmark soil materials, namely the acric, andic, histic, and vertic, only the last is not of the variable charge type. A great deal of what is learned about acric materials can therefore be applied to histic and andic materials.

There are two parameters which can be used to separate the three variable charge materials. These parameters are carbon content and specific surface. The carbon content separates histic from andic and acric materials, and specific surface separates acric from andic materials. Acric soil materials are therefore variable charge, inorganic materials of low specific surface. The difference between acric and andic materials can be visualized by examining equation 2:

$$ECEC = S\sigma_v.$$

In acric and some andic materials, ECEC is low because σ_v is near zero. An example of an andic material with this feature is the Hydrandepts of Hawaii. These Hydrandepts have positive ΔpHs, low ECECs, and pHs near 6.0. They differ from acric soils in their high 1.5 MPa (15 bar) water contents. This difference is due to the high specific surface of allophane and imogolite in andic materials and the low specific surface of oxides and kaolin minerals in acric materials.

Andic and acric materials cannot be distinguished on the basis of Equation 1. In order to separate them, equation 2 or 3, which contain specific surface in the ECEC equation, must be invoked.

There is one intrinsic feature that separates acric from andic, histic, or vertic materials. This feature is the low activity of acric materials. The low activity of acric clays is associated with variable charge materials of low specific surface and low silica-sesquioxide ratio to produce a zero point of charge greater than 4.0.

Materials of this kind correspond to those defined for the oxic horizon of *Soil Taxonomy*. The fact that materials with acric characteristics can spill over into the Ultisol and Alfisol soil orders is the cause of some of the taxonomic problems we face today.

The intent of *Soil Taxonomy* was to keep acric soil materials in one order. Insufficient knowledge during the early stages of the development of *Soil Taxonomy* resulted in a system that now allows acric and oxic materials to occur in other orders. The trend today is to rectify this situation by making certain that acric and its related oxic materials are returned to the Oxisol order where they properly belong.

References

Mattson, S. 1932. The laws of soil colloidal behavior: IX. Amphoteric reactions and isoelectric weathering. *Soil Sci.* 32:209-240.

Soil Survey Staff, SCS, USDA. 1975. Soil taxonomy: A basic system of soil classification for making and interpreting soil surveys. USDA Agric. Handb. no. 436. U.S. Govt. Printing Office, Washington, D.C.

____. 1967. Soil survey investigations report no. 12. Soil survey laboratory data and descriptions for some soils of Puerto Rico and the Virgin Islands. SCS, USDA in cooperation with Puerto Rico Agric. Exper. Sta.

Uehara, G., and G.P. Gillman. 1981. The mineralogy, chemistry and physics of variable charge clays. West View Press, Boulder, CO.

CONSTRAINTS TO THE ANALYTICAL CHARACTERIZATION OF OXISOLS[1]

C.S. Holzhey[2] and J.M. Kimble[3]

Abstract

Characterization of an Oxisol, like that of any other soil is a careful collection of physiographic, landscape, site, morphological, and analytical data. Although both field and laboratory aspects are necessary, only laboratory aspects are discussed in this paper.

Oxisol characterization involves measurements to supplement field information in determining their nature and geneses. From these observations and measurements one can predict where similar soils will be found, and what dynamic processes may exist that would affect their use. Measurements that best differentiate the soil for classification purposes, and those that help with statements about management of the land, are also included.

Data for some key properties of Oxisols are very method-dependent. A procedure for measuring a property such as cation exchange capacity may serve one of these purposes well without serving the others. Hence, it is sometimes necessary to either measure the property by more than one procedure or to have a default procedure for estimating the property.

For Oxisols a maximal measured clay is better correlated to several other properties than a measured clay determined by a gentler treatment. However, a procedure that yields maximal clay in Oxisols does not do so in all soils. For taxonomic purposes this constraint can be overcome by a protocol to choose the method, or to use a default clay based upon water retention. The protocol and the rationale upon which the protocol is based must function independently of the classification process because the choice of an analytical procedure must precede classification of the soil.

Besides rationale or purpose, it is important to consider feasible levels of accuracy and precision that can be attained in Oxisols. Cation exchange properties and particle-size distribution are currently used heavily in Oxisol criteria for classification. There is probably less constraint to accuracy and precision with some other physical analyses.

The characterization of a soil is a careful field and laboratory process which involves collection of information about physiography, site characteristics, pedon morphology, properties measured in the field, plus laboratory analysis. This paper addresses constraints in the laboratory.

[1] Contribution of Soil Management Support Services (SMSS) and National Soil Survey Laboratory (NSSL, USDA, SCS), Lincoln, Nebraska.

[2] Head, NSSL.

[3] Research Soil Scientist, SMSS, NSSL.

Characterization in this context is the collection of data to study and document the nature of a soil and the magnitudes of key properties. It is done to make genetic inferences, to classify the soil, and to make practical statements about soil performance. The purpose is distinctly different from that of fertility or engineering tests which are tied more to a place and a time or to a place and a condition. Although the purpose is different, some analyses are the same, and the rationales at times can become tangled. Some examples of rationale and constraints related to Oxisols are discussed, with some suggestions for the future.

Rationale

The rationale centers on procedures that are of most use:

1. to define the nature of the soil;
2. to infer processes that have influenced the soil;
3. to make desired taxonomic groupings;
4. to measure magnitudes of properties with as little change from field condition as possible; and
5. to measure properties that correlate well with those that are important to predict, and with those that can be sensed in the field.

There are constraints to meeting all of these objectives. First, there are few analytical methods that explore both the nature of a material and the condition or status of a property. Second, the best method for one kind of soil is not the best for all others, yet data bases and taxonomies are difficult to manage if procedures differ from soil to soil. In soil surveys, the first requirement is usually to help classify the soil, or to help calibrate a field estimate. Again, these do not necessarily help to meet all the other objectives. For example, the extractable acidity required in some definitions of *Soil Taxonomy* (Soil Survey Staff 1975) infers more about the nature of the material than about the acidity in the field. The base saturation values to differentiate orders and great groups do not necessarily represent base saturation in the field, but they serve very well to differentiate certain kinds of soils. By contrast, base saturation values based upon effective cation exchange capacity (ECEC) are closer to the field conditions, but may be so influenced by small differences in local conditions that they are poor taxonomic criteria.

Another example is particle size distribution analysis (PSDA). According to item 4, in the rationale above, it is very important to perform the analysis without breaking discrete particles into smaller pieces. However, this clashes with item 5 in those Oxisols having very strong aggregates, as is pointed out in the discussion of PSDA. Therefore, either the rationale has to change to accommodate different PSDA in highly aggregated, low activity soils, or a different criterion has to be chosen for classification.

Precision

Precision is standard deviation or variance in the measurement. Class definitions in *Soil Taxonomy* (Soil Survey Staff 1975) indicate the expected precision by the number of significant digits in the criteria. Criteria involving clay content are written to the whole percent. Those involving organic carbon are written in increments of 0.1 percent. Mineralogy classes involving kaolinite indicate one significant digit by statements that say "more than half" (indicating > 0.5).

Taxonomic criteria that require greater precision increase costs and make the classification more sensitive to small procedural differences. Table 1 shows some measurements of precision at the SCS National Soil Survey Laboratory (NSSL) at a survey level. Levels of precision attainable on a survey basis should be kept in mind when new taxonomic criteria are considered.

Mineralogy

The overall mineralogy of Oxisols is easier to characterize quantitatively than that of most other soil orders. It is mostly a mixture of kaolinite, oxyhydroxides, quartz, and iron oxides. Some Oxisols have appreciable amounts of other oxides, which can usually be identified with survey level precision. Major elements from dissolution analyses usually infer at least the gross mineralogy, and sometimes good quantitative values. Rough quantitative analysis by x-ray diffraction, thermal analysis, and cation exchange analyses are more precise for kaolinite and gibbsite than for most clay minerals.

The iron oxides in Oxisols constrain mineralogical analysis. As coatings on clays and as cementing agents they interfere with x-ray analysis and with optical microscopy. They engulf the clay minerals and coalesce into cemented aggregates which can be difficult to differentiate as either aggregates or discrete grains.

Table 1. NSSL (survey level) Precision Required by *Soil Taxonomy*

	Mean	St. Dev.	C.V.	*Soil Taxonomy*
Clay (%)	55.50	2.10	3.8	1.0%
15-bar (%)	11.60	0.41	3.5	2.5%
Org. C (%)	1.26	0.03	2.4	0.1%
Kaolinite (%)	18.20	2.00	11.0	> 0.5%[a]

[a] Defined as "more than half," meaning one significant digit.

Because of the iron-oxide cementation, and because gibbsite and kaolinite can occur as discrete grains larger than clay size, the definition of a size fraction is consistent only if tied to a specific procedure. A simple pretreatment can change the composition of a size fraction dramatically. For example, a dithionite-citrate pretreatment can release particles into the clay fraction that were not there originally. It also removes weight when it removes iron oxide coatings. This changes the weight and proportions of the original fractions. Also, moderately vigorous physical treatment may fracture grains of gibbsite while leaving iron-oxide-rich aggregates intact. Therefore, where PSDA and mineralogical analysis use different pretreatments, results may not be compatible.

For the reasons expressed above, and because clay minerals in any size fraction influence the soil, clay mineralogy of Oxisols can be assessed more consistently if based upon the whole fine earth instead of the clay fraction. Also mineralogy by grain counts can only be consistent between laboratories if pretreatments are the same.

Particle-size Distribution Analysis (PSDA)

The Oxisols range from those that disperse relatively easily, through those difficult to disperse, to those so strongly cemented that parts are considered ironstone. Those dominated by kaolinite with little gibbsite or iron oxides tend to disperse more easily than those with gibbsite or those cemented by larger than clay size that are easily broken apart. Second, it has little to no net charge over much of the pH range that is useful for dispersing most clay minerals. Climatic influences that affect desiccation and cementation also sometimes affect the ease of dispersion.

Implicit in the preceding paragraph is the problem of defining the stage at which cemented aggregates should be considered as discrete grains or even ironstone. There is the problem of distinguishing a dispersion problem from a case in which gibbsite or kaolinite grains are larger than clay size. Finally there is the operational problem of defining a procedure to disperse the aggregates without breaking the discrete, primary grains. For many Oxisols there is no such procedure.

Table 2 compares some alternative physical agitations. The agitation of a high-speed mixer yields more measured clay than reciprocal shaking of an oxic horizon sample that has the iron-cemented aggregates. This same procedure creates a great deal of measured clay from saprolite (not shown in the table) in which the clay minerals are originally in discrete particles and pseudomorphs of preexisting minerals larger than clay size.

Table 2 also shows measured clay from some samples of this workshop and from a high CEC, high Ca soil from the midwestern United States. The $(NaPO_3)_6$ is prepared following the SCS procedure (USDA 1984), and the NaOH is prepared in accord with an SNLCS method (EMBRAPA 1979). The (NaPO3)6 disperses the latter better than NaOH because it ties up Ca from solution. The NaOH disperses the Oxisol samples better because it is adjusted to a higher pH and there is little Ca. Hence, the best dispersant for Oxisols as a group may not be the best for soils having large CEC and Ca as dominant exchangeable cation.

Table 2. Some Dispersion Comparisons

	<——Clay %——>	
	$(NaPO_3)_6$	NaOH
Brazil oxic horizon		
(reciprocal shaker)	20.3	41.2
(high-speed mixer)	27.7	79.8
U.S.A mollic epipedon		
(reciprocal shaker)	19.6	9.6

Table 3. Correlations among Some Properties That Are Influenced by Clay Minerals

	<——CORRELATIONS——>			
	(r)			
	<——Water retained at——>			Sfc area
	15-bar	1/3-bar	1/10-bar	(N_2)
Clay (SNLCS)	0.93	0.94	0.93	0.93
Water at 15-bar	1.00	0.96	0.93	0.92

Note: Data for 177 samples of *Workshop Tour Guide*.

The choice of a PSDA method becomes a matter of defining what is to be predicted or calibrated from the analysis. Many of the Oxisols of this workshop are clayey with respect to total clay mineral content, plasticity after prolonged kneading, water retention at suctions exceeding 1/10 bar, and CEC. By contrast, they are more like sandy soils in their natural plasticity, contents of coarser pores, water retention at low suctions, and probably saturated hydraulic conductivity. Hence, if the preference is to predict the several properties that reflect total clay mineral content, the best procedure is one that usually reduces all the clay minerals to clay size. If the intent is to measure the cemented granules that behave like sands with respect to pores, water transmission, and water storage at low suctions, then the best method is one that measures that natural size distribution of such granules.

Soil Taxonomy (Soil Survey Staff 1975) is based on the expectation that the PSDA disperses the aggregates without breaking discrete particles. The size distribution is supposed to represent the natural size distribution of discrete particles as they occur in the field. Discrete particles are such things as mica flakes that have weathered to kaolinite, other fragile pseudomorphs that still have the continuity of the original crystal, gibbsite crystals that are larger than clay size, pieces of shale, saprolite, sandstone and other pieces of rock that retain the original rock structure, ironstone, pieces of duripan, and other cemented particles of pedogenic origin.

The SCS method (USDA 1984) is designed to accomplish this in soils having aggregates that are weaker than the discrete particles. The authors of *Soil Taxonomy* (Soil Survey Staff 1975) knew that Oxisols and some other taxa encompassed soils in which the aggregates would not break apart by this method. For those situations a default clay computation based upon 15-bar water is specified in *Soil Taxonomy* (Soil Survey Staff 1975). The default is to multiply 15-bar water times 2.5 to estimate clay content.

Table 3 shows some correlations of the SNLCS clay (EMBRAPA 1979), 15-bar water, and other properties. All data are from the soils of this workshop. SNLCS clay and the 15-bar water are strongly correlated. This infers that both measure the clay mineral content of the soils about equally. Correlations with the SCS measured clay (USDA 1984) are more complex, because they would be lower if tested over the whole data set, but fairly high for surface horizons and those low in iron oxides and gibbsite. This is a reflection of the sensitivity of the SCS clay measurement to the presence of the cemented aggregates or granules of the Bo horizons, and to gibbsite. The 15-bar water and the SNLCS clay are very strongly correlated to the other properties shown. The correlations are about equal.

The conclusions from Table 3 are that *Soil Taxonomy* (Soil Survey Staff 1975) chose a good default method for estimating clay in these soils, and that both the default method and the SNLCS clay are good for estimating the other clay-influenced properties of Table 3. It would be interesting to compare SCS clay to clay and wet consistence estimated by kneading the samples only briefly, to learn whether the SCS method is reflecting the natural colloid levels before physical comminution. The SCS method in combination with the 15-bar default clay is also good for assessing physical pedological changes within the soil profile.

With low activity clay minerals, 3 x 15-bar water is a better default clay than 2.5 x 15-bar water. This was shown in early work in Puerto Rico and the southeastern United States (USDA 1967a,b) but was not tested on a broad sampling of the world's Oxisols before publication of *Soil Taxonomy* (Soil Survey Staff 1975). The NSSL data base and this workshop confirm the earlier inferences.

If only one PSDA can be run, the strong agitation and alkaline dispersant of the SNLCS methods is preferable in these soils because it is strongly correlated to several other properties without taking into account the strength of aggregates. Also, it is a maximal clay measurement that is easier to standardize in soils of this kind.

Water Retention and Bulk Density

These measurements affected by pore size distribution can be replicated with the most precision in the horizons of Oxisols having greatest aggregate stability. Hence, those Oxisols that are most troublesome in PSDA are least troublesome with water retention and bulk density measurements.

Regardless of aggregate stability, pores can be affected by sampling technique. Some of the highly aggregated, clayey Bo horizons and some sandier horizons are soft and fragile. Clods or cores must be collected with care. Despite the fragile appearance of the highly aggregated, clayey Bo horizons, water retention characteristics and bulk density of carefully collected samples may be less sensitive to differences in methodology in

different laboratories than cation exchange and particle-size distribution.

As with other properties there is overlap with other soils in Oxisols having textural gradations and structure similar to soils of other orders. This is particularly true of some kaolinite-rich Oxisols that have modest sesquioxide contents and structure more like some Inceptisols and Ultisols. It is also true of some Oxisols with properties grading toward Andisols, some of coarser textures, and probably others beyond the experience of the authors.

Despite the gradations, Oxisols as a group tend to have frequency distributions of water retention difference (WRD) that are different from other taxa such as Alfisols and Ultisols (Figure 1). WRD in Figure 1 is the volume of water held between suctions of 1/3 bar and 15-bars, expressed as a fraction (cm/cm or mm/mm). In sandy soils 1/10-bar is usually used in place of 1/3. Where the concept of field capacity applies, it is approximated by WRD. Only 20 percent of the Oxisols round to > 0.10, where 45 percent of Ultisols and 51 percent of Alfisols exceed that value. This reflects the lower silt content and the size of structure in the Oxisols.

The influence of texture and structure on water relations in Oxisols is inferred by Figure 2. Pore-size distribution is computed from bulk density and water retention data for a Bo horizon having strong, very fine granular structure, and for an Ap horizon from the same workshop pedon (Stop 22 of the *Workshop Tour Guide*). The data sheets in the *Tour Guide* carry the standard water retention measurements and particle density data. Additional water retention data, not reported, helped construct the curves. The pattern is typical of Bo horizons of the workshop pedons having the strong very fine granular structure discussed above. The Bo horizon water retention curve is characteristic of a clay soil at the higher suctions. At intermediate suctions it reflects the low silt content. At the lowest suctions it shows a bulge which reflects a large number of intergranular pores of > 0.1 mm diameter. These are the pores that drain rapidly after a rain. These are the pores responsible for saturated hydraulic conductivities that are rapid compared to clay soils having weaker aggregation. The Ap horizon has fewer pores of this size, and the water retention curve is more like that of other clay soils.

Oxisol Bo horizons similar to the majority in this workshop, with the definite morphology that is the central concept of the order, are robust with respect to water retention, bulk density, and probably hydraulic conductivity measurements. The characteristic combination of physical properties might more consistently set these soils apart than do the chemical or mineralogical characteristics.

Cation Exchange Properties

The various cation exchange components are often very small in Oxisols. Small cation exchange capacity (CEC < 16 meq/100 g clay) is a criterion for the class. Magnitudes of measured values are subject to large relative differences from one method to another. Measurements of CEC and acidic components are especially method-dependent. Measured values of the exchangeable bases are less influenced by the method, but the quantity is often so small that measurements require greater than the usual precision to obtain meaningful results.

Where exchangeable bases are very low quantities, taxonomies usually do not require extreme precision, but fertility considerations often do. Exchangeable K, for example, can be measured to a precision of 0.1 meq/100 g for taxonomic purposes, but to 0.01 to sense K deficiency levels.

Where CEC is extremely small, extreme precision is required to determine base saturation to the nearest whole percent. CEC of some Oxisols is so small that method-dependent differences in CEC affect base saturation computations more than do differences in quantity of bases. This is a serious constraint to the precision of a base saturation calculation. Figure 3 shows the change in precision of base saturation computations as related to magnitude of CEC and precision of the measurements.

Another constraint is that good CEC procedures for grouping soils in a taxonomy are not always the best to assess ECEC of Oxisols in the field. The CEC criterion for a taxonomy should produce similar results for soils of similar nature. It should not vary with the short-term, local changes at a site that might affect CEC, such as pH differences caused by liming for agricultural purposes. If it does vary with such changes, then a simple agricultural practice can change the classification of a soil too easily, and the soil can flip-flop from one taxon to another from year to year.

Most Oxisols have a small variable charge. As discussed by Uehara and Gillman (1981), the surface charge is influenced by factors in the chemical environment that are usually changed by chemicals used to measure CEC. This is especially true with the two procedures most heavily relied upon by *Soil Taxonomy* (Soil Survey Staff 1975). The procedure utilizing pH 7 ammonium acetate (USDA 1984) generally involves both a pH and ion concentration different from the field condition. In soils having high permanent charge clays this measurement is not so different from the ECEC. In Oxisols the relative difference can be large. The procedure receives criticism on this basis, but serves very well to make desired taxonomic groupings. The CEC by sum of cations involves an extractable acidity procedure in a buffer of pH 8.2 (USDA 1984). The method is best considered a characterization of the pH-dependent component of CEC. Measurements of this component are highly method-dependent, but if a standard procedure is followed it does differentiate soils of different mineralogical nature, where the differences affect the variable charge. Of these two approaches, the ammonium acetate method is the most robust with respect to uniformity of results from laboratory to laboratory. The extractable acidity accentuates differences in variable charge, but is more sensitive to small differences in technique.

The ECEC in the field is quite another matter. This is a CEC under a given set of field conditions. ECEC plus other measurements of CEC under other conditions is excellent for evaluating the status of the soil at the time of sampling, and also for predicting the cation retention under other possible conditions. Different procedures for assessing ECEC produce different results. Complete agreement does not exist about which most nearly represents field conditions. The competing

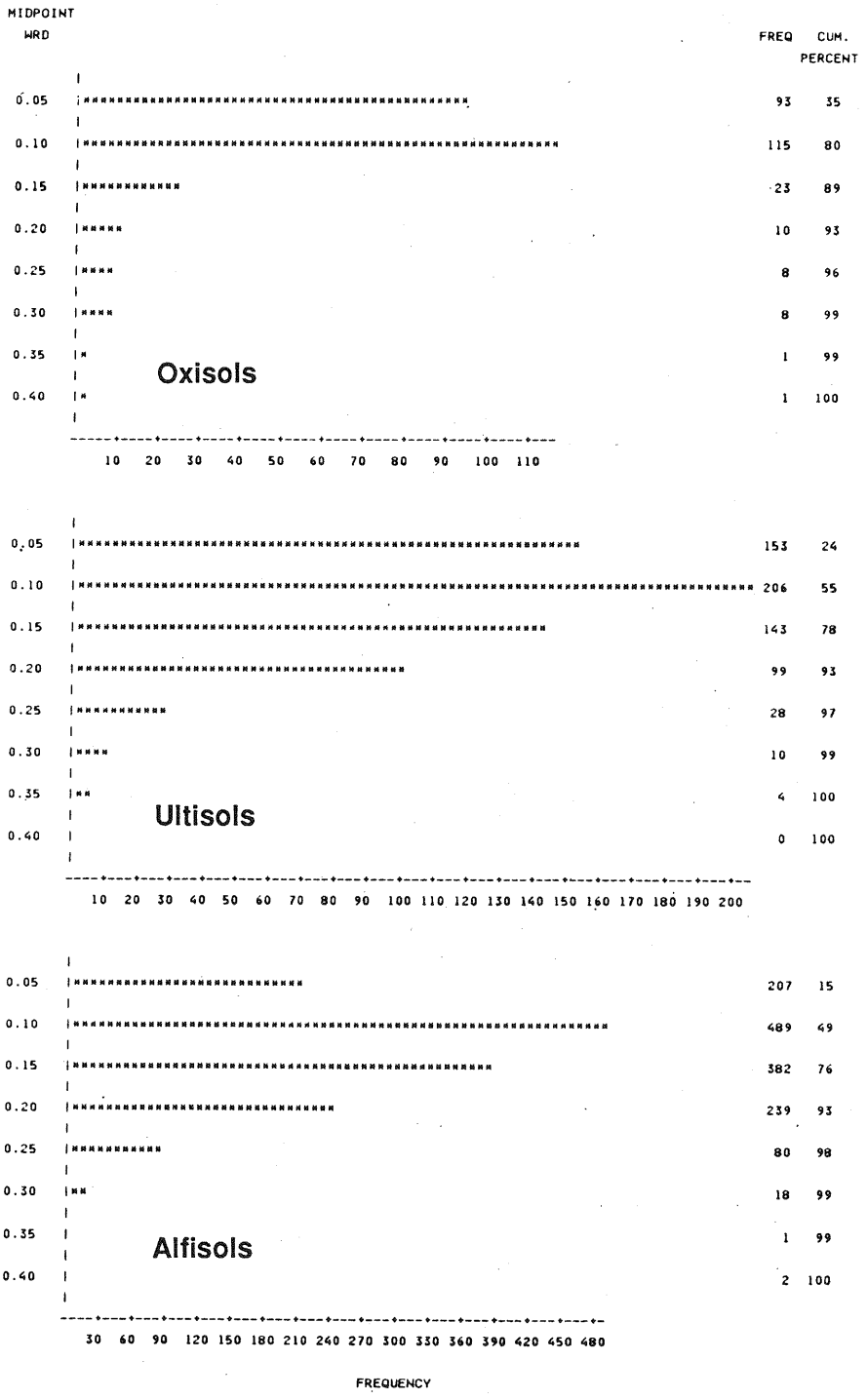


Fig. 1. Frequency distribution of water retention difference (WRD) computed from the data base, National Soil Survey Laboratory (USDA, SCS, NSSL, Lincoln, Nebraska USA).

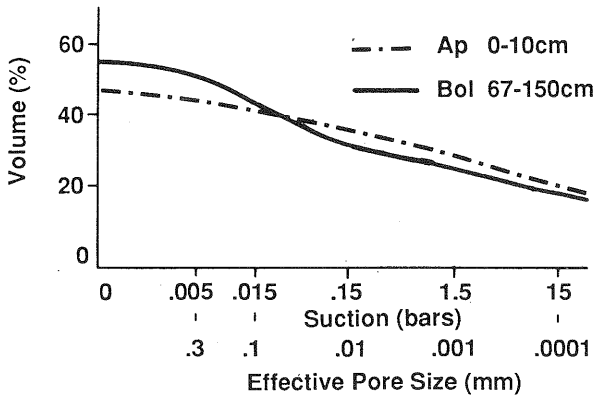


Fig. 2. Volume % water versus suction and volume % pores versus pore size. Two samples from soil at Stop 22 *Workshop Tour Guide.*

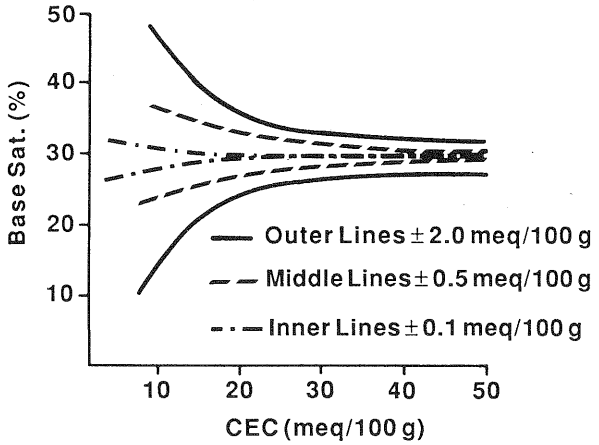


Fig. 3. Relative precision of computed base saturation versus CEC at three levels of analytical precision.

analyses will likely array the conditions similarly, but produce different values.

It is therefore useful to measure CEC by two or more methods in the characterization process. This allows insight into the nature of the soil and the condition in field.

There is interest in relationships between CEC measured by ammonium acetate and ECEC computed by summing extractable bases and extractable aluminum. The generalization most tested is whether kaolinitic and oxidic soils with CEC of 16 meq/100 g or less by ammonium acetate at pH 7 would always have ECEC of 12 meq/100 g or less. The generalization is good for the majority of samples that have CEC < 16 meq/100 g (Figure 4), but is not as good for samples having ECEC <12 meq/100 g (Figure 5). Again, this demonstrates that as the method becomes more sensitive to small differences in condition, it becomes less useful for grouping soils of similar nature.

Most of the other usual chemical analyses used to characterize Oxisols are constrained much the same as in the general spectrum of other soils.

Conclusions

Analytical constraints in Oxisols vary with contents of ion oxides, oxyhydroxides, degrees of cementation of aggregates, and with the small variable charge of the clays. There is debate about the best methods for measuring CEC, ECEC, and PSDA in the soils of this workshop that are the classical, sesquioxide-rich members of the order. The correct choice differs with objective, forcing the use of more than one procedure to measure a property in cases where procedures are not too expensive. CEC and ECEC are not expensive. PSDA is fairly costly. A PSDA that measures a maximal clay is desirable in Oxisols because it predicts other properties with considerable accuracy, and it is the clay measurement easiest to reproduce in different laboratories. It is probable that physical properties other than PSDA could be more heavily used in criteria, at least within the order, probably in combination with morphology such as the strong very fine granular structure. Quantitative clay mineralogy of the fine earth (<2 mm) is less subject procedural differences than that of a size fraction within the fine earth.

Some further operational definitions are needed to define which circumstance are better served by a maximal clay content, as the SNLCS method used for this workshop, and which by a gentler procedure, as the SCS method. Each method appears to be best in a different set of soils. However, if different procedures are to be used with different kinds of soils, then there must be a protocol for deciding when to use each method. An analysis should not be chosen because the soil is an Oxisol if the analysis is the one used to test whether the soil is an Oxisol. The protocol could be tied to a test such as 15-bar/measured clay, perhaps in combination with some information about the kind of material.

Alternatively, the 15-bar default clay specified in *Soil Taxonomy* (Soil Survey Staff 1975) would serve well in these soils with some embellishment to account for organic matter and the water retention of the low activity clays.

References

Empresa Brasileira de Pesquisa Agropecuaria. Servico Nacional de Levantamento e Conservacao de Solos. 1979. Manual de metodos de analise de solo. Rio de Janeiro.

Soil Survey Staff, USDA, SCS. 1975. Soil Taxonomy: A basic system of soil classification for making and interpreting soil surveys. Agric. Handbook No. 436, Soil Conservation Service, U.S. Dept. Agric. U.S. Govt. Printing Office, Washington, D.C.

U.S. Department of Agriculture. 1984. Procedures for collecting soil samples and methods of analysis for soil survey. Soil Survey Investigations Rpt. no. 1.

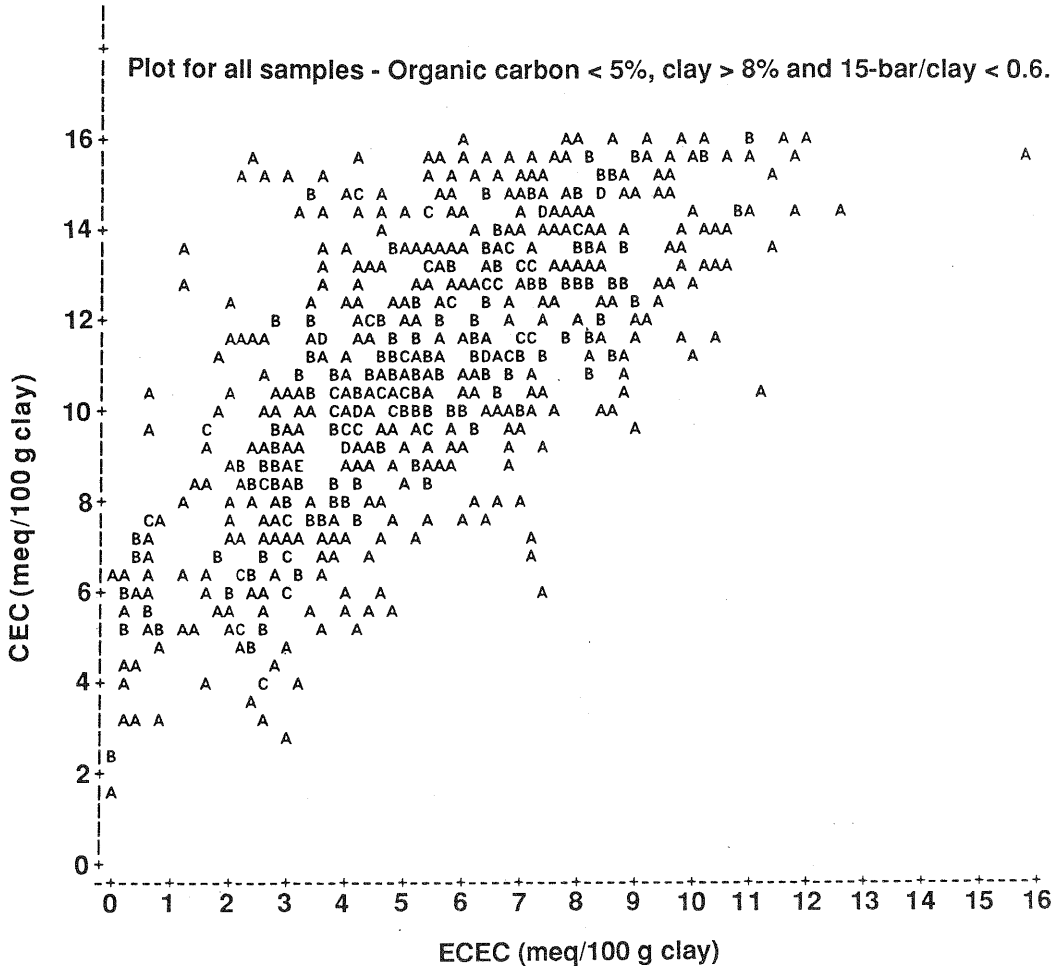


Fig. 4. CEC (NH_4OAc, pH7) versus ECEC (exchangeable bases + Al extracted by N KCl) for samples having ECEC < 12. National Soil Survey Laboratory (USDA, SCS, NSSL, Lincoln, Nebraska). A = 1 observation, B = 2 observation, etc.

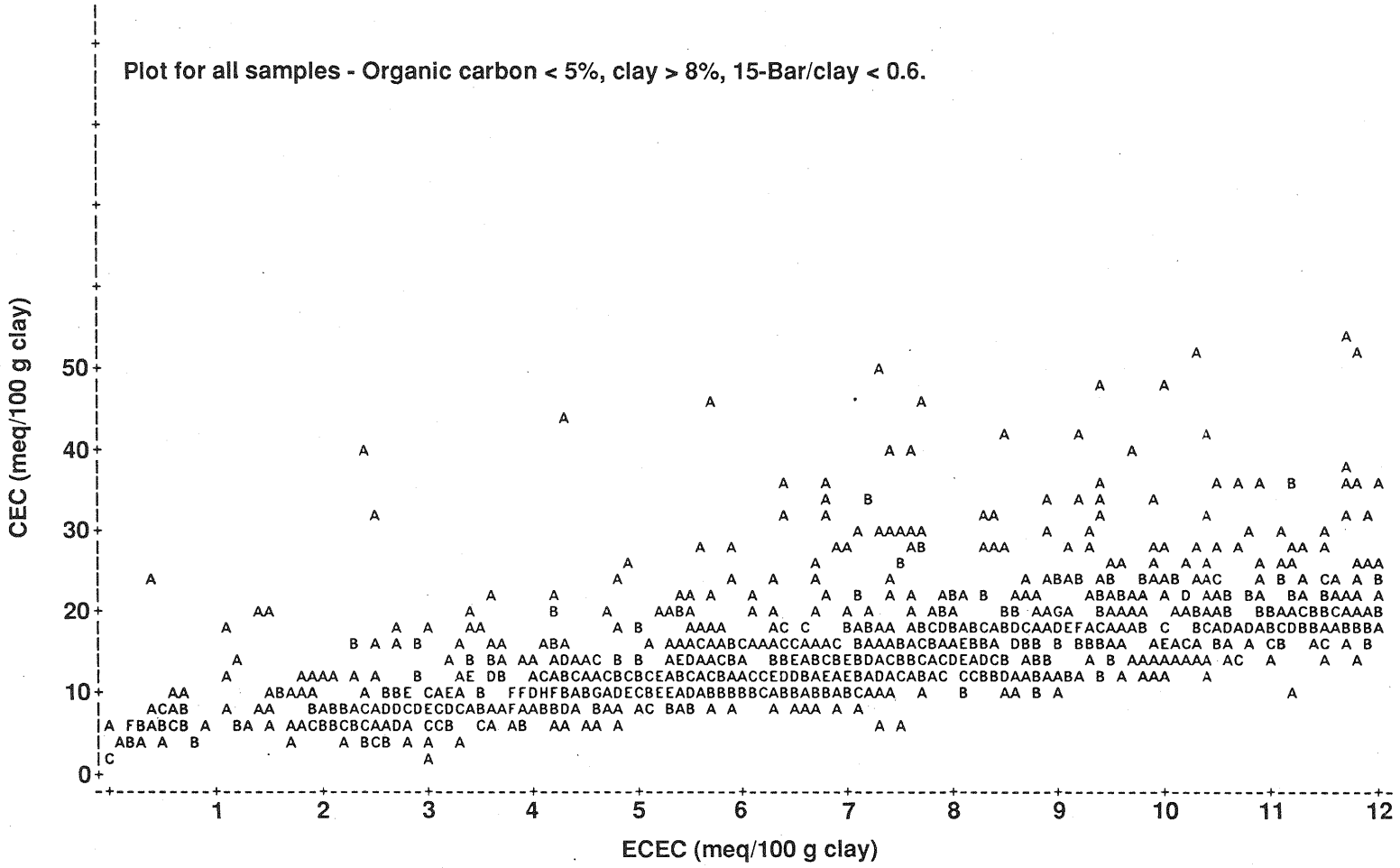


Fig. 5. CEC (NH_4OAC, PH7) versus ECEC (exchangeable bases + Al extracted by N KCl) for samples having ECEC < 12. National Soil Survey Laboratory (USDA, SCS, NSSL, Lincoln, Nebraska). A = 1 Observation, B = 2 Observations, etc.

___. 1967a. Soil survey laboratory data and descriptions for some soils of Puerto Rico and the Virgin Islands. Soil Survey Investigations Rpt. no. 12.

___. 1967b. Soil survey laboratory data and descriptions for some soils of Georgia, North Carolina and South Carolina. Soil Survey Investigations Rpt. no. 16.

Uehara, G., and G. Gillman. 1981. The mineralogy, chemistry and physics of tropical soils with variable charge clays. Westview Press, Boulder, Colorado.

FAMILIES IN THE OXISOL ORDER

B.F. Hajek[1] and R.L. Guthrie[2]

The family category is defined in *Soil Taxonomy* (Soil Survey Staff 1975) by stating that the intent is to group soils within a subgroup having similar physical and chemical properties that affect their responses to management and manipulation for use. Soil properties are used without regard to their significance as marks of soil-forming processes or the lack of them.

The following soil properties are used to distinguish families within subgroups:

1. particle size—sandy, loamy, clayey, and coarse fragment modifiers
2. mineralogy—whole soil, loamy and clayey fractions
3. calcareous and reaction—if not inferred in higher categories
4. soil temperature—mean annual, summer, and winter
5. soil depth—< 18 cm, < 50 cm, and < 1 m
6. slope or soil shape—level, sloping
7. soil consistence—orstein, cementation
8. classes of coatings on sands—coated, uncoated
9. classes of permanent cracks—cracked.

In classes of Oxisols, as in most classes, families are usually distinguished by only three subclasses: particle size, mineralogy, and soil temperature. The soil-depth class is used if there is a petroferric contact within 1 m of the surface. Particle size and mineralogy are determined from the same depth limits (control section). Soil temperature is the mean annual, summer, and winter soil temperature at a depth of 50 cm. Table 1 gives a summary of Oxisol family criteria and control sections (Cornell Staff 1983).

Table 1. Oxisol Family Criteria and Control Sections

Subclass	Criteria
Particle size	Control section = 0.25 - 1 m Clayey families > 35% clay Loamy families — all
Mineralogy	Control section = 0.25 - 1 m
Temperature	At a depth of 50 cm used in all families
Depth	Shallow — < 1 m to a lithic petroferric contact

Current Criteria

Particle size

The limits of fine earth size subclasses are shown on the triangle in Figure 1. If soils contain more than 35 percent rock fragments, the term *skeletal* is included in the name and modifiers of loamy are not used. For example, soils with greater than 35 percent clay and 40 percent rock fragments would be classed as clayey skeletal; if clay is less than 35 percent the class would be loamy skeletal. The broken line was shown in the triangle at 60 percent clay to indicate the limit between fine and very fine families used in most orders and currently being proposed for use in Oxisols (Moormann 1985).

Mineralogy

Mineralogical subclasses are determined by using the vertical listing of classes as given in *Soil Taxonomy*. First, subclasses are considered on a whole-soil basis. The first criteria that fits the data is the class given. Figure 2 shows the limits for whole soil between ferritic and gibbsitic and other classes. The oxidic class is not shown since the oxidic definition does not form a continuum with other classes. If no whole soil class limits are met then mineralogy subclasses are named for the mineralogy of the coarse (2 mm–0.02 mm) or fine (< 0.002 mm) fractions depending on the particle-size subclass. Figure 3 is a triangle showing the limits of clay fraction mineralogy. The clay activity limits that define oxic horizons limit Oxisol clayey family mineralogy to the region below the horizontal line at 10 percent 2:1 expanding minerals. The limits between kaolinitic, halloysitic, and mixed and siliceous are based on the family particle-size subclass (Fig. 4). Oxisol clay mineral subclass limits are shown in Figure 5.

[1] Professor of Soils, Agronomy and Soils Department, Auburn University, Alabama 36849.

[2] Professor and Head, Agronomy and Soil Department, Auburn University, Alabama 36849.

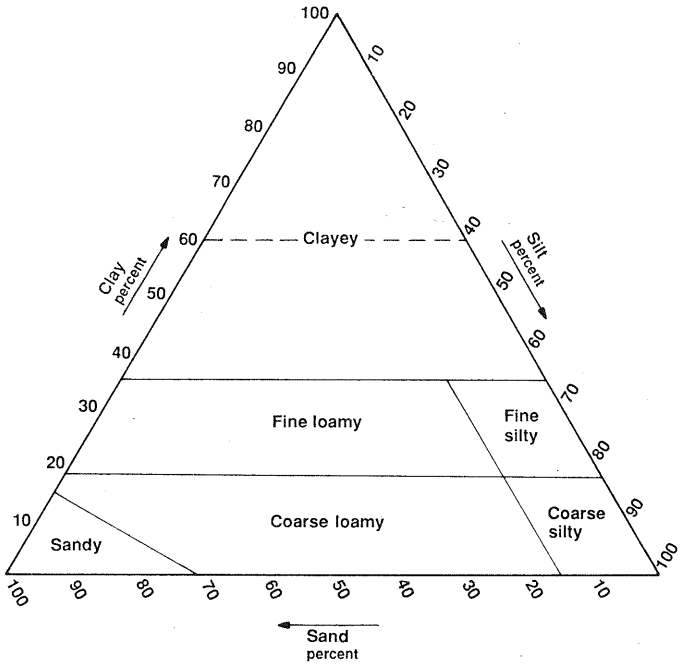


Fig. 1. Particle size family classes in *Soil Taxonomy* and proposed by ICOMOX.

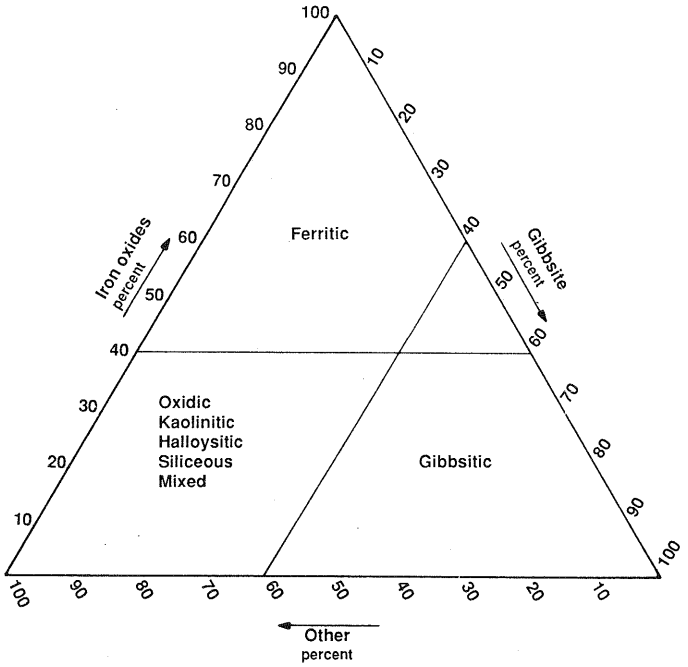


Fig. 2. Whole soil, loamy, and clayey Oxisol mineralogical classes in *Soil Taxonomy*.

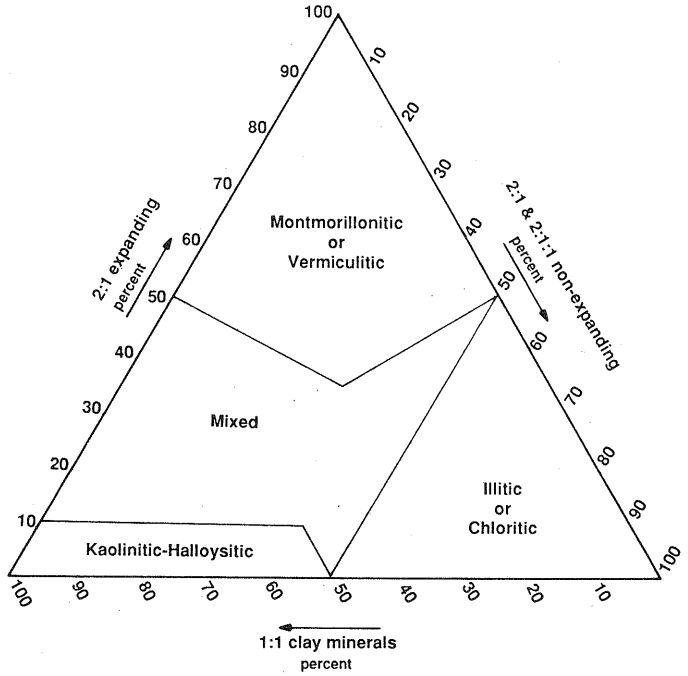


Fig. 3. Guide to clayey mineralogical families in *Soil Taxonomy*.

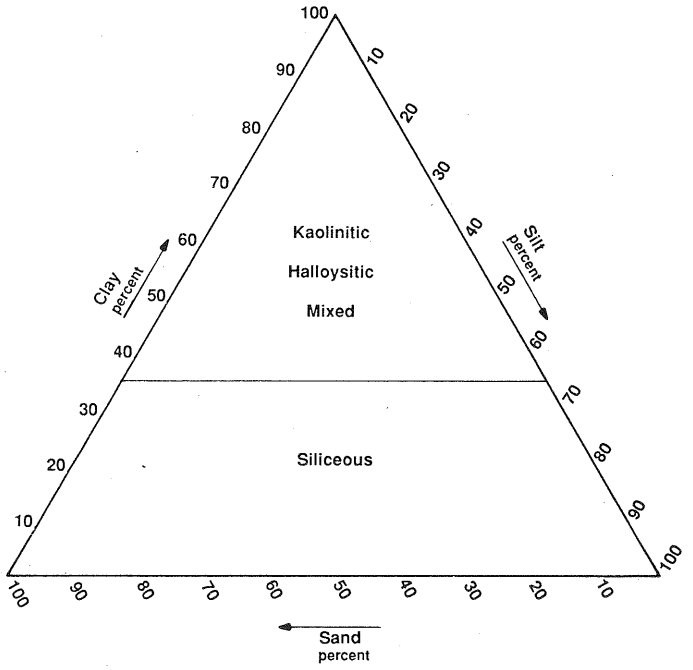


Fig. 4. Oxisol clayey and loamy mineralogical families in *Soil Taxonomy*.

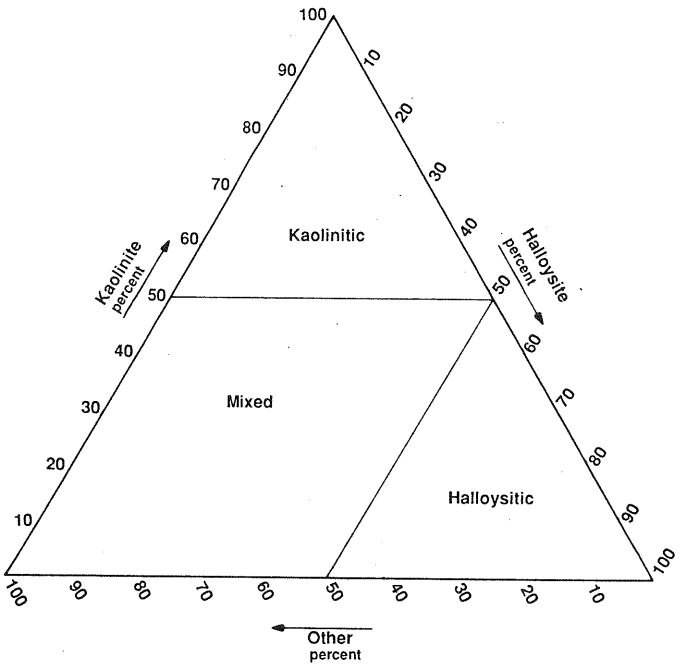


Fig. 5. Guide to Oxisol clayey mineralogical families in *Soil Taxonomy*.

The following is a list of Oxisol mineralogy subclasses:

Whole Soil
- ferritic
- gibbsitic
- oxidic

Loamy
- siliceous

Clayey
- kaolinitic
- halloysitic
- mixed

Temperature

The mean annual soil temperature at a depth of 50 cm is used to determine Oxisol temperature subclasses. The following are temperature subclasses of Oxisols:

hyperthermic > 22°C
thermic 15-22°C
mesic 8-15°C

If there is less than 5°C difference between the mean soil temperature for summer and winter, the prefix iso- is added to the names given above.

Proposed Family Classes

Because of class differentia at higher categories, mineralogical subclasses at the family level as presently defined often have little significance for use, management, manipulation, or as marks of soil genesis. This is especially true for Oxisols as well as Vertisols, Spodosols, and many classes of Ultisols and Aridisols.

The low clay activity definition of Oxisols places limits on the mineral assemblages that can possibly be present. This is also the case for the proposed Kandi great groups of Ultisols and Alfisols (International Committee on Low Activity Clays [ICOMLAC] proposal) (Moormann 1985). The members of ICOMOX (International Committee on Oxisols) addressed this problem in their proposed revision by developing mineralogy classes based on known mineralogy of soils with low acivity clays and low amounts of weatherable minerals. In this proposal there are no mixed subclasses. Table 2 gives ICOMOX mineralogy subclasses. As in *Soil Taxonomy* subgroups, more than one definition may fit. When this occurs dual names are used. Subclass limits are easily shown by use of the triangle in Figures 6 and 7. Since allic is not defined in mineralogical terms, it cannot be represented in a mineral assemblage continuum.

Figure 8 shows a triangle that is somewhat similar to the ICOMOX Fe-Al oxyhydroxide classes. These names and limits where proposed for low activity clay soils. The classes were suggested by Hajek and Herbillon (1984) and by Hajek (1986). If the bauxitic class was omitted and the horizontal limits for the sesquioxidic class extended, classes would nearly match the ICOMOX proposal. In the Hajek-Herbillon proposal, the class shown as "other" is in fact the most common assemblage. In the case of Oxisols this would be soil material

Table 2. Mineralogical Family Differentia Proposed for the Oxisol Order by ICOMOX

Definitions

1. more than 40% iron oxide (28% Fe) by sulfuric acid or 32% by CBD (22.4% Fe)
2. 18-40% Fe_2O_3 (12.6-28% Fe) by sulfuric acid or 14-32% Fe_2O_3 (9.8-22.4% Fe) by CBD
3. more than 25% gibbsite on a whole soil basis, including gravel
4. more than 50% of the clay (< .002 mm) halloysite
5. more than 2 meq KCl extractable Al/100 gm soil (< 2 mm) in some 30 cm layer of the mineralogy control section
0. none of the above

Nomenclature

1 = ferruginous
2 = ferritic
3 = gibbsitic
4 = halloysitic
5 = allic
1 and 3= ferruginous-gibbsitic
1 and 5= ferruginous-allic
3 and 5= gibbsitic-allic
2 and 3= ferritic-gibbsitic
2 and 5= ferritic-allic
0 = kaolinitic

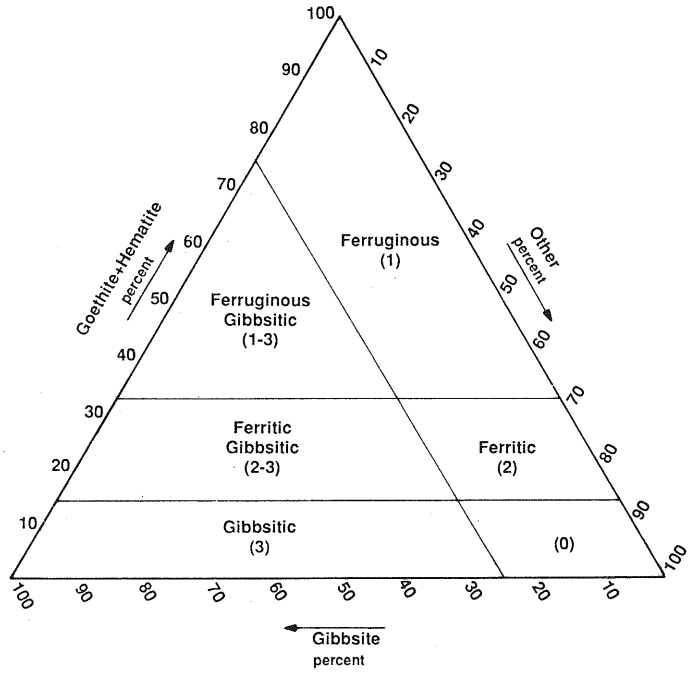


Fig. 6. Whole soil mineralogy classes proposed by ICOMOX.

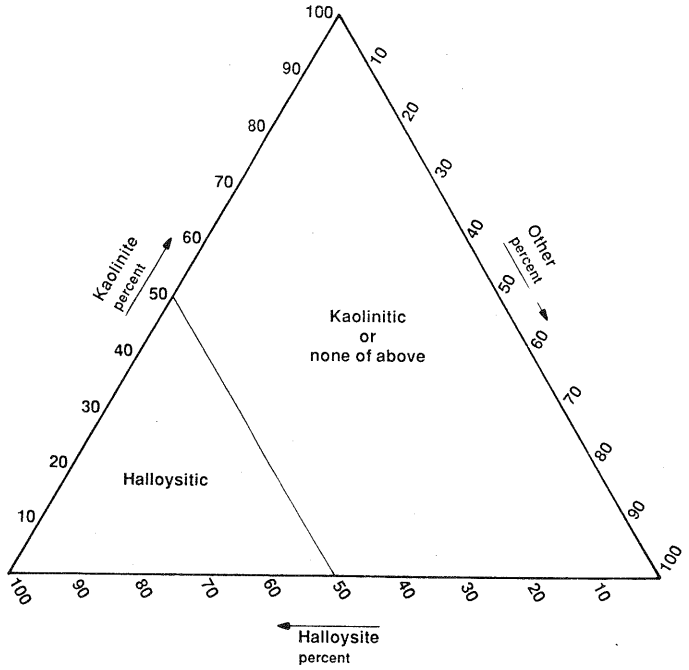


Fig. 7. Clay fraction mineralogical classes proposed by ICOMOX.

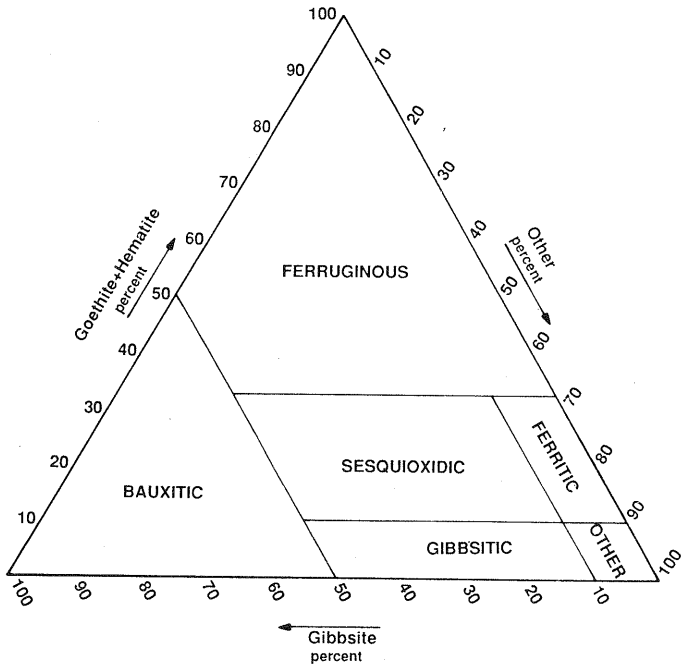


Fig. 8. Mineralogical classes proposed for soils with low activity clays.

consisting of kaolinite and/or halloysite, quartz, hydroxy-interlayered vermiculite (pedogenetic chlorite), and less than 10 percent of any other mineral (goethite, hematite, gibbsite, and other resistant minerals of any size fraction). This "normal" or "orthic" assemblage is analogous to the "typic" subgroup.

The allic class was also proposed. It appears that both proposals should consider chemical properties, such as Al saturation, as another subclass at the family level separate from mineralogy. An example of a complex family class could be: clayey, sesquioxidic, allic, isohyperthermic + subgroup element or as simple as clayey, orthic, isohyperthermic.

There are only minor revisions suggested or proposed in particle-size and temperature family subclasses. As was pointed out before, ICOMOX proposes that clayey be separated at 60 percent into fine (35-59 percent clay) and very fine (> 60 percent clay) for Oxisols.

Defining family classes by use of properties and limits within constraints of diagnostics used at higher categories will improve the usefulness of the family category for making and interpreting soil surveys as well as for adding to a better understanding of soil genesis.

References

Cornell Staff. 1983. Keys to soil taxonomy. SMSS Tech. Mono. no. 6 Agron. Dept., Cornell Univ., Ithaca, NY.

Hajek, B.F. 1986. Final report of a review of criteria for family classes. Unpublished report, Soil Management Support Services.

Hajek, B.F. and A.J. Herbillon. 1984. Mineralogy of low activity clays. *Agron. Abst.*, Amer. Soc. of Agron., Madison, WI.

Moormann, F.R. 1985. Excerpts from the circular letter of the International Committee on Low Activity Clays (ICOMLAC). Soil Management Support Services, Tech. Mono. 8. Washington, D.C.

Soil Survey Staff, SCS, USDA. 1975. Soil taxonomy: A basic system of soil classification for making and interpreting soil surveys. USDA Agric. Handb. no. 436. U.S. Govt. Printing Office, Washington, D.C.

CHEMICAL ESTIMATION OF WEATHERABLE MINERALS PRESENT IN THE DIAGNOSTIC HORIZONS OF LOW ACTIVITY CLAY SOILS

A.J. Herbillon[1]

Abstract

This paper documents a proposal made previously to the ICOMOX (International Committee on Oxisols) members concerning the possibility of estimating the weatherable minerals (WM) content of oxic horizons from their total chemical analyses. A priori calculations based on the chemical composition of primary minerals, the most common in highly weathered soils, shows that the limit in WM content given in the definiton of the oxic horizon corresponds generally to a total reserve in bases (TRB) of less than 25 meq/100 g of fine earth. The same calculations also point out that the precise value of TRB depends not only on the amount and nature of WM present in the silt- and sand-size fractions but also on the textural class of the soil. The compilation of TRB values from 40 oxic horizons of Oxisols originating from Hawaii, Puerto Rico, Cameroon, Central Africa, Malaysia, and Brazil shows that 90 percent of these samples have a TRB value lower than 40 meq. TRB data for the subsurface diagnostic horizons of other LAC (low activity clay) soils (i.e., soils classified as LAC Alfisols, Ultisols, and Inceptisols) have also been examined. In these soils, TRB covers a broader range of values going from those characteristic for the oxic horizon (< 40 meq) to those characteristic for HAC (high activity clay) tropical soils (< 40 meq/100 g). The results suggest that (1) the TRB parameter has a potential value to delineate the limit in WM necessary to distinguish a LAC Alfisols and Ultisols belong to two different categories, the first one regrouping soils as depleted in WM as the Oxisols whereas the second regroups soils having a WM status more similar to Inceptisols.

The amount of weatherable minerals (WM) present in the soil silt- and sand-size fractions is a criterion that appears at two different levels in *Soil Taxonomy* (Soil Survey Staff 1975); it is one of the characteristics allowing the distinction between an oxic and a cambic horizon and, in the upper part of the argillic horizons of all pedons belonging to the Pale great groups of the Ultisols, a limit is also set up on their contents in WM.

At present, the identification of WM is based on the microscopic examination of their silt plus fine sand particle-size fractions, and the limits set up in *Soil Taxonomy* rest upon the results obtained by grains counting. A perusal of some published and unpublished data (see e.g., Antonello 1983) shows that when the grains-counting technique is applied to clayey weathered soils, several practical difficulties may hinder a quantitative interpretation of the results. Actually, the sand- and silt-size fraction of such soils contains, besides fresh primary minerals, mineral grains weathered to different extents. Further, clay aggregates as well as individual mineral grains coated by oxides occur frequently in these samples. In all these instances, it is clear that the grains-counting technique does not provide more than a rough approximation of the amount of major nutrients really trapped in the soil coarse fractions. Within the framework of a soil classification system based upon the utilization of quantitative criteria, such poor accuracy is certainly not desirable.

It is the purpose of this paper to propose that, whenever the grains-counting techniques for estimating the WM contents provide inaccurate or ambigous results, one could, as an alternative, rely on a criterion taking into account the total reserve in alkaline and alkaline-earth cations present in soil. This criterion has been called the total reserve in bases (TRB) and, for the sake of convenience, it will be expressed here in terms of meq/100 g of soil. To document our proposal, we have collected TRB data for about 70 diagnostic subsurface horizons and compared their values to TRB calculated from the mean chemical compositon of WM most likely in the highly weathered soils environments.

Total Reserve in Bases in the Most Common Soil Primary Weatherable Minerals and in Some Hypothetic Soil Diagnostic Horizons

The approach here follows the reverse order of that used by most mineralogists (see e.g., Van der Plas and Van Schuylenborgh 1970) when attempting to establish the normative mineralogical composition of a rock (or a soil) from its total elemental analysis. It consists in associating to each of the primary WM likely to be present in LAC soils a characteristic TRB value (Table 1). From Table 1, the

[1] Centre de Pédologie Biologique du CNRS, B.P. 5, F-54501 Vandoeuvre-les-Nancy Cédex, France.

Table 1. Total Reserve in Major Plant Nutrients (TRB) Trapped in Some Common Primary Minerals

Mineral	Elemental composition (%)				Bases trapped (meq/100 g)				TRB (meq/100 g)
	CaO	MgO	K_2O	Na_2O	Ca^{++}	Mg^{++}	K^+	Na^+	
K Feldspar[a]			16.92				359		359
Anorthite[a]	20.15				719				719
Albite[a]				11.82				381	381
Hornblend[b]	10.91	9.15		2.01	389	453		65	907
Augite[b]	20.24	9.10			722	451			1,173
Olivine[b]		23.41				1,161			1,161
Muscovite[a]			12.5				265		265
Biotite[b]		10.00	11.73			496	249		745

[a] End member formula.
[b] Mean chemical formula.

theoretical TRB value for some hypothetical LAC soil diagnostic horizons can then be easily calculated (Table 2).

Although depicting a limited number of possible scenarios, Table 2 allows the following comments to be made. When calculated from the total analysis of a given soil sample, TRB does not only include the bases trapped in the coarse primary minerals but also those located on the exchangeable sites and possibly in the minerals of the clay fraction as well. In LAC soils, however, the contribution of bases from the clay fraction to TRB should be always limited so that it should not affect too heavily the discriminating capacity of this parameter. On the other hand, the figures in Table 2 indicate well how the TRB value is sensitive to the textural class to which the sample belongs. Actually, this is a characteristic that TRB shares with the grains-counting technique since, in this last procedure too, the significance to be attached to the WM contents in the coarse fractions should ideally be corrected for the respective weight of the examined fraction in the whole soil sample. Finally, Table 2 illustrates that oxic horizons as presently defined by *Soil Taxonomy* (less than 3 percent WM in their fine sand- plus silt-size fractions) should never have TRB values higher than 25-30 meg/100 g of fine earth.

TRB in Actual Subsurface Horizons of LAC Soils

In this paragraph are reported a number of TRB values obtained from the compilation of total chemical analyses found in the literature. These analyses were performed on the fine-earth fraction (< 2 mm) and, therefore, the TRB data listed here refer to the same material. The results are presented in the form of diagrams where are illustrated the range of TRB values found in oxic horizons (major B2 horizons) and in other subsurface horizons of LAC soils (major B2 horizons). For the sake of comparison, the range of TRB found in the subsurface horizons from some soils classified as *sol ferrallitiques* (CPCS 1967) as well as from some HAC (high activity clay) soils have also been presented.

Oxic Horizons

Amongst the collected data, there are only three samples (~ 8 %) showing a TRB higher than 40 meq(Figure 1 and Table 3). A closer examination of these exceptional cases allows the following remarks. In the case of pedon Hawaii 6, TRB shows a clear tendency to decrease with depth so that, if the deeper B horizons were also considered, its mean characteristic TRB value would be somewhat lower (60 instead of 80). A TRB decreasing with depth is probably a sign of rejuvenation and if so, the high reserve in Mg++ found in the top of this profile should exclude it from the Oxisol order. In pedon Puerto Rico 6, some free $CaCO_3$ is present (Jones, Hudwall, and Sakai 1982). As calcite is not defined as a WM by *Soil Taxonomy* (see p. 64), substracting its Ca^{++} content from TRB is allowed. Then the corrected TRB drops to 42 meq/100 g (sample 6*, Figure 1). In profile Malaysia 11, high Mg^{++} contents are a characteristic for both the fine earth and the clay. Its high TRB is therefore not solely due to bases trapped in its coarse fraction.

Figure 1 and Table 3 show also that 70 percent of the examined oxic horizon exhibit, as expected (see Table 2), TRB values lower than 25 meq. However, setting up a TRB limit for the oxic horizon at 40 meq instead of 25 would seem appropriate if we wish to accommodate within the Oxisol order more pedons presently classified as tropeptic, andic, and eutric.

Subsurface Diagnostic Horizons of Other LAC Soils

Amongst the collected TRB data, four only refer to cambic horizons of LAC soils (Hawaii 1 and 2, Brasil 1 and 2) (Figure 2 and Table 4). They are all higher than 25 meq even though one of them falls between 25 and 40 meq. Obviously and unfortunately, the information concerning the reserves in bases of LAC cambic horizons is presently too limited to allow any generalization.

In contrast, Figure 2 indicates rather clearly that the TRB for the argillic horizons of LAC Alfisols and Ultisols cover a broad range of values going from those characteristic for oxic

Table 2. Evaluation of TRB in Varied Hypothetical Soil Situations

Hypothetic soil horizon	Bases trapped in WM (meq/100 g soil)	TRB (meq/100 g soil)
(a) Oxic horizon - 50% clay; 50% silt plus sand; 3%[a] hornblend in the coarse fractions. Exchangeable bases: 3 meq/ 100 g soil	13.6	16.6
(b) Cambic horizon - Same texture as (a) hereabove; 9%[a] hornblend in the coarse fractions. Exchangeable bases: 3 meq/ 100 g soil.	40.8	43.8
(c) Oxic horizon - 30% clay; 70% silt + sand; 1% K feldspar; 1% augite; 1%[a] biotite in the coarse fractions. Exchangeable bases: 3 meq/100 g soil.	17.0	20.0
(d) Cambic horizon - Same texture as (c) hereabove, 2% K feldspar; 3% biotite; 3%[a] hornblend, in the coarse fractions. Exchangeable bases: 5 meq/100 g soil	39.2	44.2
(e) Oxic horizon - Same texture as (c) hereabove, 6%[a] muscovite, in the coarse fractions. Exchangeable bases: 3 meq/100 g soil	11.3	14.3
(f) Cambic horizon - Same texture as (c) hereabove, 9% muscovite; 2% hornblend; 1%[a] anorthite. Exchangeable bases: 5 meq/100 g soil	27.2	32.2
(g) Oxic horizon - 80% clay; 20% silt plus sand; 2% augite; 1%[a] hornblend, in the coarse fractions. Exchangeable bases: 4 meq/100 g soil.	6.6	10.4
(h) Cambic horizon - Same texture as g hereabove; 5% augite; 2% hornblend; 1%[a] olivine. Exchangeable bases: 6 meq/100 g soil	17.6	23.6

[a] Note that % here means weight % not grains %.

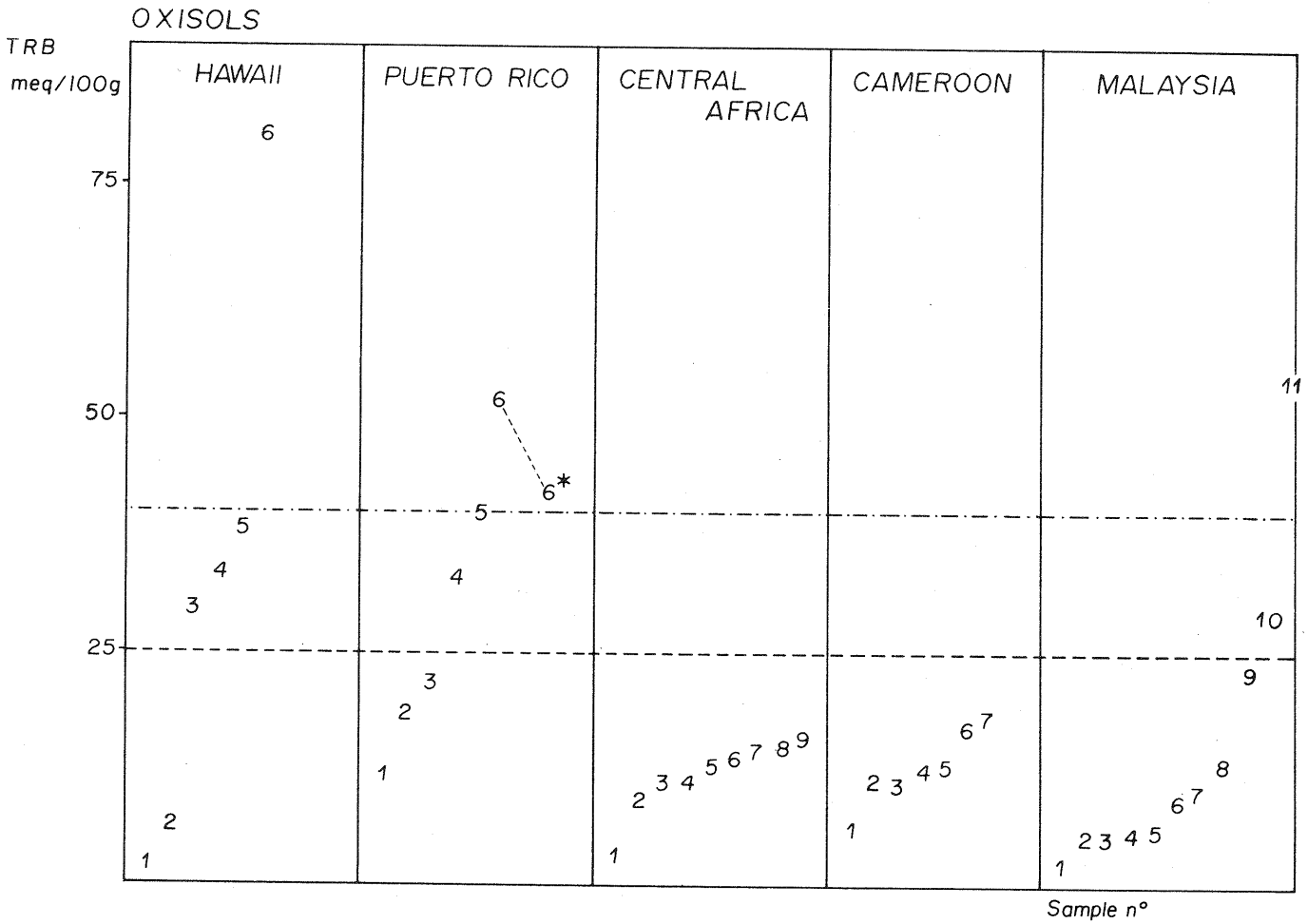


Fig. 1. Diagram showing the range of TRB values encountered in 39 oxic horizons. The number on the figure refers to the pedons identified in Table 3.

Table 3. Origin and Classification of Oxisols to Which the Number appearing in Figure 3 Refers

Number	Classification	Comments
HAWAII[a]		
1	Typic Gibbsiorthox (Pooku series)	
2	Typic Gibbsiorthox (Kapaa series)	
3	Tropeptic Umbriorthox (Puhi series)	
4	Typic Acrohumox (Mahana series)	
5	Tropeptic Umbriorthox (Makapili series)	
6	Tropeptic Umbriorthox (Puli series)	
PUERTO RICO[b]		
1	Typic Acrorthox (Nipe series)	
2	Typic Haplorthox (Pina series)	
3	Tropeptic Haplorthox (Bayamon series)	
4	Tropeptic Haplorthox (Coto series)	
5	Tropeptic Haplorthox (Catalina series)	
6	Tropeptic Eutrothox (Matanzas series)	$CaCO_3$ present
CENTRAL AFRICA[c]		
1	Typic Haplorthox	
2	? Sombrihumox	
3	? Sombrihumox	
4	Typic Haplustox	
5	Typic Haplustox	
6	? Sombrihumox	
7	? Sombrihumox	
8	Typic Haplustox	
9	Typic Haplustox	
CAMEROON[d]		
1	Tropeptic Haplorthox	
2	? Haplorthox	
3	Typic Haplorthox	
4	Tropeptic Haplorthox	
5	Typic (?) Haplorthox	
6	Tropeptic Haplorthox	
7	Typic Haplorthox	
MALAYSIA[e]		
1	Haplic Acrorthox	
2	Haplic Acrorthox	
3	Haplic Acrorthox	
4	Haplic Acrorthox	
5	Haplic Acrorthox	
6	Haplic Acrorthox	
7	Typic Eutrorthox	
8	Typic Gibbsiorthox	
9	Typic Eutrorthox	
10	Tropeptic Haplorthox	
11	Typic Eutrorthox	The clay is as rich in Mg^{++} as the soil

Additional TRB values not shown on Figure 1

Origin	*Name*	*TRB meq/100 g*
Brasil[f]	Latossolo Vermelho Amarelo Alico (Haplorthox)	10
Chili[g]	Andic Kurudox (Los Ulmos series)	38

Sources:

[a] USDA (1976) Soil Survey Report nº 29.
[b] Jones *et al.* (1982).
[c] Frankart (1983), pers. comm.
[d] Vallerie (1973) (classification according to *Soil Taxonomy* kindly from F.R. Moormann).
[e] Paramanantham (1977).
[f] Antonello (1983).
[g] See ICOMOX C.L. nº 12 and 14.

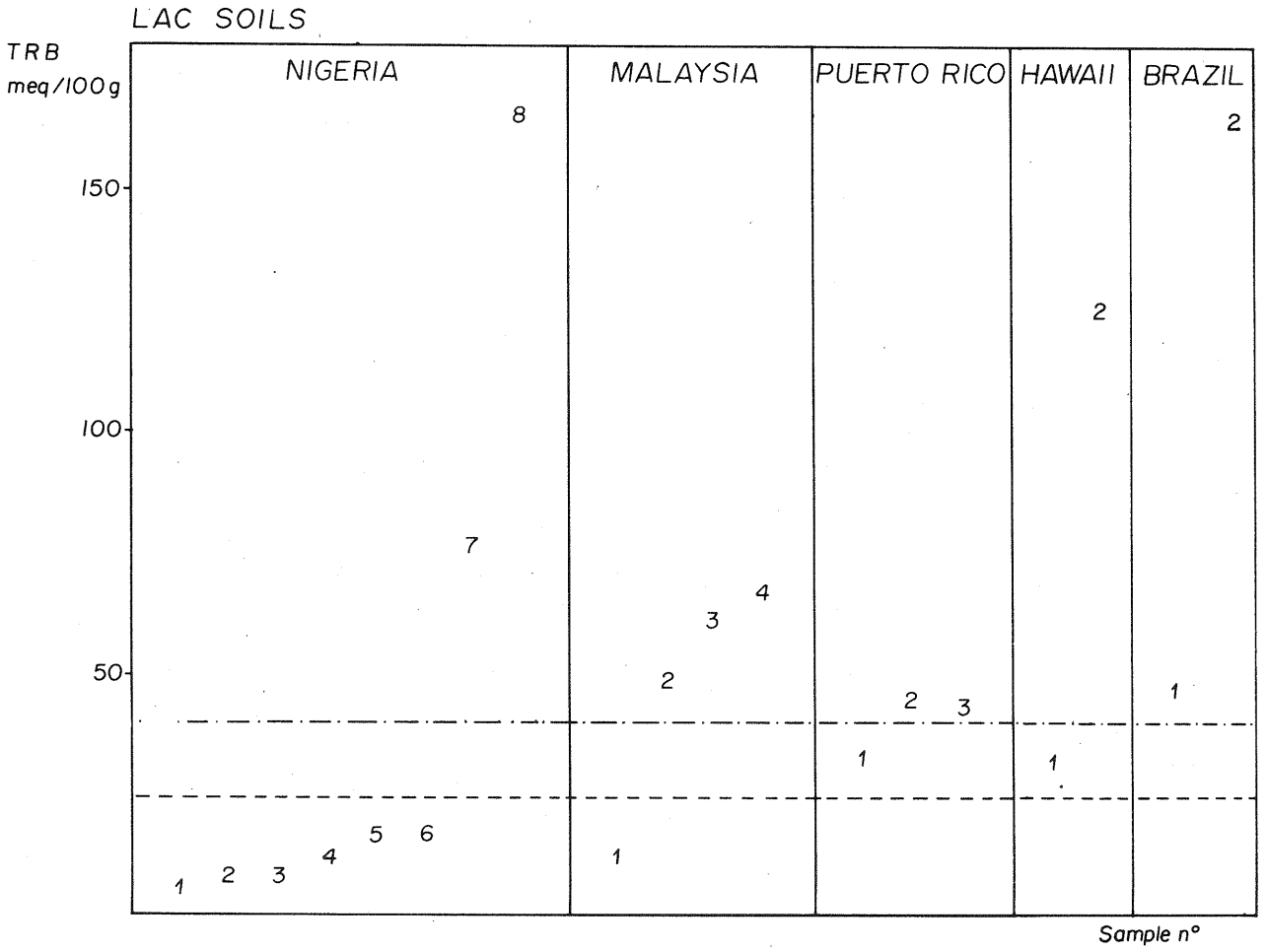


Fig. 2. Diagram showing the range of TRB values encountered in cambic or argillic horizons from LAC soils. The number on the figure refers to pedons identified in Table 4.

Table 4. Origin and Classification of Pedons to Which the Numbers Appearing on Figure 2 Refer

Number	Classification
NIGERIA[a]	
1	Oxic Paleustalf (Alagba series)
2	Oxic Paleustalf (Iwo series)
3	Typic Paleustult (Itagunmodi)
4	Oxic Paleustalf (Egbeda series)
5	Plinthic Orthoxic Tropudult (Cgra series)
6	Orthoxic Tropudult (Etioni series)
7	Orthoxic Tropudult (Ndian series)
8	Orthoxic Tropudult (Balogun series)
MALAYSIA[b]	
1	Orthoxic Tropudult
2	Aquic Orthoxic Tropudult
3	Orthoxic Tropohumid
4	Orthoxic Tropohumid
PUERTO RICO[c]	
1	Orthoxic Tropohumid (Daguey series)
2	Epiaquic Orthoxic Tropohumid (Los Guineos series)
3	Orthoxic Tropohumid (Torres series)
HAWAII[e]	
1	Oxic Ustropept
2	Oxic Ustropept
BRAZIL[d]	
1	Cambissolo Alico (Ochrept)
2	Cambissolo Alico (Umbrept)

Sources:
[a] Moormann (1981) and pers. comm. (1983).
[b] Paramanantham (1977).
[c] Jones, Hudwall, and Sakai (1982) (see also Beinroth 1982).
[d] Soil Conservation Service, USDA (1976).
[e] Antonello (1983).

horizons to those indicating a moderate weathering stage of their course fractions. Up to now, it is only in the upper part of the argillic horizons of pedons belonging to the Pale great group of Ultisols that *Soil Taxonomy* makes reference to the presence of a limited amount of WM. In this respect, Figure 2 indicates that the "Pale" Ultisols share this property with several other LAC Alfisols and Ultisols. Actually, the fact that the content in WM is presently not considered in the definition of LAC Alfisols and Ultisols leads to groupings that seem to be neither rational nor desirable. In Figure 2, for instance, there are six pedons that are similarly classified as "Orthoxic Tropudult" in spite of the fact that the TRB values of their diagnostic horizons are as different as 8 and 166 meq! By considering the results of grains counting rather than TRB values, Hughes (1981) also had already pointed out the same anomaly.

Subsurface Horizons from *Sols Ferrallitiques* and HAC Soils

Actually, there are more data available in the French literature dealing with the characterization of soils classified as *ferrallitiques* than the limited numer of TRB values shown on Figure 3A (Figure 3 and Table 5). This limited sampling illustrates well, however, that in these highly weathered soils too, TRB does not generally exceed 40 meq/100 g soil. In Figure 4A, the only exception (sample 10) is from a pedon that Chatelin (1966) had classified as *faiblement ferrallitique* (weakly ferrallitic). On the other hand, and although TRB is not a parameter explicitly considered in the CPCS (1967) system, Martin and Sieffermann (1966) had already reported that a TRB limit set up at 40 meq/100 g can adequately distinguish old from younger soils developed on the same type of parent material (basalt) in Cameroon.

Finally, Figure 3B illustrates the range of TRB values found in a number of tropical and temperate HAC soils. In both geographic areas, the argillic and cambic horizons of these soils exhibit TRB values much higher than 25 or even 40 meq. Although it should not be precluded that some HAC soils developed on very siliceous parent materials (some Psamments and some Spodosols for instance) could well have TRB located in the same range of values as Oxisols, Figure 3 gives confidence that TRB could become an adequate and convenient parameter to describe the stage of weathering of soils, somewhat in the same manner as the CEC of the clay is presently considered as a good criterion to distinguish soils with contrasting clay minerals suites (Fig. 4).

Final Comments

At the outset of this work our hope was to evaluate whether the controversy that had once existed (Sys 1969), concerning the precise muscovite content to be allowed in the oxic horizon, could not be solved by considering the chemical significance to be attached to muscovite rather than its content (Herbillon 1981). Actually, there seem to be two good reasons to allow more muscovite to be present in Oxisols than ferromagnesian primary minerals for instance. Number one is the limited weatherability of muscovite (see e.g., Goldich 1938). However, if the amounts of bases trapped in WM are also considered (Table 1), then a second reason for justifying a higher amount of muscovite in highly weathered soils is also pointed out. It is this observation that prompted in more detail the potential value of TRB as a classification criterion.

At this stage of our study, two observations emerge clearly: (1) TRB has the capacity to regroup soils and diagnostic horizons according to their degree of weathering and (2) for this reason it might be substituted for the results of grains-counting whenever *Soil Taxonomy* wishes to make reference to a quantitative and convenient criterion taking into account this degree of weathering. Finally, our results show that such a reference could be appropriate not only in the definitions of the oxic and cambic horizons but also amongst the criteria delineating lower level categories of all LAC Alfisols and Ultisols (Fig. 4).

Acknowledgments

The author thanks sincerely L.L. Antonello, R. Frankart, F.R. Moormann, M. Gury, and J. Rouiller who kindly made available several unpublished data appearing in this paper.

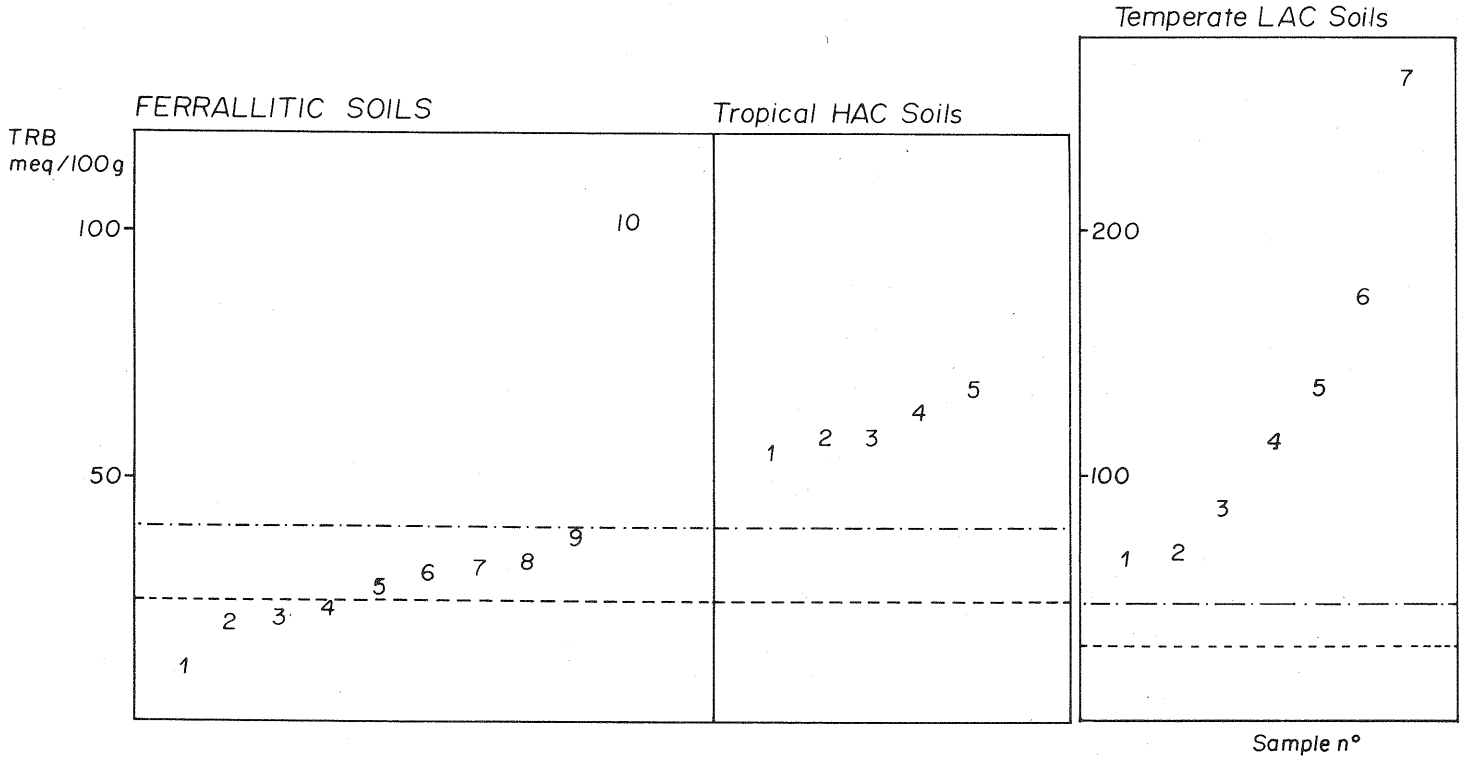


Fig. 3. Range of TRB values found in the subsurface horizons of some pedons classified as *sols ferrallitiques* (A) and in the subsurface horizons of some HAC soils (B). The number on the figure refers to details given in Table 5.

Table 5. Sources of Data for Figure 3

Number	Country and classification	Reference
Sols Ferrallitiques		
1	French Guyana	Lelong (1964)
2	Central African Republic	Beaudou (1971)
3	Idem	Idem
4	"	Boulvert (1971)
5	"	Idem
6	"	"
7	"	"
8	Gabon	Chatelin (1966)
9	Idem	Idem
10	"	"
HAC Tropical Soils		"
1	Nigeria (Aeric Tropaqualf)	Moormann (1981)
2	Nigeria (Vertic mollic Tropaquept)	Idem
3	Cameroon (Typic Tropudalf)	Vallerie (1973)
4	Puerto Rico (Typic Tropohumult)	Jones, Hudwall, and Sakai (1982)
5	Hawaii (Ustic Humitropept)	USDA (1976)
HAC Temperate Soils		
1	France (Aeric Glossaqualf)	Gury (1986)
2	France (Typic Dystrochrept on Sandstone)	Rouiller (1986) pers. comm.
3	France (Typic Glossaqualf)	Gury (1986) pers. comm.
4	France (Typic Glossaqualf)	Gury (1986) pers. comm.
5	France (Typic Glossaqualf)	Gury (1986) pers. comm.
6	France (Typic Dystrochrept on granite)	Lelong and Souchier (1970)
7	France (Typic Dystrochrept on granite)	Lelong and Souchier (1970)

References

Antonello, L.L. 1983. Genese de uma sequencia de solos de rochas alcalinas do Nacico de Stataia. Ph.D. thesis. Rio de Janeiro, Brazil.

Beaudou, A.G. 1971. Sols rouges et beiges. Etude d'une séquence sur quartzite en pays ferrallitique forestier (RCA). Cah. ORSTOM, sér. Pédol., IX, 1:39-79.

Beinroth, F.H. 1982. Some highly weathered soils of Puerto Rico, 1. Morphology, formation and classification. *Geoderma* 27:1-73.

Boulvert, Y. 1971. Différenciation suvant le matériau originel de plusieurs toposéquences en milieu ferrallitisant (près de Bouca - RCA). Cah. ORSTOM, sér. Pédol., IX, 1:43-81.

Chatelin, Y. 1966. Essai de classification des sols ferrallitiques au Gabon. Cah. ORSTOM, sér. Pédol., IV, 4:45-60.

CPCS (Commission de Pédologie et de Classification des sols). 1967. lassification des sols. INA, Grignon. 87 pp.

Goldich, S.S. 1938. A study in rock weathering. *J. Geol.* 46:17-23.

Hughes, J.C. 1981. Mineralogy. pp. 30-50. In D.J. Greenland (ed.). Characterizaiton of soils. Oxford Science Publ.

Herbillon, A.J. 1981. Degree of weathering and surface properties of clays. pp. 80-96. *In* D.J. Greenland (ed.). Characterization of soils. Oxford Science Publ.

Jones, R.C., W.H. Hudwall, and W.S. Sakai. 1982. Some highly weathered soils of Puerto Rico, 2. Mineralogy. *Geoderma* 27:75-137.

Lelong, F. 1964. Etude minéralogique d'un profil d'altération sur roche granitique en Guyane française. *Bull. Serv. Carte Géol.* 4:263-286.

Lelong, F., and B. Souchier. 1970. Bilans d'altération dans la séquence de sols vosgiens, sol bruns acides à podzols, sur granite. *Bull. Serv. CCarte* Géol. 3-4:113-143.

Martin, D., and G. Sieffermann. 1966. Le département du Mungo (Ouest-Cameroun). Etude des sols et de leur utilisation. Cah. ORSTOM, sér. Pédol., IV, 2:27-49.

SOIL WEATHERING STAGES OF THE SUBSURFACE DIAGNOSTIC HORIZONS

CEC and ECEC (meq/100g Clay) \ TRB (meq/100g Soil)	TRB > 40	25 < TRB < 40	TRB < 25
a) CEC > 16	HAC_{Soils}	HAC_{Soils} ?	HAC_{Soils} ?
b) CEC < 16 and ECEC > 2	OXIC INCEPTISOLS CAMBOXIC ALFISOLS CAMBOXIC ULTISOLS	OXISOLS OXIC ALFISOLS OXIC ULTISOLS	OXISOLS OXIC ALFISOLS OXIC ULTISOLS
c) CEC < 16 and ECEC < 2	CAMBOXIC ULTISOLS ?	OXISOLS OXIC ULTISOLS	OXISOLS OXIC ULTISOLS

Fig. 4. Schematic regrouping of mineral soils according to the CEC of their clay fraction and the TRB of their fine earth.

Moormann, F.R. 1981. Representative toposequences of soils in southern Nigeria and their pedology. pp. 10-29. In D.J. Greenland (ed.). Characterization of soils. Oxford Science Publ.

Paramanantham, S. 1977. Ph.D. thesis. Univ. of Ghent, Belgium.

Soil Conservation Service, USDA. 1976. soil survey laboratory data and descriptions for some soils of Hawaii. Soil Survey Investigations Report No. 29. U.S. Govt. Printing Office, Washington D.C. 208 pp.

Soil Survey Staff. SCS, USDA. 1975. Soil taxonomy agricultural handbook, nº 436. U.S. Govt. Printing Office, Washington D.C. 754 pp.

Vallerie, M. 1973. Contribution à l'étude des sols du Centre-Sud Cameroun. Travaux et documents ORSTOM, nº 29. 111 pp.

Van der Plas, L., and J. Van Schuylenborgh. 1970. Petrochemical calculations applied to soils - with special reference to soil formation. *Geoderma* 4:357-385.

Sys, C. 1969. Les sols d'Afrique Centrale dans la classification américaine. 7ème approximation. *Sols Africains* 14:5-24.

APPARENT ECEC IN SOME BRAZILIAN SOILS WITH VARIABLE CHARGES DETERMINED USING THREE DIFFERENT EXTRACTORS

M.A.M. Duriez, M.E.C.C.M. Melo, R.A.L. Johas, and W.S. Araujo[1]

Abstract

This is a study of the relationships among three different extractors for the determination of apparent ECEC values in 40 soil samples with dominant variable charges selected from 25 soil pedons. In the first method (Serviço Nacional de Levantamento e Conservação de Solos [SNLCS]), N KCl was used to extract calcium, magnesium, and extractable acidity, and North Carolina extractor was used for sodium and potassium. The second method used NH_4OAc for calcium, magnesium, sodium, and potassium and the same values of N KCl for extractable acidity. The third one used unbuffered dilute silver thiourea (AgTU) solution (0.01MAg+) for measuring exchangeable bases and extractable acidity. The apparent ECEC was obtained by the sum of all cations expressed in meq/100 g soil or meq/100 g clay. Potassium and sodium were measured by flame photometry, calcium and magnesium by atomic absorption spectro photometry, and extractable acidity by volumetric titration with dilute NaOH using phenolftalein as indicator. All soil samples used satisfied the criteria for low activity clay: apparent ECEC ≤ 12 meq/100 g clay. The apparent ECEC values are highly correlated when referred to 100 g of soil or 100 g of clay. According to statistical analysis and tests of paired observations, AgTU extractor is significantly different from the others.

Determination of exchangeable cations and apparent ECEC in soils with variable charge is widely used in characterizing weathered soils of tropical regions.

The usual methods for determination of CEC extract exchangeable bases with neutral ammonium acetate pH = 7 and extractable acidity with unbuffered potassium chloride. The sum of all cations determined in such a manner is called apparent ECEC (Kamprath 1970 cited in Pleysier and Juo 1980).

Methods using NH_4OAc (Chapman 1965a, b) and $BaCl_2TEA$ (Peech 1965) often overestimate values of CEC of highly weathered soils with reference to their field conditions (Juo, Ayanlaja, and Ogunwale 1976; Gillmann and Bell 1978).

[1] Authors are Soil Researchers at EMBRAPA-SNLCS, Rua Jardim Botânico, 1024, Rio de Janeiro, 22460.

Pleysier and Cremers (1973, 1975) have shown that Ag-thiourea cation has a much stronger affinity for soil colloids than cations commonly occurring in soils so AgTU is a highly effective cation in displacing exchangeable cations in soils and clays at relative low ionic strength. Chhabra, Pleysier, and Cremers (1975) described a method using Ag thiourea for determination of CEC. Pleysier and Juo (1980) developed a single-extraction procedure using an unbuffered dilute Ag-thiourea solution to determine the exchangeable cations and effective CEC in soils with dominant variable charges.

The present paper compares data of exchangeable bases, extractable acidity, and apparent ECEC using three different extractors: Normal ammonium acetate pH = 7, normal potassium chloride, and Ag thiourea comprising 40 samples of high by weathered soils from Brazil.

Materials and Methods

Forty soil samples of B horizons comprising low activity clay soils from Brazil were selected (Table 1).

Methods used in the determination of exchangeable bases, extractable acidity, and apparent ECEC are described in *Manual de Métodos de Análise de Solo* (Empresa Brasileira de Pesquisa Agropecuaria [EMBRAPA] 1979); Chapman (1965a, b); Yuan (1959); and Pleysier and Juo (1980). The apparent ECEC was considered as the sum of cations Ca, Mg, Na, K, and extractable acidity. The procedure described in the *Manual de Métodos* (EMBRAPA 1979) uses normal CaOAc pH = 7 in the determination of extractable acidity but, in the present study, normal KCl is employed for this extraction (Yuan 1959).

Soil extractor ratio is the same for all three methods: 5 g soil/ 50 ml extractor. Time of shaking is 5 min for SNLCS and NH_4 OAc and 120 min for AgTU. In all procedures soil samples and extractors remained in contact overnight.

Analytical data relative to chemical and physical properties of the soil samples used are described in Congresso Brasileiro de Ciência do Solo (1979); Reunião de Classificação, Correlação de Solos e Interpretação de Aptidão Agrícola (1984); and VIIIth International Soil Classification Workshop (1986).

Table 1. Soil Selected Pedons

	Soil classification
ISCW 1	Humic Akrudox; fine, kaolinitic, isothermic
ISCW 2	Humic Akrudox; very fine, allic, isothermic
ISCW 3	Rhodic Hapludox; fine-loamy, kaolinitic, isohyperthermic
ISCW 4	Rhodic Akrudox; very fine, kaolinitic, isohyperthermic
ISCW 5	Typic Akrudox; very fine, kaolinitic, isohyperthermic
ISCW 6	Typic Eutrudox; very fine, kaolinitic, isohyperthermic
ISCW 7	Humic Rhodic Akrudox; very fine, ferritic-gibbsitic, isohyperthermic
ISCW 8	Rhodic Eutrudox; very fine, ferritic, isohyperthermic
ISCW 9	Humic Akrudox; fine, kaolinitic, isohyperthermic
ISCW 10	Typic Akrudox; fine-loamy, kaolinitic, isohyperthermic
ISCW 11	Typic Akrudox; very fine, ferritic-gibbsitic, isothermic
ISCW 12	Plinthic Akraquox; very fine, gibbsitic, isohyperthermic
ISCW 13	Typic Haplustox; coarse-loamy, kaolinitic, isohyperthermic
ISCW 14	Humic Rhodic Eutrustox; very fine, ferritic, isohyperthermic
ISCW 15	Typic Eutrustox; fine, kaolinitic, isohyperthermic
ISCW 16	Ustic Kandihumult; clayey, kaolinitic, isohyperthermic
ISCW 17	Humic Rhodic Akrustox; fine, kaolinitic, isohyperthermic
ISCW 18	Typic Akrustox; very fine, gibbsitic, isohyperthermic
ISCW 19	Humic Akrustox; clayey-skeletal, ferritic, isohyperthermic
ISCW 20	Typic Akrustox; very fine, gibbsitic, isohyperthermic
ISCW 22	Rhodic Haplustox; fine, kaolinitic, isohyperthermic
ISCW 23	Aeric Ochraquox; fine, kaolinitic, isohyperthermic
IIIRCC-4RJ	Typic Haplorthox; clayey, kaolinitic, hyperthermic
SBCS M-3	Aplic Acrorthox; very fine, kaolinitic, isohyperthermic

Results and Discussion

The ECEC values and exchangeable cations determined using three different extractors are shown in Tables 2, 3, and 4. The results are in good agreement for exchangeable bases and ECEC, but for most samples they seem a little higher for extractable acidity when AgTU is used. According to Gallez et al. (1976), cited by Pleysier and Juo (1980): "Errors in exchangeable acidity may arise from the adsorption or release of protons from the oxide surface during the extraction with normal KCl solution. Nevertheless, such errors are generally small for most well-weathered soils because the soil pH value in N KCl suspensions is often near the point zero charge (PZC) of the soil." In measuring exchangeable acidity, the dilute AgTU solution minimizes the adsorption or desorption of protons at the oxide surface that may occur during extraction with N KCl (Pleysier and Juo 1980).

The apparent ECEC values are highly correlated when referred to 100 g of soil or 100 g of clay (Table 5), although in some samples the ECEC seems higher when AgTU is used due to extractable acidity data.

The statistical analysis points out that the mean values of ECEC using AgTU differ statistically from the others (Table 6). All soil samples fit in the criteria for low activity clay (ECEC $\leq$ 12 meq/100 g clay) for all extractors used.

According to the results obtained we can conclude that for strongly weathered soils with a predominance of variable charge colloids, the apparent ECEC may be determined by any of these three extractors which are highly correlated.

Acknowledgment

The authors express their thanks to Neli do Amaral Meneguelli for the statistical analysis of data.

References

Chapman, H.D. 1965a. Cation-exchange capacity. *In* C.A. Black, D.D. Evans, J.L. White, L.E. Ensminger, and F.E. Clark, (eds.). Methods of soil analysis, v.2. Amer. Soc. of Agron., Madison, WI. pp. 891-901.

——— 1965b. Total exchangeable bases. *In* C.A. Black, D.D. Evans, J.L. White, L.E. Ensminger, and F.E. Clark, (eds.). Methods of soil analysis, v.2. Amer. Soc. of Agron., Madison, WI. pp. 902-904.

Chhabra, R., J.L. Pleysier, and A. Cremers. 1975. The measurement of the cation exchange capacity and exchangeable cations in soils; a new method. *In* Proc. International Clay Conference, Mexico. pp. 439-448.

Congresso Brasileiro De Ciência Do Solo, 17. Manaus, AM. 1979. Guia de excursão. EMBRAPA-SNLCS/SBCS. Rio de Janeiro, Brazil. 72 p.

Table 2. Exchangeable Cations and Apparent ECEC Using Three Different Extractors

Pedons ISCW	Horizon	SNLCS				Extr.	AgTU				Extr.	NH_4OAc			
		Ca	Mg	Na	K	Al[a]	Ca	Mg	Na	K	Al[b]	Ca	Mg	Na	K
		(meq/100 g soil)													
1	Bo2	0.03	0.01	0.01	0.02	0.85	0.01	0.01	0.01	0.01	1.18	0.05	0.01	0.01	0.01
2	B01	0.07	0.02	0.02	0.01	0.20	0.01	0.01	0.01	0.01	0.30	0.04	0.02	0.01	0.01
3	BA	0.02	0.22	0.02	0.03	1.25	0.01	0.25	0.02	0.03	1.23	0.03	0.22	0.01	0.02
3	Bo1	0.02	0.04	0.02	0.02	1.10	0.03	0.03	0.03	0.03	1.10	0.03	0.04	0.01	0.01
4	Bo1	0.06	0.15	0.02	0.06	1.33	0.03	0.13	0.02	0.03	1.75	0.19	0.15	0.01	0.01
4	Bo2	0.06	0.05	0.03	0.10	0.35	0.03	0.05	0.07	0.14	0.50	0.03	0.04	0.01	0.08
5	Bto2	0.70	0.36	0.02	0.04	1.20	0.47	0.36	0.02	0.03	1.57	0.80	0.34	0.01	0.04
5	Bo2	0.04	0.11	0.01	0.05	0.85	0.06	0.10	0.04	0.06	1.77	0.05	0.11	0.01	0.06
5	BC	0.01	0.10	0.02	0.05	2.65	0.01	0.09	0.02	0.04	3.10	0.02	0.14	0.01	0.05
6	Bto2	4.38	1.25	0.02	0.08	0.40	4.20	1.30	0.04	0.05	0.20	4.14	1.18	0.02	0.09
6	Bo1	0.44	0.68	0.03	0.05	1.23	0.25	0.72	0.03	0.07	1.78	0.47	0.70	0.02	0.05
6	Bo2	1.40	2.83	0.03	0.09	0.25	1.41	2.78	0.04	0.06	0.18	1.41	2.79	0.02	0.10
6	BC	0.02	0.12	0.03	0.35	1.57	0.01	0.11	0.04	0.32	2.36	0.05	0.14	0.04	0.40
7	Bo2	0.11	0.04	0.02	0.05	0.20	0.12	0.05	0.03	0.04	0.17	0.10	0.03	0.01	0.05
8	Bo2	2.34	0.96	0.02	0.02	0.12	2.30	1.12	0.02	0.04	0.10	2.25	0.94	0.01	0.01
9	Bo1	0.06	0.01	0.01	0.01	0.23	0.02	0.01	0.01	0.03	0.20	0.02	0.01	0.01	0.01
10	Bo2	0.07	0.01	0.01	0.01	0.27	0.03	0.01	0.02	0.04	0.34	0.03	0.01	0.01	0.01
11	Bo3	0.04	0.01	0.01	0.01	0.10	0.02	0.01	0.02	0.02	0.10	0.01	0.01	0.01	0.01
12	Bovl	0.03	0.01	0.01	0.01	0.10	0.02	0.01	0.01	0.02	0.26	0.02	0.01	0.01	0.01
13	Bo1	0.04	0.03	0.01	0.02	0.90	0.01	0.03	0.02	0.04	1.07	0.04	0.03	0.01	0.01
13	Bo2	0.04	0.02	0.01	0.02	0.70	0.01	0.02	0.02	0.08	1.14	0.05	0.02	0.01	0.01
14	Bo2	2.40	0.46	0.02	0.52	0.15	2.48	0.46	0.04	0.40	0.14	2.45	0.46	0.05	0.41
15	Bto1	1.08	0.40	0.01	0.20	0.13	1.07	0.41	0.02	0.14	0.20	1.06	0.41	0.01	0.16
16	Bto1	1.16	0.48	0.02	0.06	0.18	1.16	0.47	0.02	0.04	0.19	1.13	0.45	0.01	0.04
16	Bo	0.53	0.63	0.02	0.18	0.15	0.48	0.66	0.02	0.12	0.12	0.45	0.70	0.01	0.14
17	Bo3	0.80	0.13	0.02	0.04	0.07	0.78	0.14	0.02	0.03	0.06	0.79	0.15	0.01	0.03
18	Bo	0.09	0.01	0.01	0.01	0.20	0.09	0.01	0.02	0.03	0.26	0.06	0.01	0.01	0.01
18	Boc2	0.07	0.02	0.01	0.01	0.10	0.06	0.03	0.02	0.01	0.34	0.04	0.02	0.01	0.01
19	Bocl	0.08	0.02	0.01	0.01	0.20	0.05	0.02	0.01	0.03	0.27	0.04	0.02	0.01	0.01
20	Bo2	0.06	0.01	0.02	0.01	0.14	0.03	0.01	0.022	0.04	0.16	0.02	0.01	0.01	0.01
22	BA	0.02	0.02	0.03	0.04	1.50	0.03	0.01	0.02	0.04	1.50	0.05	0.02	0.01	0.02
22	Bo1	0.02	0.01	0.03	0.04	1.38	0.01	0.01	0.02	0.02	1.35	0.03	0.01	0.01	0.01
22	Bo2	0.02	0.02	0.03	0.02	0.95	0.01	0.01	0.02	0.01	1.10	0.05	0.02	0.01	0.01

Table continued on next page

Table 2. Continued

Pedons ISCW	Horizon	SNLCS				Extr.	AgTU				Extr.	NH_4OAc			
		Ca	Mg	Na	K	Al[a]	Ca	Mg	Na	K	Al[b]	Ca	Mg	Na	K
		(meq/100 g soil)													
23	Bogl	0.03	0.02	0.02	0.03	1.95	0.01	0.2	0.01	0.02	1.95	0.14	0.02	0.01	0.04
23	Bcvg	0.02	0.01	0.03	0.02	1.67	0.04	0.01	0.02	0.02	1.80	0.07	0.02	0.01	0.01
IIIRCC-4RJ	BA	0.04	0.02	0.01	0.01	2.35	0.03	0.02	0.02	0.05	2.34	0.13	0.02	0.01	0.01
IIIRCC-4RJ	Bol	0.01	0.01	0.01	0.01	2.23	0.01	0.01	0.01	0.01	2.30	0.08	0.01	0.01	0.01
IIIRCC-4RJ	Bo3	0.08	0.02	0.01	0.01	0.80	0.07	0.03	0.04	0.06	1.40	0.15	0.03	0.01	0.07
SBCS M-3	BA	0.01	0.07	0.10	0.09	2.10	0.01	0.06	0.10	0.09	2.00	0.06	0.08	0.09	0.07
SBCS M-3	Bol	0.07	0.08	0.14	0.10	1.15	0.06	0.09	0.12	0.11	1.30	0.19	0.08	0.12	0.11

[a] Extractable acidity titrated with 0.025N NaOH in KCl extract.
[b] Extractable acidity titrated with 0.025N NaOH in AgTU extract.

Table 3. Apparent Effective Cation Exchange Capacity Using Three Different Extractors Referred to 100 g Soil

Pedon ISCW	Horizon	SNLCS	NH_4OAc	AgTU
		----------(meq/100 g soil)----------		
1	Bo2	0.92	0.93	1.22
2	Bo1	0.32	0.28	0.42
3	BA	1.54	1.53	1.54
3	Bo1	1.20	1.19	1.22
4	Bo1	1.62	1.69	1.96
4	Bo2	0.59	0.52	0.79
5	Bto2	2.32	2.39	2.45
5	Bo2	1.06	1.08	2.03
5	BC	2.83	2.87	3.26
6	Bto2	6.13	5.83	5.79
6	Bo1	2.43	2.47	2.85
6	Bo2	4.60	4.57	4.47
6	BC	2.09	2.20	2.84
7	Bo2	0.42	0.39	0.41
8	Bo2	3.46	3.33	3.58
9	Bo1	0.32	0.28	0.27
10	Bo2	0.37	0.33	0.44
11	Bo3	0.17	0.14	0.17
12	Bov1	0.16	0.15	0.32
13	Bo1	1.00	0.99	1.17
13	Bo2	0.79	0.79	1.27
14	Bo2	3.55	3.52	3.52
15	Bto1	1.82	1.77	1.84
16	Bto1	1.90	1.81	1.88
16	Bo	1.51	1.45	1.40
17	Bo3	1.06	1.05	1.03
18	Bo	0.32	0.29	0.41
18	Boc2	0.21	0.18	0.46
19	Boc1	0.32	0.28	0.38
20	Bo2	0.24	0.19	0.26
22	BA	1.61	1.60	1.60
22	Bo1	1.48	1.44	1.41
22	Bo2	1.04	1.04	1.15
23	Bog1	2.05	2.16	2.01
23	Bcvg	1.75	1.78	1.89
IIIRCC-4RJ	BA	2.43	2.52	2.46
IIIRCC-4RJ	Bo1	2.27	2.34	2.34
IIIRCC-4RJ	Bo3	0.92	1.01	1.60
SBCS M-3	BA	2.37	2.40	2.26
SBCS M-3	Bo1	1.54	1.65	1.68

Table 4. Apparent Effective Cation Exchange Capacity Using Three Different Extractors Referred to 100 g Clay

Pedons ISCW	Horizons	SNLCS	NH_4OAc	AgTU
		----------(meq/100 g soil)----------		
1	Bo2	2.22	2.27	2.98
2	Bo1	0.48	0.42	0.63
3	BA	4.40	4.37	4.49
3	Bo1	3.53	3.41	3.59
4	Bo1	2.16	2.25	2.61
4	Bo2	0.77	0.68	1.04
5	Bto2	2.97	3.06	3.14
5	Bo2	1.41	1.44	2.71
5	BC	4.10	4.07	4.72
6	Bto2	7.86	7.47	7.42
6	Bo1	3.15	3.21	3.70
6	Bo2	6.05	6.01	5.88
6	BC	2.78	2.93	3.79
7	Bo2	0.55	0.51	0.54
8	Bo2	4.74	4.56	4.90
9	Bo1	0.78	0.66	0.66
10	Bo2	1.68	1.50	2.00
11	Bo3	0.19	0.16	0.20
12	Bov1	0.25	0.25	0.50
13	Bo1	5.88	5.82	6.88
13	Bo2	4.39	4.39	7.06
14	Bo2	4.93	4.88	4.89
15	Bto1	4.55	4.42	4.60
16	Bto1	3.72	3.33	3.69
16	Bo	3.14	3.02	2.92
17	Bo3	1.96	1.94	1.91
18	Bo	0.40	0.36	0.51
18	Boc2	0.28	0.24	0.64
19	Bocl	0.38	0.34	0.46
20	Bo2	0.30	0.23	0.33
22	BA	3.35	3.33	3.33
22	Bo1	3.08	3.00	2.94
22	Bo2	2.36	2.36	2.61
23	Bogl	3.41	3.60	3.35
23	Bcvg	2.96	3.01	3.20
IIIRCC-4RJ	BA	5.40	5.60	5.47
IIIRCC-4RJ	Bo1	4.83	4.98	4.98
IIIRCC-4RJ	Bo2	1.80	1.98	3.14
SBCS M-3	BA	2.96	3.00	2.83
SBCS M-3	Bo1	1.81	1.94	1.98

Table 5. Correlation Coefficient (*r*) between ECEC Values

Extractors	*r* (100 g soil)	*r* (100 g clay)
SNLCS x NH_4OAc	0.998**	0.997**
SNLCS x AgTU	0.980**	0.960**
NH_4OAc x AgTU	0.983**	0.964**

** Significant at the 0.01 level

Table 6. Comparison of Means According to Tests of Paired Observations between ECEC Values

Extractors	Means* (100 g soil)	Means (100 g clay)
AgTU	a 1.7025	a 3.0805
SNLCS	b 1.5680	b 2.7990
NH_4OAc	b 1.5557	b 2.7750

* Means with the same letter are not significantly different.

Empresa Brasileira de Pesquisa Agropecuária (EMBRAPA). Serviço Nacional de Levantamento e Conservação de Solos. 1979. Manual de Métodos de análise de solo. Rio de Janeiro, Brazil. 1 v.

Gillman, G.P., and L.C. Bell. 1978. Soil solution studies on weathered soils from tropical North Queensland. *Aust. J. Soil Res.* 16(1):67-77.

International Soil Classification Workshop (VIIIth)., Brazil. 1986. Tour Guide, s.l. SMSS/EMBRAPA-SNLCS/UPR. 285 p.

Juo, A.S.R., S.A. Ayanlaja, and J.A. Ogunwale. 1976. An evaluation of cation exchange capacity measurements for soils in the tropics. *Commun. Soil Sci. Plant Anal.* 7(8):751-761.

Peech, M. 1965. Exchange acidity. *In* C.A. Black, D.D. Evans, J.L. White, L.E. Ensminger, and F.E. Clark, (eds.). Methods of soil analysis. v.2. Amer. Soc. of Agron., Madison, WI. Pp. 905-913.

Pleysier, J.L., and A. Cremers. 1973. Adsorption of the silver-thiourea complex in montmorillonite. *Nature Phys. Sci.* 243:86-87.

——— 1975. Stability of silver-thiourea complexes in montmorillonite clay. *J. Chem. Soc. Faraday Trans.* 71:256-264.

Pleysier, J.L., and A.S.R. Juo. 1980. A single-extraction method using silver-thiourea for measuring exchangeable cations and effective CEC in soils with variable charges. *Soil Sci.* 129(4):205-211.

Reunião De Classificação, Correlação De Solos e Interpretação De Aptidão Agrícola, 3., Rio de Janeiro, RJ, 1984. Guia de excursão de estudos de solos nos Estados de Minas Gerais, Rio de Janeiro, São Paulo e Paraná. EMBRAPA-SNLCS/SBCS, Rio de Janeiro, Brazil. 104 p.

Yuan, T.L. 1959. Determination of exchangeable hydrogen in soils by a titration method. *Soil Sci.* 88(3):164-167.

PHOSPHORUS ADSORPTION CHARACTERISTICS OF BRAZILIAN OXISOLS

N. Curi[1] and O.A. de Camargo[2]

Abstract

The phosphorus adsorption maximum (PAM) from selected soil samples was determined, with the aim of further verifying its viability and usefulness as an additional criterion to differentiate Oxisols. Soil:solution ratios of 1:20 were utilized. The adsorption data were evaluated assuming two types of sites and by applying the Langmuir two-surface equation.

There was a great range of variation in the PAM values, from 596 to 3450 μgPg^{-1} soil, which seems to indicate the possibility of considering this parameter an additional characteristic to differentiate Oxisols, although the adsorption maximum is a very complex process. Many parameters are needed to explain its variability, especially in the case of so general a soil order as Oxisols, which was confirmed in this study.

The multiple regression study stressed that the parameters which better explain the variability of the PAM values are, in decrescent grade, SiO_2/R_2O_3 (or SiO_2/Al_2O_3) molecular ratio and clay content. The inclusion of additional variables to the model did not improve the r^2 value. Assuming that Oxisols with low SiO_2/R_2O_3 molecular ratio tend to be clayey and that this molecular ratio was in operation during the trials to establish and separate the classes, two classes of PAM are proposed for further testing, indicated by that quotient, in the following arrangement: low to medium [PAM $\leq$ 2100 μgg^{-1} ($SiO_2/R_2O_3 > 0.75$)]; and high [PAM > 2100 μgg^{-1} ($SiO_2/R_2O_3 \leq 0.75$)].

Revalidation of these findings through future, more universal studies is not only desirable but necessary.

There is good evidence that P availability to plants is related to P in the soil solution (Mattingly 1975). On the other hand, this P-solution concentration seems to depend closely upon the adsorbed P on the surface of the soil components. Thus, adsorption is a very important phenomenon occurring in soils and should be taken into consideration in an analysis of the P-soil-plant relationships. This led Fox (1982) to suggest the inclusion of P adsorption characteristics in the criteria for soil classification at the management level (i.e. among the soil family criteria).

Ideally, P fixation should be estimated independent of other soil properties. However, at the present time it is not feasible for a routine soil survey laboratory to determine this parameter. Some Brazilian researchers have tried to use variables usually found in soil survey reports, which could present a significant grade of explanation of the phosphorus adsorption maximum variability, for helping in the establishment and classes differentiation of Oxisols (Curi et al. 1986).

In recent years there has been an increased interest in the phosphorus adsorption maximum quantification in Brazilian Oxisols (Resende 1976; Lopes 1977; Bigham et al. 1978; Bahia Filho 1982; Curi 1983; Gualberto 1984; Correa 1984; Souza 1985). The idea of using phosphorus adsorption as a classification criterion for Brazilian Oxisols was discussed by Curi et al. (1986).

The objective of this paper is to study further the viability and usefulness of using P adsorption as an additional criterion to differentiate Oxisols, through the use of other indicator parameters generally present in soil survey reports.

Background

Three subjects will be dealt with here: mineralogy, mechanisms of adsorption, and relationships between P adsorption and other soil properties.

Mineralogy

Among the factors influencing adsorption directly soil mineralogical composition is a very important one. According to Fox and Searle (1978), soils of the tropics may be divided into five groups, depending on the quality of P adsorbed, as follows: quartz = aluminum-free organic matter < 2:1 clays < 1:1 clays < crystalline oxides of iron and aluminum < amorphous oxides of Al and Fe. Juo and Fox (1977) have quantified these relationships in terms of standard P sorption as very low (< 10 µg P/g soil), low (10 to 100 µg/g), medium (100 to 500 µg/g), high (500 to 1000 µg/g), and very high (> 1000 µg/g) for each class, respectively.

[1] Departamento de Ciência do Solo, Escola Superior de Agricultura de Lavras (ESAL). Caixa Postal 37. CEP 37200-Lavras, Minas Gerais, Brazil.
[2] Seção de Pedologia Instituto Agronômico de Campinas (IAC). Caixa Postal 28. CEP 13100-Campinas, São Paulo, Brazil.

Oxisols are distinguished mainly in terms of two major criteria (Soil Survey Staff 1975): (1) the presence of an oxic horizon at some depth within 2 m of the soil surface and (2) the occurrence of plinthite that forms a continuous phase within the first 30 cm of the pedon. Also they do not have a spodic or an argillic horizon that overlays the oxic horizon. An oxic horizon has as major constituents, following Resende (1976) and Herbillon (1980), quartz as primary mineral and kaolinite, goethite, hematite, and gibbsite as secondary ones. These secondary minerals are very important in the P-adsorption process and have been considered the P-reactive fraction in soils (Larsen 1967; Parfitt 1978). Karim and Adams (1984) studied a catena of Oxisols in Malawi and observed a correlation between DCB-extractable iron and aluminum and P sorption and hypothesized that an Al-substituted goethite was the mineral mainly responsible for phosphate sorption capacity. Ainsworth and Summer (1985) studied Al-substitution in goethite and detected an effect on surface area decreasing the crystal size, and the overall accessibility of A-type hydroxyls toward ligand exchange with phosphate was affected.

Adsorption Mechanisms

Studies involving P adsorption by iron and aluminum oxides based on the effect of pH (Hingston, Posner, and Quirk 1972; Breeuwsma and Lyklema 1973) and on the release of hydroxyl ions during P adsorption (Breeuwsma and Lyklema 1973; Rajan 1975; Parfitt, Atkinson, and Smart 1975) led these researchers to propose some mechanisms which invariably involved ligand exchange reactions at the hydrated oxide surface (Mott 1981).

In this mechanism oxygen ions of the oxide surface can be replaced by the phosphate oxyacid that enters into sixfold coordination with aluminum or iron rendering the surface more negative, as shown below (Bohn, McNeal, and O'Conner 1979):

$$\left[\begin{matrix} OH^{-0.5} \\ \\ OH^{-0.5} \end{matrix}\right]^{-1} \ldots Na^{+} + NaH_2PO_4^{-} \rightleftharpoons \begin{matrix} PO_4H_{1.5}^{-1.5} \\ | \\ OH^{-0.5} \end{matrix} \ldots 2Na^{+} + 0.5H_2O. \left[\begin{matrix} \\ \\ \\ \end{matrix}\right]^{-2}$$

This kind of reaction model is able to explain the adsorption maxima on goethite at pH values near the pK values of the phosphate oxyacids as was observed by Hingston et al. (1986).

As mentioned earlier kaolinite is also an important mineral component of general occurrence in the clay fraction of Oxisols. The adsorption of phosphate by this clay mineral has long been studied by several researchers (Black 1943; Chakravarti and Talibudeen 1961; Kittrick and Jackson 1956). Low and Black (1950) and Kuo and Lotse (1972) showed that at low P-solution concentrations phosphate is adsorbed on these clay mineral surfaces, and Wada (1959) and Chen, Buttler, and Stumm (1973) proposed that at high concentrations precipitation occurred forming crystalline phases such as taranakite.

Muljadi, Posner, and Quirk (1966) were able to distinguish at least three different energetic regions of adsorption isotherms for kaolinite and aluminum oxides. They showed that phosphate adsorption on kaolinite took place on the edges of the crystals where the ion reacts with the Al(OH)-H_2O groups (Kyle, Posner, and Quirk 1975). Phosphate may not be adsorbed in the planar surface side which consists of Al-OH groups, according to Parfitt et al. (1977), because the hydroxyls are coordinated with two Al atoms and probably are unreactive at low concentrations. Other researchers (Low and Black 1950; Rajan and Perrot 1975) have proposed the replacement of silica from the silicate framework at high solution P concentration as an additional mechanism of P adsorption.

Despite the fact that noncrystalline forms may be of less concentration in Oxisols, they can also contribute to the P-adsorption process. Generally these forms sorb more phosphate per unit weight than will crystalline ones (Bache 1964; McLaughlin, Ryden, and Syers 1981) and this fact helps to explain the reason why some researchers (Bromfield 1965; Khalid, Patrick, and DeLuanc 1977; Hughes and Le Mare 1982) found that Al and Fe solubilized by acid oxalate extractant were related to P adsorption.

It should be mentioned here that the above reactions described for phosphate are fast reactions which occur in a matter of days at most (Fox and Kamprath 1970). However, the phosphate concentration in the equilibrium solutions continues to diminish slowly over longer periods of time (Barrow and Shaw 1975a; Helyar, Munns, and Burau 1976; Munns and Fox 1976). Munns and Fox described this slow fixation as having a first order kinetics with respect to P and showed that for three Oxisols equilibrium was achieved in 100-200 days. They estimated that 30 to 50 percent of the added phosphate remained available for plant growth. Barrow and Shaw (1975b) also observed a decrease of the added exchangeable phosphate fraction through the use of radioactive phosphate, and Barrow (1974) also noticed that the effectiveness of the added P for plant growth decreased.

Relationships between P Adsorption and Other Soil Properties

Several workers (Udo and Uzu 1972; Leal and Velloso 1973; Ballard and Fiskell 1974; Camargo, van Raij, and Grohmann 1974; Faria, Braga, and Pinto 1976; Juo and Fox 1977; Kanabo, Halm, and Obeng 1978; Bahia Filho 1982; Curi and Franzmeier 1984; Gualberto 1984; Souza 1985; Curi et al. 1986) have tried to correlate P adsorption with the aluminum and iron oxides content of soils and have found good correlations. This is good evidence that aluminum and iron oxides are among the most important soil parameters influencing P retention by soils. Bigham et al. (1978) studied some Oxisols from Brazil to determine how the colors of the samples were influenced by the nature and distribution of iron oxides, and found that the yellow clays with a small proportion of hematite in relation to goethite were more efficient adsorbers of phosphate. Besides these oxides, several other characteristics and properties have been described to be significantly correlated with P adsorption. Clay

amount has been found to be correlated in some cases (Leal and Velloso 1973: Camargo, van Raij, and Grohmann 1974; Faria, Braga, and Pinto 1976; Lopes 1977), although Camargo, van Raij, and Grohmann (1974) explained that this significant and positive correlation might be associated with the high correlation existing between iron and aluminum oxides and clay content in some soils. This fact seems to be important because more recently Curi et al. (1986) found for 14 Oxisols from Brazil low correlation of P adsorption and amount of clay.

The soil pH has been indicated by some workers as being correlated with P adsorption (Udo and Uzu 1972; Camargo, van Raij, and Grohmann 1974), although Lopez-Hernandez and Burnham (1974) and Fox (1982) found no apparent relationship between these parameters for a group of soils. The increase in pH of a soil seems not to decrease P retention (Mokwunye 1975), although Camargo, van Raij, and Grohmann (1974) observed for some Brazilian Oxisols that the elevation of their pH with $Ca(OH)_2$ did not influence P adsorption, but when their pH was increased with NaOH there was a decrease in P adsorption. This fact agrees with Lopez-Hernandez and Burnham (1974) who described that liming increased the pH but also the amount of soluble calcium, which have opposing effects on the retention of P, causing no alteration in the system.

Fox, Hasan, and Jones (1971) showed a close relationship between P sorption and silica:sesquioxides ratio but no correlation with the amounts of the extracted elements. Curi et al. (1986) found that the Fe_2O_3 extracted by 9M sulfuric acid from 14 Oxisols of southeast and south Brazil was very highly correlated with P-adsorption maximum, the necessity for revalidation of which gave rise to this paper.

Finally, it is important to stress that a coadsorption of cations may happen as a consequence of phosphate ion adsorption, increasing the cation exchange capacity of the system (Schalscha et al. 1972; Sawhney 1974; Ryden and Syers 1976; Wann and Uehara 1978).

Materials and Methods

Soils

Samples from Brazilian Oxisols (B horizon) were selected for P adsorption studies, being those among the soil profiles of the VIIIth International Soil Classification Workshop (ISCW).

Characteristics and Properties

The following characteristics and properties were elected in order to study the correlations with the phosphorus adsorption maximum: SiO_2/Al_2O_3 molecular ratio (9M H_2SO_4 digestion), $Fe_2O_{3\,(s)}$ (9m H_2SO_4 digestion), $Fe_2O_{3\,(d)}$ (CBD extraction), moist Munsell hue (10R=OYR), SiO_2/R_2O_3 molecular ratio (9M H_2SO_4 digestion), clay percentage, $Al_2O_{3\,(s)}$ (9M H_2SO_4 digestion), Al^{3+} (1M KCl extraction), and $P_2O_{5\,(s)}$ (9M H_2SO_4 extraction); all of these data were furnished by EMBRAPA/SNLCS.

Phosphorus Adsorption

A 2-g whole-soil sample was shaken for 12 hours with a series of 40-mL P solutions (0-160 mg/L) prepared in 0.01M $CaCl_2$. The samples were centrifuged and the P in the supernatant was determined by the method of Murphy and Riley (1962). The amount of P adsorbed was calculated from the difference between the initial concentration of P in solution minus the final concentration of P in solution. The adsorption data were evaluated assuming two types of sites and applying the Langmuir two-surface equation (Syers et al. 1973; Rajan and Fox 1975).

Results and Discussion

P-Adsorption Data

The data for PAM (phosphorus adsorption maximum) of selected B horizons can be visualized in Table 1.

The PAM values ranged from 596 μgPg^{-1} soil (sample of pedon VIII ISCW-15) till 3450 μgPg^{-1} soil (sample of pedon VIII ISCW-12), evidencing a much differentiated behavior. Burnham and Lopez-Hernandez (1982) found that samples from Oxisols from Ghana, Malaya, and Venezuela varied greatly in sorption index.

Relationships between P-adsorption and Some Parameters of the Oxisols Studied

In order to relate phosphorus adsorption with some characteristics and properties of the Oxisols studied, correlations between adsorption and other parameters of the materials in question were performed. In a first analysis, the simple correlation coefficients were determined (Table 2). With exception of the moist hue and Al^{3+}, all of the other parameters were significantly correlated with the PAM at 5 percent level.

Aiming to get the functional relationship between any one of the X_i variables and the PAM dependent variable, the least-squares method was used. The following models were tested: straight line ($Y = b_0 + b_1x_i$), second grade polynominal ($y = b_0 + b_1x_i + b_2x_i^2$), third grade polynominal ($y = b_0 + b_1x_i + b_2x_i^2 + b_3x_i^3$), logarithmic ($y = b_0 + b_1 \log x_i$), and exponential ($y = b_0x_i^{b_1}$). The results are shown in Table 3.

Due to the fact that the individual adjustments are not good (see r values), we changed to a multiple regression study by the stepwise process, obtaining the following final equation: $y = 1715.045 - 540.4831_{x5} + 12.8720_{x6}$ with $r = 0.61$, stressing that the parameters which better explain the variability of the PAM values are, in decrescent grade, SiO_2/R_2O_3 molecular ratio and clay percentage. SiO_2/Al_2O_3 molecular ratio presented the same trend as SiO_2/R_2O_3. The inclusion of additional variables to the model did not improve the r^2 value.

The low correlation coefficient for soil color (moist hue) and PAM deserves to be commented on. For high correlation the soils should be otherwise similar (Curi and Franzmeier 1984) which absolutely does not occur with the materials under study; furthermore, the pedoenvironments are highly different in some cases, suggesting that the generalizations with respect to the behavior of yellowish or reddish soil material in relation to PAM should be restricted for a while to specific conditions (Gualberto 1984; Correa 1984).

Table 1. Phosphorus Adsorption Maximum (PAM) of Selected B Horizons from Oxisols of the VIIIth ISCW

Pedon number	Horizon	Sample number	PAM (μgPg^{-1} soil)
VIII ISCW-1	Bo2	85.0610	812
2	Bo1	85.0618	2280
3	Bo1	85.0625	2140
4	Bo2	85.0632	2100
6	Bto2	85.0636	1536
6	Bo2	85.0639	2286
5	Bto2	85.0645	2060
5	Bo2	85.0647	2100
7	Bo2	85.0655	2160
8	Bo2	85.0661	2490
9	Bo1	85.0669	2646
10	Bo2	85.0676	2295
11	Bo3	85.0684	2500
12	Bov3	85.0692	3450
13	Bo2	85.0699	790
14	Bo2	85.0706	2214
15	Btol	85.0713	596
16	Btol	85.0719	1176
16	Bo	85.0721	2180
17	Bo3	85.0730	2260
18	Bo	85.0738	2240
18	Boc2	85.0740	2100
19	Bocl	85.0746	2100
20	Bo2	85.0753	2260
22	Bol	85.0759	1650
23	Bogl?	85.0765	1602
23	BCvg	85.0767	1365

Table 2. Simple Correlation Coeficients between Phosphorus Adsorption Maximum (PAM) and Other Properties and Characteristics of the Oxisols Studied

Parameters	PAM
SiO_2/Al_2O_3	-0.47[a]
$Fe_2O_{3(6)}$	0.47[a]
$Fe_2O_{3(d)}$	0.44[a]
Moist hue	-0.25
SiO_2/R_2O_3	-0.47[a]
Clay percentage	0.42[a]
Al_2O_3	0.46[a]
Al^{3+}	-0.36
$P_2O_{5(6)}$	0.42[a]

[a] Significant at 5% level.

Table 3. Adjusted Regression Equations and Correlation Coefficients for P Adsorption and Some Characteristics and Properties of the Selected B Horizons

	Phosphorus Adsorption Maximum (y)	
x_i	Best equation	
x_1 (SiO_2/Al_2O_3)	$y = 2610.11 - 511.986\ x_1$	-0.47
x_2 ($Fe_2O_{3(6)}$)	$y = 1611.11 + 32.314\ x_2$	0.41
x_3 ($Fe_2O_{3(d)}$)	$y = 1552.96 + 43.140\ x_3$	0.44
x_4 (Moist hue)		-0.25
x_5 (SiO_2/R_2O_3)	$y = 2531.08 - 567.187\ x_5$	-0.47
x_6 (Clay percentage)	$y = 1138.98 + 13.661\ x_6$	0.42
x_7 ($Al_2O_{3(6)}$)	$y = 941.325 + 46.543\ x_7$	0.46
x_8 (Al^{3+})		-0.36
x_9 ($P_2O_{5(6)}$)	$y = 1575.31 + 5566.48\ x_9$	0.42

Classes of Phosphorus Adsorption Maximum

In the new systems of soil classification there is a trend to place emphasis upon properties which are more relevant for agricultural purposes, intending soil classes differentiation (Finkl 1982).

As shown in Table 1, there was a great range in the adsorption maximum of the studied soil materials, from 596 to 3450 $\mu g g^{-1}$ soil, which seems to indicate the opportunity of considering this parameter as a possible additional characteristic to differentiate Oxisols, although the PAM is a very complex process and for explaining its variability there is need of many parameters, especially in the case of so general a soil order as Oxisols, which was confirmed in this study.

The multiple regression study evidenced that the SiO_2/R_2O_3 (or SiO_2/Al_2O_3) molecular ratio and clay content presented a significant grade of PAM explanation in comparison with the other variables. Keeping in mind that Oxisols with low SiO_2/R_2O_3 molecular ratio tend to be clayey (Resende 1982), and that the observation of Figure 1 reveals two distinct groups of PAM as a function of the SiO_2/R_2O_3 molecular ratio it seems, by now,

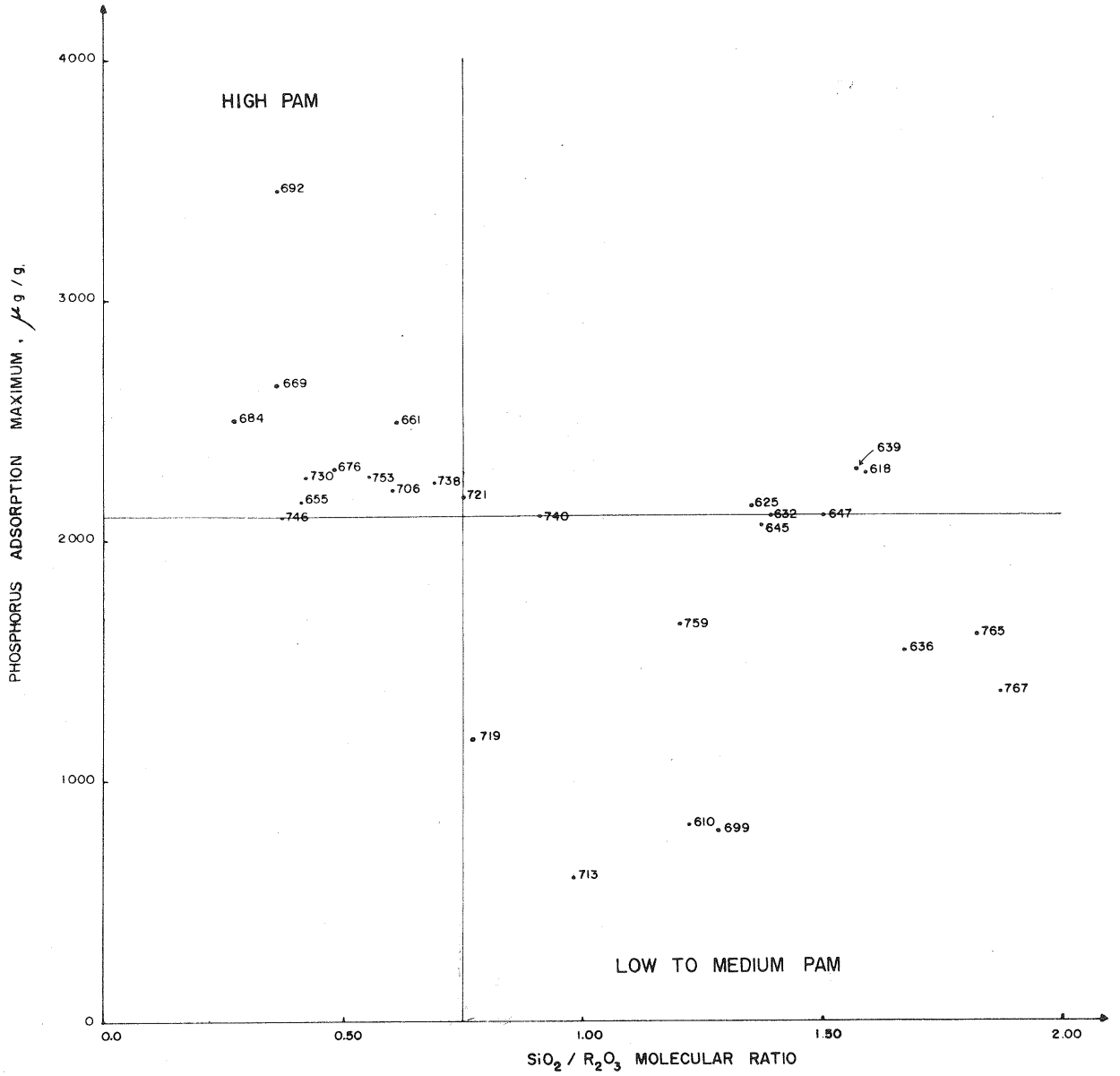


Fig. 1. Relationship between phosphorus adsorption maximum (PAM) and SiO_2/R_2O_3 molecular ratio, and the tentative classes of PAM for the studied Oxisols.

to be justifiable in terms of P adsorption to subdivide the Oxisols taking into consideration only that quotient.

In a recent paper, Resende and Santana (1986) concluded that for Brazilian Oxisols the SiO_2/R_2O_3 molecular ratio can be used as a characteristic to differentiate kaolinitic (> 0.75) from gibbsitic (≤ 0.75) Oxisols and that by similar assumptions the $Si0_2/Al_2O_3$ molecular ratio differentiates kaolintic (>0.75) from gibbsitic (≤ 0.75) Oxisols, which furnishes a genetic basis for further subdividing Oxisols taking into account these parameters. Thus, we proposed for further testing two classes of PAM for Oxisols, indicated by the SiO_2/R_2O_3 molecular ratio as follows: low to medium [PAM ≤ 2100 μgg^{-1} (SiO_2/R_2O_3 > 0.75)]; and high [PAM > 2100 μgg^{-1} ($SiO_2/R_2O_3 \leq 0.75$)].

The application of these criteria to the pedomaterials selected for P-adsorption studies of the VIII ISCW forms the following groups: low to medium PAM (sample numbers 0610, 0632, 0636, 0645, 0647, 0699, 0713, 0719, 0740, 0759, 0765, and 0767), and high PAM (sample numbers 0655, 0661, 0669, 0676, 0684, 0692, 0706, 0721, 0730, 0738, and 0753). The sample number 0746 is borderline between low to medium and high PAM classes having much more affinity with the high PAM class (SiO_2/R_2O_3 = 0.37 and PAM value of 2100μgg^{-1}). The sample number 0625 had a slightly higher PAM value (2140 μgg^{-1}) and the sample numbers 0618 and 0639 had somewhat higher PAM values (2280 and 2286 μgg^{-1}, respectively) than the expected ones (≤ 2100 μgg^{-1}) based upon their SiO_2/R_2O_3 molecular ratio (> 0.75).

It is important to stress that this study constitutes the second trial in terms of using PAM as an additional characteristic to differentiate Brazilian Oxisols, requiring more universal studies to reach a definite conclusion.

Acknowledgment

Appreciation is expressed to Gilnei de Souza Duarte, Departamento de Ciências Exatas, Escola Superior de Agricultura de Lavras, for helping during the statistical analysis.

References

Ainsworth, C.C., and M.E. Summer. 1985. Effect of aluminium substitution in goethite on phosphorus adsorption: II. Rate of adsorption. *Soil Sci. Soc. Amer. J.* 49:1149-1153.

Bache, B.W. 1964. Aluminium and iron phosphate studies relating to soils. II. Reactions between phosphate and hydrous oxides. *J. Soil Sci.* 15:110-116.

Bahia Filho, A.F.C. 1982. Índices de disponibilidade de fósforo em Latossolos do Planalto Central com diferentes características texturais e mineralógicas. Ph.D thesis. Univ. Federal de Viçosa.

Ballard, R., and J.G.A. Fiskell. 1974. Phosphorus retention in coastal plain forest soils: I. Relationship to soil properties. *Soil Sci. Soc. Amer. Proc.* 38:250-255.

Barrow, N.J. 1974. The slow reactions between soils and anions. Effects of time, temperature, and water content of a soil on the decrease of effectiveness of phosphate for plant growth. *Soil Sci.* 118:380-386.

Barrow, N.J., and T.C. Shaw. 1975a. The slow reactions between soils and anions. 2. Effect of time and temperature on the decrease in phosphate concentration in the soil solution. *Soil Sci.* 119:167-177.

———. 1975b. The slow reactions between soils and anions. 3. The effects of time and temperature on the decrease in isotopically exchangeable phosphate.. *Soil Sci.* 119:190-197.

Bigham, J.M., D.C. Golden, S.W. Buol, S.B. Weed, and L.H. Bowen. 1978. Iron oxide mineralogy of well-drained Ultisosl and Oxisols. II. Influence on color, surface area, and phosphate retention. *Soil Sci. Soc. Amer. J.* 42:825-830.

Black, C.A. 1943. Phosphate fixaiton by kaolinite and other clays as affected by pH, phosphate concentration and the time of contact. *Soil Sci. Soc. Amer. Proc.* 7:123-133.

Bohn, H., B.L. McNeal, and G.A. O'Connor. 1979. Soil chemistry. John Wiley, New York.

Breeuwsma, A., and J. Lyklema. 1973. Physical and chemical adsorption of ion in the electrical double layer on hematite (α - Fe2O3). J. Coll. Interface Sci. 43:437-448.

Bromfield, S.M. 1965. Studies on the relative importance of iron and aluminium in the sorption of phosphate by some Australian soils. *Aust. J. Soil Res.* 3:31-44.

Burnham, C.P., and D. Lopez-Hernandez. 1982. Phosphate retention in different soil taxonomy classes. *Soil Sci.* 134:376-380.

Camargo, O.A. de, B. van Raij, and F. Grohmann. 1974. Fixação de fósforo em solos avaliada pelo índice de Bache e Williams e sua correlação com outras propriedades. *Cienc. Cult.* 28:681-685.

Chakravarti, S.N., and O. Talibudeen. 1961. Phosphate interactions with clay minerals. *Soil Sci.* 92:232-242.

Chen, Y.S.R., J.N. Buttler, and W. Stumm. 1973. Kinetic study of phosphate reaction with aluminum oxides and kaolinite. *Environ Sci. Technol.* 7:327-332.

Correa, G.F. 1984. Modelo de evolução e mineralogia da fração argil de solos do planalto de Viçosa, MG. M.S. thesis. Univ. Federal de Viçosa.

Curi, N. 1983. Litosequence and toposequence of Oxisols from Goiás and Minas Gerais States, Brazil. Ph.D thesis. Purdue Univ., Lafayette, IN.

Curi, N., O.A. de Camargo, G.A.A. Guedes, and J.V. Silveira. 1986. Sorçao de fósforo em materiais de Latossolos do Brasil Sudeste e Sul. Anais da III Reunião de Classificação, Correlação de Solos e Interpretação da Aptidão Agrícola. September 1984. EMBRAPA/SNLCS, Rio de Janeiro, Brazil.

Curi, N., and D.P. Franzmeier. 1984. Toposequence of Oxisols for the central plauteau of Brazil. *Soil Sci. Soc. Amer. J.* 48:341-346.

Faria, C.M.B., J.M. Braga, and O.C.B. Pinto. 1976. Sorção de fósforo em cinco solos do Estado de Minas Gerais: Influência de alguns fatores. *R. Ceres* 23:166-179.

Finkl, C.W. 1982. Soil classification. Benchmark papers in soil science, v.l. Hutchinson Ross Publ. Co., Stroudsburg, PA.

Fox, R.L. 1982. Some highly weathered soils of Puerto Rico. 3. Chemical properties. Geoderma 27:139-176.

Fox, R.L., S.M. Hasan, and R.C. Jones. 1971. Phosphate and sulfate sorption by latosols. Proc. Int. Symp. Soil Fert. Evaln., New Delhi, India 1:857-864.

Fox, R.L., and E.J. Kamprath. 1970. Phosphate adsorption isotherms for evaluating the phosphate requirements of soils. *Soil Sci. Soc. Amer. Proc.* 34:902-906.

Fox, R.L., and G.E. Searle. 1978. Phosphate adsorption by soils of the tropics. *In* Diversity of soils in the tropics. ASA Special Publ. 34. Madison, WI. Pp. 97-117.

Gualberto, V. 1984. Caracterização física, química e mineralógica de alguns latossolos, com altos teores de ferro, da Amazônia e do Planalto Central. M.S. thesis. Univ. Federal de Viçosa.

Helyar, K.R., D.N. Munns, and R.G. Burau. 1976. Adsorption of phosphate by gibbsite. I. Effects of neutral chloride salts of calcium, magnesium, sodium, and potassium. *J. Soil Sci.* 27:307-314.

Herbillon, A.J. 1980. Mineralogy of Oxisols and oxic materials. *In* B.K.G. Theng (ed.) Soils with variable charge. New Zealand Soc. of Soil Sci., Lower Hutt, N.Z. Pp. 109-126.

Hingston, F.J., R.J. Atkinson, A.M. Posner, and J.P. Quirk. 1968. Specific adsorption of anions on goethite. *Trans. 9th Int. Cong. Soil Sci.* 1:669-677.

Hingston, F.J., A.M. Posner, and J. Quirk. 1972. Anion adsorption by goethite and gibbsite. I. The role of proton in determing adsorption envelops. *J. Soil Sci.* 23:177-193.

Hughes, J.C., and P.H. Le Mare. 1982. High gradient magnetic separation of some soil clays from Nigeria, Brazil and Colombia. II. Phosphate adsorption characteristics, the interrelationships with iron, aluminium and carbon, and comparison with whole soil data. *J. Soil Sci.* 33:521-533.

Juo, A.S.R., and R.L. Fox. 1977. Phosphate sorption capacity of some benchmark soils in West Africa. *Soil Sci.* 124:370-376.

Kanabo, I.A.K., A.T. Halm, and H.B. Obeng. 1978. Phosphorus adsorption by surface samples of five ironpan soils of Ghana. *Geoderma* 20:299-306.

Karim, M.I., and W.A. Adams. 1984. Relationships between sesquioxides. kaolinite, and phosphate sorption in a catena of Oxisols in Malawi. *Soil Sci. Soc. Amer. J.* 48:406-409.

Khalid, R..A., W.H. Patrick Jr., and R.D. Deluanc. 1977. Phosphorus sorption characteristics of flooded soils. *Soil Sci. Soc. Amer. J.* 41:305-310.

Kittrick, J.A., and M.L. Jackson. 1956. Electron microscope observations on the reaction of phosphate with minerals, leading to a unified theory of phosphate fixation in soils. *J. Soil Sci.* 7:81-89.

Kuo, S., and E.G. Lotse. 1972. Kinetics of phosphate adsorption by calcium carbonate and Ca-kaolinite. *Soil Sci. Soc. Amer. Proc.* 36:725-729.

Kyle, J.H., A.M. Posner, and J.P. Quirk. 1975. Kinetics of isotropic exchange of phosphate adsorbed on gibbsite. *J. Soil Sci.* 26:32-43.

Larsen, S. 1967. Soil phosphorus. *Adv. Agron.* 19:151-210.

Leal, J.R., and A.C.X. Velloso. 1973. Adsorção de fosfato em latossolos sob vegetação de cerrado. *Pesq. Agropec. Bras.* 8:81-88.

Lopes, A.S. 1977. Available water, phosphorus fixation, and zinc levels in Brazilian cerrado soils in relation to their physical, chemical, and mineralogical properties. Ph.D thesis. North Carolina State Univ., Raleigh, NC.

Lopez-Hernandez, K., and C.P. Burnham. 1974. The effect of pH on phosphate adsorption in soils. *J. Soil Sci.* 25:207-216.

Low, P.F., and C.A. Black. 1950. Reactions of phosphate with kaolinite. *Soil Sci.* 70:273-290.

Mattingly, G.E. 1975. Labile phosphate in soils. Soil Sci. 119:369-375.

McLaughlin, J.R., J.C. Ryden, and J.K. Syers. 1981. Sorption of inorganic phosphate by iron and aluminium containing soil components. *J. Soil. Sci.* 32:365-377.

Mokwunye, U. 1975. The influence of pH on the adsorption of phosphate by soils from the Guinea and Sudan savanna zones of Nigeria. *Soil Sci. Soc. Amer. Proc.* 39:1100-1102.

Mott, C.J.B. 1981. Anion and ligand exchange. *In* D.J. Greenland and M.H.B. Hayes (eds.). Chemistry of soil processes. John Wiley, New York. Pp. 179-219.

Muljadi, D., A.M. Posner, and J.P. Quirk. 1966. The mechanism of phosphate adsorption by kaolinite, gibbsite and pseudoboehmite. Part 1. The isotherms and the effect of pH on adsorption. *J. Soil Sci.* 17:212-229.

Munns, D.N., and R.L. Fox. 1976. The slow reaction which continues after phosphate adsorption: Kinetics and equilibrium in some tropical soils. *Soil Sci. Soc. Amer. J.* 40:46-51.

Murphy, J., and J.P. Riley. 1962. A modified single solution method for the determination of phosphate in natural waters. *Anal. Chim. Acta* 27:31-36.

Parfitt, R.L. 1978. Anion adsorption by soils and soil materials. *Adv. Agron.* 30:1-50.

Parfitt, R.L., R.J. Atkinson, and R. St. C. Smart. 1975. The mechanism of phosphate fixation by iron oxides. *Soil Sci. Soc. Amer. Pro.* 39:837-841.

Parfitt, R.L., A.R. Fraser, J.D. Russell, and V.C. Farmer. 1977. Adsorption on hydrous oxides. II. Oxalate, benzoate and phosphate on gibbsite. *J. Soil Sci.* 28:40-47.

Rajan, S.S.S. 1975. Adsorption of divalent phosphate on hydrous aluminium oxide. *Nature* 253:434-436.

Rajan, S.S.S., and R.L. Fox. 1975. Phosphate adsorption by soils: II. Reactions in tropical acid soils. *Soil Sci. Soc. Amer. Proc.* 39:846-851.

Rajan, S.S.S., and K.W. Perrot. 1975. Phosphate adsorption by synthetic amorphous aluminosilicates. *J. Soil. Sci.* 26:257-266.

Resende, M. 1976. Mineralogy, chemistry, morphology and geomorphology of some soils of the central plateau of Brazil. Ph.D thesis. Purdue Univ., Lafayette, IN.

Resende, M. 1982. Pedologia. Imprensa Univ. Viçosa.

Resende, M., and D.P. Santana. 1986. Uso das relações Ki e Kr na estimativa da mineralogia para classificação dos Latossolos. Anais da III Reunião de Classificação, Correlação de Solos e Interpretação da Aptidão Agrícola. September 1984. EMBRAPA/SNLCS, Rio de Janeiro, Brazil.

Ryden, J.C., and J.K. Syers. 1976. Calcium retention in response to phosphate sorption by soils. *Soil Sci. Soc. Amer. Proc.* 40:845-846.

Sawhney, B.L. 1974. charge characteristics of soils as affected by phosphate sorption. *Soil Sci. Soc. Amer. Proc.* 38:159-160.

Schalscha, E.B., P.F. Pratt, T. Kinjo, and J. Amar. 1972. Effect of phosphate salts as saturating solutions in cation exchange capacity determinations. *Soil Sci. Soc. Amer. Proc.* 36:912-914.

Soil Survey Staff, SCS, USDA. 1975. Soil taxonomy: A basic system of soil classification for making and interpreting soil surveys. USDA Agric. Handb. no. 436. U.S. Gov. Printing Office, Washington, D.C.

Souza, J.A. 1985. Relações entre formas de ferro e sorção de fósforo em Latossolos sob cerrado do Planalto Central. M.S. Thesis. Escola Superior de Agricultura de Lavaras.

Syers, J.K., M.G. Browman, G.W. Smillie, and R.B. Corey. 1973. Phosphate sorption by soils evaluated by the Langmuir adsorption equation. *Soil Sci. Soc. Amer. Proc.* 37:358-363.

Udo, E.J., and F.O. Uzu. 1972. Characteristics of phosphorus adsorption by some Nigerian soils. *Soil Sci. Soc. Amer. Proc.* 36:879-883.

Wada,. K. 1959. Reaction of phosphate with allophane and halloysite. *Soil Sci.* 87:325-330.

Wann, S.S., and G. Uehara. 1978. Surface charge manipulation of constant surface potential soil colloids: I. Relation to sorbed phosphorus. *Soil Sci. Soc. Amer. J.* 42:565-570.

CONTRIBUTION OF ORGANIC MATTER TO EXCHANGE PROPERTIES OF OXISOLS[1]

E. Klamt[2] and W.G. Sombröek[3]

Abstract

Organic matter, clay content, and cation exchange capacity (CEC) were determined on 39 profiles of Oxisols of the International Soil Reference and Information Centre's (ISRIC) monoliths collection. These soils were described and sampled in 14 tropical countries. By means of multiple regression analysis the contribution of organic matter to the CEC was calculated.

The mean CEC of 1 g of carbon was found to be 3.36 me (range: 1.4-9.4 me) and is slightly lower in Haplorthox, Haplustox, and Acrorthox, than in Humox, Acrustox, and Eutrustox + Eutrorthox. The contribution of organic matter to soil CEC is high ($\bar{x}$ = 51 percent) in A horizons, especially in Acrustox (44 to 77 percent), Acrorthox (49 to 76 percent) and Humox (39 to 68 percent). In the B horizons this contribution is lower ($\bar{x}$ = 18 percent), being very low in Haplorthox (8 to 18 percent) and Haplustox (3 to 35 percent). This contribution should be considered in determining the CEC of the clay fraction, a parameter used in the classification of Oxisols. The types of vegetation and climatic zones in which these soils occur do not significantly influence the CEC of the organic fraction.

The decomposition products of plant and animal tissue constitute the principal carbon source for humus formation in soils (Tate and Theng 1980). The general concept that tropical soils contain lower amounts of organic carbon than soils found in temperate regions, due to strong humification and mineralization processes in the tropical environment, has been disproved (Sanchez 1976; Jenkinson and Ayanaba 1977; Bohn 1976; Tate and Theng 1980). Jenkinson and Ayanaba (1977) found that the decomposition rate of fresh plant material added to soils was four times higher in Nigeria than in England. Similar data have been presented by Sanchez (1976), who concluded that under tropical rain forest the production and decomposition of organic matter is four times higher, with the result that the final addition is equivalent in these different regions.

Factors such as temperature, precipitation, and soil conditions control the production and decay of organic matter. Production mostly increases with increasing precipitation (Birch and Friend 1956) while the optimum temperature for plant growth is between 20 and 25°C; but that for bacterial activity and organic matter decomposition is between 30 and 35°C (Mohr and Van Baren 1954). This is the reason for increased organic matter accumulation with altitude (Birch and Friend 1956), since the precipitation mostly increases and temperature decreases with increasing altitude.

Clearing of tropical forest for crop production strongly increases the decomposition of organic matter. This is associated to the reduction of rates of incorporation of organic matter residues to soils under agriculture and leads to a decrease in soil organic matter in cultivated tropical soils (Young 1976), and hence to a decrease in their cation exchange capacity (CEC). Brams (1971) reported a 30 percent reduction in soil CEC when the level of organic matter was reduced to 50 percent by cultivation.

Minerals in the clay fraction also contribute to the CEC of tropical soils. The main species are kaolinite, iron, and aluminium (oxihydro) oxides, and poorly crystalized aluminosilicates (Rodrigues and Klamt 1976; Juo 1980; Herbillon 1980; Wada 1980); but the charge density of humic substances averages 300 me/100 g at pH 7.0 (Tate and Theng 1980), which is 30 times that of kaolinite (Goh 1980).

The contribution of organic matter to the exchange properties is difficult to determine in detail, because of the intimate association between humic substances and inorganic soil constituents. Goh (1980) presented two alternatives to study this subject: (a) the selective removal of the organic or mineral component or (b) the use of multiple regression analysis to separate the effect of the different components. The statistical alternative was chosen because it does not interfere with the soil charge characteristics.

---

[1] Joint contribution of the International Soil Reference and Information Centre (ISRIC), Wageningen, The Netherlands, and Soil Science Department of UFRGS, Porto Alegre, Brazil.

[2] Guest Researcher at ISRIC, on leave from Soil Science Department of UFRGS with Post-Doctoral Fellowship from CNPq.

[3] Director, ISRIC.

Materials and Methods

Thirty-nine profiles of Oxisols of the ISRIC's monoliths collection, sampled and described in 14 countries, were used for the present study.

Samples were air dried and slightly crushed to pass a 2 mm sieve. This fine-earth fraction was used to perform the analysis of organic matter expressed as organic carbon particle size distribution, and CEC, by methods described in detail by Van Reeuwijk (1986). Organic matter determination followed the wet combustion method, while clay content was determined by pipette method after removal of organic matter with H_2O_2 and CEC by replacing of the NH_4 of samples leached with NH_4OAc 1N pH 7.0 by Na, using 1 N NaOAc pH 7.0. After washing the excess Na with 50 percent ethanol and replacement of the absorbed Na by NH_4, samples were leached again with 1N NH_4OA_c pH 7.0 and Na was determined by flame emission (modified from USDA 1972). The CEC obtained was corrected for organic matter by regression analysis using the equation proposed by Bennema (1966) and Bennema and Camargo (1979):

$$CEC_{soil} = a'X_1 + b'X_2,$$

in which:

CEC_{soil} = CEC of 100 g soil,
X_1 = amount of clay,
X_2 = amount of organic carbon,
a' = CEC of 1 g of clay, and
b' = CEC of 1 g of organic carbon.

By multiplying the equation by $100/X_1$, it becomes:

$$100\ CEC_{soil}/X_1 = 100\ a' + 100\ b'\ X_2/X_1,$$

which can also be written as:

$$Y = a + bX,$$

in which:

$Y = 100\ CEC_{soil}/X_1 = 100\ CEC_{soil}/\%$ clay,
$X = 100X_2/X_1 = 100\%$ C/% clay,
a = CEC of 1 g of carbon, and
$b = 100\ a'$ = CEC of 100 g clay.

Graphically, this equation (Fig. 1[4]) results in a straight line, in which the intercept b represents the CEC of 100 g of clay and the slope a the CEC of 1 g of carbon. This procedure is valid only if: (1) the CEC of the soils is originated only from organic matter and clay and (2) the CEC per gram of organic matter and per 100 grams of clay is constant in the solum, which is the case in the Oxisols studied, in view of the straight uniform lines obtained.

The contribution of organic carbon to soil CEC was calculated by the equation:

$$\frac{\text{CEC of 1 g carbon} \quad X\ \%\ C}{CEC_{soil}} \times 100.$$

Results and Discussion

The Oxisols under investigation show a mean content of 2.73 percent organic carbon in the surface horizon (Table 1), ranging from 0.64 to 10.19 percent. In the B horizon the mean value is 0.48 percent (0.07-1.37). The surface horizons of Humox ($x = 3.87$), Haplorthox ($x = 3.42$), and Acrorthox ($x = 3.18$) have slightly higher values than Haplustox ($x = 1.44$), Eutrustox + Eutrorthox ($x = 1.99$), and Acrustox ($x = 2.79$). Humox, Acrustox, and Acrorthox, with mean values of 1.11, 0.63, and 0.57 percent respectively, have higher contents of organic carbon in subsurface horizons than Haplustox, Haplorthox, and Eutrustox + Eutrorthox with 0.23, 0.39, and 0.48 percent respectively.

The mean clay content is 47.4 percent (9-91) and 54.5 percent (22-92), respectively, in the surface and subsurface diagnostic horizons (A and Bw horizons, Table 1).
Mean CEC_{soil} and CEC_{clay} of subsurface horizons of the Oxisols under investigation are respectively 4.9 and 10.7 me/100 g (Table 2). The frequency distributions are assymetric since values of the modes are 1.9 and 2.8 me/100 g, for soil and clay respectively.

Regression statistics applied to CEC resulted in low correlation coefficients between CEC_{soil} and clay content, irrespective if all samples ($r = 0.33$) or only of subsurface horizons ($r = 0.37$) were analyzed. The coefficients are also low for CEC_{soil} and organic carbon content if all horizons ($r = 0.47$) or only subsurface horizons ($r = 0.32$) were considered.
Multiple regression analysis in which the independent variables clay, organic carbon, and silt content were analyzed stepwise, according to their importance in explaining the variation of the dependent variable CEC_{soil}, resulted in the following equation when all horizons (surface and subsurface) were analyzed:

$$CEC_{soil} = 1.67 + 2.96\ carbon + 0.03\ clay$$

with $r = 0.47$. Organic matter thus explained most of the CEC_{soil}. Similar analysis performed only for subsurface horizons yielded the following equation:

$$CEC_{soil} = 0.66 + 0.55\ clay + 0.07\ silt$$

with $r = 0.49$. Because of its low values, organic carbon content, when used, did not affect the results of multiple regression analysis in subsurface horizons. The low correlation coefficients obtained are most probably related to the low values and the positively skewed distribution of CEC of Oxisols.

The equation proposed by Bennema (1966) and Bennema and Camargo (1979) to evaluate the contribution of organic matter to the CEC of Oxisols resulted in very high correlation

[4] The graphs have been reversed in comparison to the form presented by Bennema and Camargo (1979) because CEC is dependent on organic matter and thus plotted at the ordinate and not as used by those authors. Problems related to analytical procedures, as for example dispersion of samples for particle-size analysis, combustion of organic matter, and replacement of absorbed ions in CEC determination, may affect the value of the present contribution.

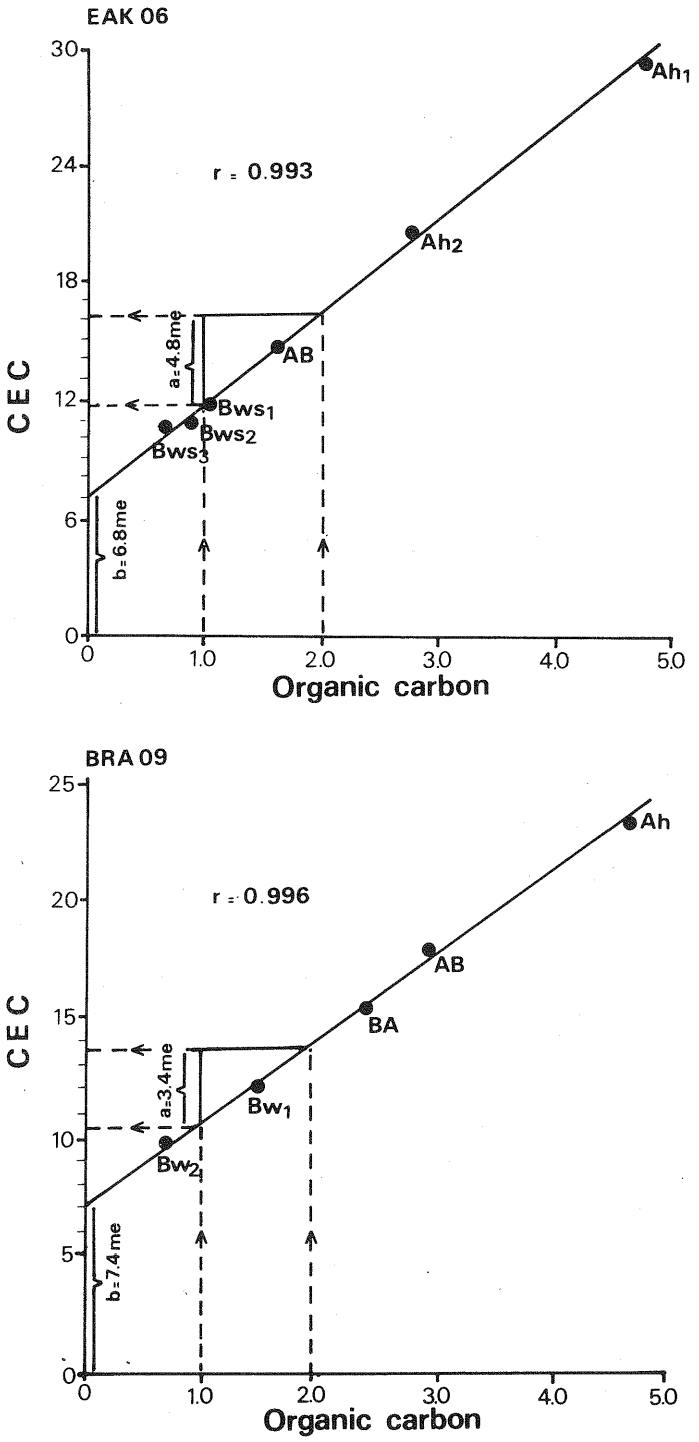


Fig. 1. Cation exchange capacity of clay and organic carbon of profiles EAK 06 and BRA 09. Ordinate: CEC soil recalculated to me/100 g clay fraction. Absecissa: organic carbon, recalculated to g/100 g clay fraction. Soil horizons are indicated at data points.

Table 1. Content of Organic Carbon, Clay, CEC of Soil, Carbon, and Clay, and Contribution of Carbon to Soil CEC

ISRIC Code	Sampling Sites		Regimes[a]		Land Use	Soil Classification		Carbon-%		Clay-%		CEC-me				Contribution of C to CEC-%	
												100g Soil		1gC	100g		
	Country	Province	Moisture	Temp.		FAO/UNESCO	Soil Taxonomy	A[b]	B_w[c]	A	B_w	A	B_w		Clay	A	B_w
BRA.03	Brazil	Rio de Janiro	US/UD	HT	Grassland	Acric/Ferralsol	Acrustox	1.74	0.52	50	59	4.1	1.8	2.0	1.4	71	43
BRA.04	Brazil	São Paulo	UD	HT	Sugar Cane	Rhodic/Ferralsol	Eutrorthox	1.98	0.52	61	56	12.0	4.5	5.1	2.7	79	50
BRA.05	Brazil	São Paulo	UD	HT	Grass/Sugar Cane	Humic/Acric Ferralsol	Acrorthox	2.47	0.80	61	65	7.7	1.6	3.6	-1.7	-	-
BRA.06	Brazil	São Paulo	US	HT	Grassland	Rhodic/Ferralsol	Haplustox	0.83	0.22	15	22	3.3	1.4	3.2	4.4	38	14
BRA.08	Brazil	Paraná	UD	TH	Maize/Soybeans	Humic/Ferralsol	Acrorthox	2.58	0.75	82	84	12.2	7.3	2.5	6.8	49	22
BRA.09	Brazil	Paraná	UD	TH	Grassland	Humic/Ferralsol	Acrohumox	3.67	1.09	76	74	17.9	9.0	3.4	7.4	63	33
BRA.10	Brazil	Paraná	UD	TH	Grass/Crops	Humic/Ferralsol	Acrohumox	5.52	1.37	55	55	20.3	8.3	3.1	8.1	68	18
BRA.11	Brazil	Pará	US	IH	Grassland	Xanthic/Ferralsol	Haplustox	1.42	0.20	9	28	6.7	1.4	4.5	1.7	79	35
BRA.13	Brazil	Pará	US	IH	Tropical Forest	Acric/Ferralsol	Acrustox	2.64	0.35	84	92	6.9	2.6	2.2	1.7	77	31
BRA.14	Brazil	Federal District	US	HT	High Cerrado	Rhodic/Ferralsol	Haplustox	2.26	0.86	44	43	7.3	4.1	2.6	4.2	58	35
BRA.15	Brazil	Federal District	US	HT	Cerrado	Humic/Acric Ferralsol	Acrustox	2.98	1.16	75	71	6.6	2.5	2.0	-0.1	-	-
BRA.SP1	Brazil	Rio de Janeiro	US	TH	Grass/Bushes	Xanthic/Ferralsol	Haplorthox	2.06	0.40	42	48	6.4	3.4	2.0	5.4	43	13
BRA.SP2	Brazil	Rio Grande Do Sul	UD	TH	Maize	Rhodic/Ferralsol	Haplorthox	2.30	0.42	74	83	13.0	6.7	3.4	6.5	55	18
CO.18	Columbia	San José	UD	HT	Tropical Forest	Xanthic/Ferralsol	Haplorthox	1.60	0.18	11	25	5.1	3.9	2.2	4.8	42	8
GBN.01	Gabon	Layon	UD	IH	Tropical Forest	Xanthic/Ferralsol	Haplorthox	3.27	0.36	56	57	12.6	5.6	2.3	7.4	50	10
GBN.04	Gabon	Lebamba	US	IH	Grassland	Xanthic/Ferralsol	Haplorthox	2.73	0.29	18	27	9.8	1.6	3.5	-0.8	-	-
INS.01	Indonesia	Parung	UD	IH	Bananas	Orthic/Ferralsol	Euthrorthox	1.40	0.32	85	90	12.1	8.1	4.4	7.7	44	16
INS.15	Indonesia	Kalimantan	UD	IH	Tropical Forest	Xanthic/Ferralsol	Haplorthox	10.19	0.30	35	41	25.0	3.0	2.2	7.4	74	8
CI.04	Ivory Coast	Tai Forest	UD	IH	Tropical Forest	Xanthic/Ferralsol	Haplorthox	0.93	0.38	10	38	2.3	3.0	1.8	6.6	20	9
JA.03	Jamaica	Madeville	UD	IH	Citrus Orchard	Acric/Orthic Ferralsol	Acrorthox	3.75	0.05	68	67	17.3	4.6	3.4	6.5	66	4
EAK.06	Kenya	Embu	US	TH	Grassland	Rhodic/Ferralsol	Eutrustox	2.59	0.74	54	67	15.9	7.4	4.8	6.8	65	34
EAK.07	Kenya	Embu	US	TH	Bushed Grassland	Humic/Ferralsol	Haplohumox	2.31	0.96	72	87	19.5	12.4	5.7	8.2	62	40
EAK.11	Kenya	Kilifi	US	IH	Forest	Rhodic/Ferralsol	Haplustox	0.70	0.12	15	37	3.3	3.3	2.4	8.3	17	3
EAK.29	Kenya	Kilifi	US	IH	Cocoa/Cashew	Rhodic/Ferralsol	Haplustox	0.64	0.07	10	23	6.5	1.9	9.4	4.4	60	13
MAL.01	Malaysia	Serdang	UD	IH	Forest	Acric/Ferralsol	Acrorthox	1.38	0.34	69	71	4.3	2.4	2.0	2.4	54	22
MAL.03	Malaysia	Kuatang	UD	IH	Rubber	Humic/Ferralsol	Acrorthox	5.18	0.73	55	74	16.4	5.3	2.7	4.4	76	31
MAL.05	Malaysia	Kuatang	UD	IH	Forest	Acric/Ferralsol	Acrorthox	4.12	0.55	91	94	14.8	2.0	3.7	-0.3	-	-
MAL.07	Malaysia	Puchong	UD	IH	Bushes	Acric/Ferralsol	Acrorthox	2.78	0.34	60	65	6.1	3.2	1.4	3.4	53	12
SK.06	Sarawak	Kuching	UD	IH	Rubber	Orthic/Ferralsol	Haplorthox	6.62	0.87	67	55	23.6	6.6	2.5	8.9	65	18
SK.07	Sarawak	Lundu-Sekambal	PQ	IH	Forest	Xanthic/Ferralsol	Haplorthox	1.07	0.30	11	33	5.7	2.9	3.8	13.2	24	8
MOC.02	Mozambic	Lichinga	US	TH	Maize	Rhodic/Ferralsol	Haplustox	1.19	0.14	37	62	9.1	5.4	4.9	8.8	40	7
ZA.02	S. Africa	Natal	US	TH	Grassland	Humic/Ferralsol	Acrustox	3.82	0.47	46	52	13.6	6.1	2.3	11.0	44	9
USA.08	USA	Kunia	TO	IH	Sugar Cane	Rhodic/Ferralsol	Torrox	2.32	0.56	33	41	18.1	6.7	6.5	10.8	58	25
USA.09	USA	Waipio	US	IH	Maize	Rhodic/Ferralsol	Eutrustox	2.00	0.37	68	74	17.7	12.4	3.3	15.0	31	8
USA.10	USA	Wailua	UD	IH	Grassland	Humic/Ferralsol	Gibbsihumox	3.98	1.04	43	34	16.5	7.8	2.6	16.2	39	14
Z.02	Zambia	Kasama	US	TH	Grassland	Orthic/Ferralsol	Haplustox	2.68	0.13	21	29	7.1	1.9	2.3	6.8	47	4
Z.04	Zambia	Mbala	US	IT	Wheat/Potatos	Orthic/Ferralsol	Haplustox	2.10	0.27	51	61	14.8	9.4	3.7	13.8	36	7
Z.05	Zambia	Kasama	US	TH	Scrub/Grass	Xanthic/Ferralsol	Haplustox	0.91	0.14	17	27	3.5	2.8	2.7	7.6	24	5
Z.09	Zambia	Misanfu	US	TH	Forest	Xanthic/Ferrasol	Haplustox	1.72	0.20	21	45	5.7	5.4	6.8	11.7	50	10
							Mean	2.73	0.48	47.4	54.5	11.3	4.9	3.36	7.04	51	18
							Minimum	0.64	0.07	9	22	33	1.4	1.4	1.7	17	2
							Maximum	10.19	1.37	91	92	25.0	12.4	9.4	33.1	79	50

[a] Moisture regimes: UD = Udic, US = Ustic, PQ = Perudic, TO = Torric,
Temperature regimes: TH = Thermic, HT = Hyperthermic, IH = Isohyperthermic.

[b] A = Surface horizon.

[c] B_w = Subsurface horizon which englobes the depth of 100 cm.

Table 2. Descriptive Statistics of CEC_{soil} and CEC_{clay} in Subsurface Horizons (B_w) of Oxisols

Properties	Values (me/100 g)					
	Minimum	Maximum	Mean	Mode	Median	Standard Deviation
CEC_{soil}	0.7	12.5	4.9	1.9	8.9	5.3
CEC_{clay}	1.3	15.9	10.7	2.8	8.7	8.5

coefficients ($r = 0.99$, Fig. 1), indicating that in these soils the exchange properties are related mainly to their organic matter and clay content. The contribution of these fractions seems to be constant in the solum. The same procedure when applied to similar soils, such as Ultisols, Inceptisols, and Alfisols, resulted in lower correlation coefficients ($r = 0.85$), indicating that the contribution of organic matter and clay to CEC is not uniform throughout the profile and/or that other mineral fractions also contribute considerably to the exchange capacity.

Table 1 shows that the CEC of the clay of predominantly oxidic soils (e.g., BRA 05 and 15, GBN 04 and MAL 05) is negative by this procedure, because their net charge is positive. The average contribution of 1 g of carbon to the CEC is 3.36 me. This value is lower than the correction factor of 4.5 used in the equation:

$$CEC_{clay} = \frac{CEC_{soil} - (\%C \times 4.5)}{\%\ clay} \times 100,$$

which is used to calculate the CEC of the clay fraction corrected for organic matter in the Brazilian system of soil classification if no graphical estimate per individual profile is carried out (EMBRAPA 1971). The value is, however, close to the 300 me/100 g of the CEC at pH 7 of organic functional groups, as presented by Tate and Theng (1981). The higher correction factor of the Brazilian system may be due in part to the indirect method of CEC determination employed by them.

The CEC per 1 g of carbon appears to be lower in Acrustox ($\bar{x} = 2.1$), Haplorthox ($\bar{x} = 2.6$), and Acrorthox ($\bar{x} = 2.7$) than in Humox ($\bar{x} = 3.7$), Haplustox ($\bar{x} = 4.2$), and Eutrustox + Eutrorthox ($\bar{x} = 4.4$).

The contribution of organic matter to CEC is high in A horizons of all soils (Fig. 2) and in particular in Acrustox (44-77 percent), Acrorthox (49-76 percent), and Humox (39-68 percent). As expected, in the B horizon, the contribution is lower, being very low in Haplorthox (8-18 percent) and Haplustox (3-14 percent), with two exceptions for Haplustox.

The type of vegetation and land use seems to have some influence on the contribution of organic matter on the CEC of Oxisols. In B horizons of soils found under forest the contribution is in general lower than under other forms of land use (Fig. 3). The use of soils for agriculture appears to have no negative influence on the CEC, as was suggested by Brams (1971).

The climatic zone in which soils occur appears to have a slight influence on the CEC of organic matter, since in the two soils sampled in perudic/isohyperthermic moisture and temperature regimes the values are very low in A and B_w horizons (Fig. 4). The contribution is also lower in most B horizons of soils found in udic/isohyperthermic and ustic/thermic regimes.

Conclusions

Oxisols are soils in which one of the main diagnostic characteristics is the presence of an oxic subsurface horizon with a CEC of the fine-earth fraction of 16 me or less per 100 g of clay. This value is generally obtained by calculation:

$$CEC_{100\ g\ clay} = \frac{CEC_{100\ g\ soil} \cdot 100}{\%\ clay},$$

which indicates that the contribution of humic substances and inorganic soil constituents are not considered separately.

The contribution of organic matter to the CEC of Oxisols under investigation is very high in the A horizons ($\bar{x} = 51$ percent), particularly in Acrustox (44-77 percent), Acrorthox (49-76 percent), and Humox (36-67 percent). This contribution is lower but still significant in the diagnostic subsurface horizon ($B_w = \bar{x} = 18$ percent), ranging from 11.5 percent to 27.7 percent for different soil great groups. This indicates that the contribution of organic matter should be considered in determining the CEC_{clay}, as is performed in the Brazilian system of soil classification.

The type of vegetation, land use, and climatic zones in which Oxisols occur have no major effect on the contribution of organic matter to their CEC. Since there are no clear trends in the distribution of the data obtained, the determination of the contribution of organic matter to the CEC of these soils has to be done for each profile individually, using the equation or graphical procedure proposed by Bennema (1966) and Bennema and Camargo (1979).

References

Bennema, J. 1966. Classification of Brazilian soils. Report to the Government of Brazil, report no. 2197. FAO, Rome. 83 p.

Bennema, J., and M.N. Camargo. 1979. Some remarks on Brazilian Latosols in relation to Oxisols of *Soil Taxonomy*. IInd Int. Soil Class. Work. Bangkok, Thailand. Pp. 233-261.

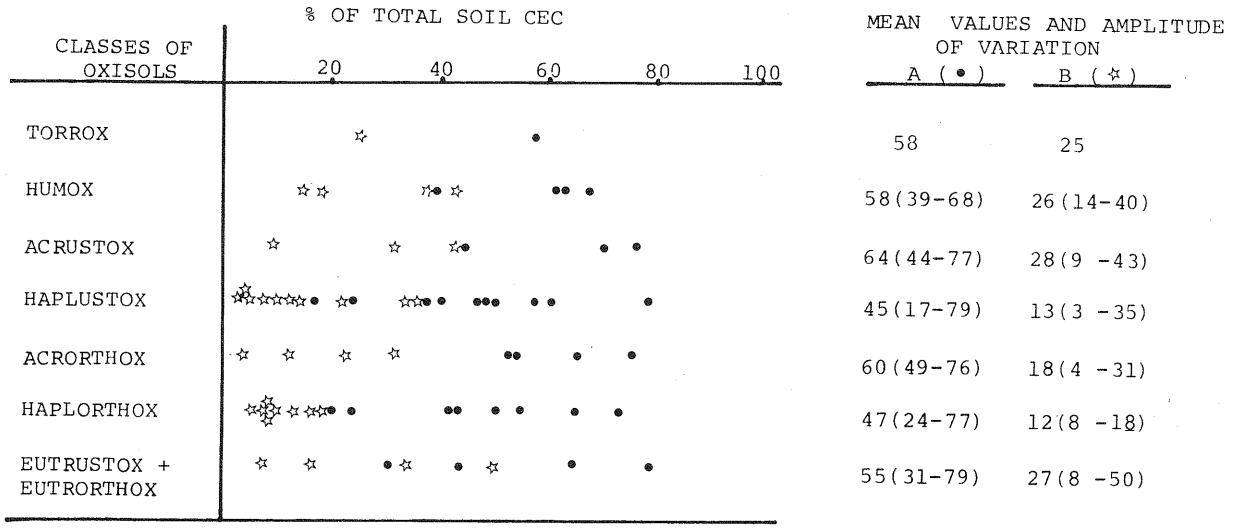


Fig. 2. Contribution (%) of organic carbon to cation exchange capacity of A (•) and B_w (☆) horizons of Oxisols.

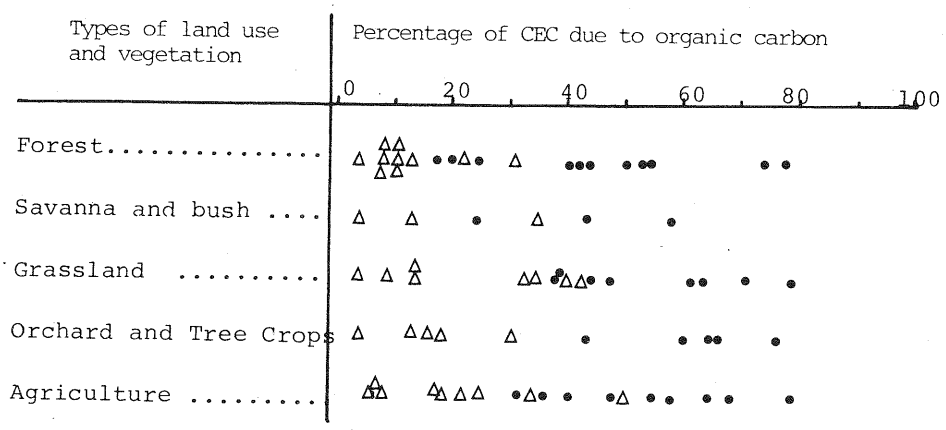


Fig. 3. Influence of type of land use and vegetation on the contribution (in %) of organic carbon to the CEC of A (•) and B_w (Δ) horizons of Oxisols.

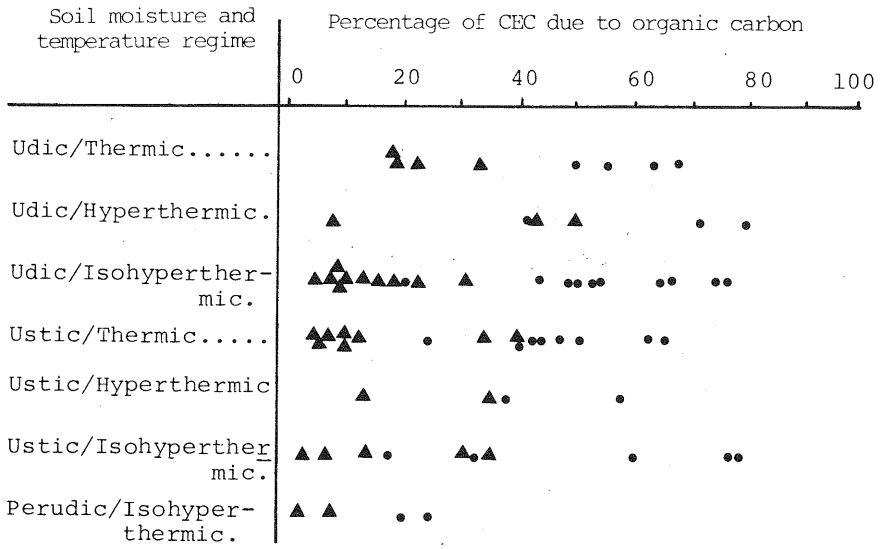


Fig. 4. Influence of the moisture and temperature regimes on the contribution (in %) of organic carbon to the CEC of A (•) and B_w (▲) horizons of Oxisols.

Birch, H.F., and M.T. Friend. 1956. The organic matter and nitrogen status of East African Soils. *J. Soil Sci.* 7:156-167.

Bohn, H.L. 1976. Estimate of organic carbon in world soils. *Soils Sci. Soc. Amer. J.* 40:468-470.

Bowden, J.W., A.M. Posner, and J.P. Quirk. 1980. Adsorption and charging phenomena in variable charge soils. *In* B.K.G. Theng (ed.). Soils with variable charge. New Zealand Soc. Soil Sci. Soil Bureau, Lower Hutt, N.Z. Pp. 147-164.

Brams, E.A. 1971. Continuous cultivation of West African soils: Organic matter diminution and effects of applied lime and phosphorus. *Plant Soil* 35:401-414.

EMBRAPA, SNLCS. 1981. Bases para leitura de mapas de solos. SNLCS, *Serie Miscelanea* 4:1-89.

Goh, K.M. 1980. Dynamic and stability of organic matter. *In* B.K.G. Theng (ed.). Soils with variable charge. New Zealand Soc. Soil Sci. Soil Bureau, Lower Hutt, N.Z. Pp. 373-393.

Herbillon, A.J. 1980. Mineralogy of oxisols and oxic materials. *In* B.K.G. Theng (ed.). Soils with variable charge. New Zealand Soc. Soil Sci. Soil Bureau, Lower Hutt, N.Z. Pp. 109-123.

Juo, A.S.R. 1980. Mineralogical characteristics of Alfisols and Ultisols. *In* B.K.G. Theng (ed.). Soils with variable charge. New Zealand Soc. Soil Sci. Soil Bureau, Lower Hutt, N.Z. Pp. 69-84.

Jenkinson, D.S., and A. Ayanaba. 1977. Decomposition of carbon 14 labeled plant materials under tropical conditions. *Soil Sci. Soc. Amer. J.* 41:912-915.

Keng, J.C.W., and G. Uehara. 1974. Chemistry, mineralogy and taxonomy of Oxisols and Ultisols. *Proc. Soil Crop Sci. Soc.* Fla. 33:119-126.

Mohr, E.C.J., and F.A. Van Baren. 1954. Tropical soils. W. van Hoeve, The Hague. 498 p.

Rodrigues, T.E., and Klamt. 1978. Mineralogia e genese de uma sequencia de solos do Distrito Federal. *R. Bras. Ci. Solo* 2:132-139.

Sanchez, P.A. 1976. Properties and management of soils in the tropics. John Wiley and Sons, New York. 618 p.

Tate, K.R., and B.K.G. Theng. 1980. Organic matter and its interactions with inorganic soil constituents. *In* B.K.G. Theng (ed.). Soils with variable charge. New Zealand Soc. Soil Sci. Soil Bureau, Lower Hutt, N.Z. Pp. 225-244.

USDA-SCS. 1972. Soil survey laboratory methods and procedures for collecting soil samples. Soil Survey Investigation Report no. 1. U.S. Govt. Printing Office. Washington, D.C. 63 p.

Van Reeuwijk, L.P. 1986. Procedures for soil analysis. Technical Paper 9, ISRIC, Wageningen, The Netherlands. 106 p.

Wada, K. 1980. Mineralogical characteristics of Andisols. *In* B.K.G. Theng (ed.). Soils with variable charge. New Zealand Soc. Soil Sci. Soil Bureau, Lower Hutt, N.Z. Pp. 87-104.

Young, A. 1976. Tropical soils and soil survey. Cambridge Univ., Press, London. 468 p.

IRON OXIDES IN BRAZILIAN OXISOLS

N. Kämpf,[1] M. Resende,[2] and N. Curi[3]

Abstract

Information on amounts, types, isomorphous substitution, and crystallinity of iron oxides in Brazilian Oxisols were surveyed.

The registered amount of iron varies from 0.7 to 44 percent Fe, and the Fe (CBD)/Fe(H_2SO_4) ratio indicates that 80-100 percent of it is in the form of the pedogenic oxides goethite, hematite, and maghemite. The proportion of the dominant oxides hematite and goethite (Hm/Hm+Gt ratio) ranges from zero to 0.97. Maghemite is commonly found in hematitic Oxisols developed from mafic and itabiritic rocks. The red, brown, and yellow colors of Oxisols are due to the proportion of hematite and goethite.

In southern Brazil, under udic to perudic regimes and thermic to mesic regimes, Hm/Hm+Gt is more clearly related to the present climate, whereas in isohyperthermic regimes Oxisols may present ample variation of goethite and hematite related to parent material, bioclimatic conditions, or drainage.

Goethite and hematite are Al substituted with ranges of 15 to 36 moles% Al and 4 to 17 moles% Al, respectively.

The low Fe_o/Fe_d values (< 0.03) indicate the dominance of crystalline forms of iron oxides, but the crystallinity (structural perfection and particle size) is worse when compared to iron ores, and has a wide variation: the observed WHH 110 of goethite and WHH 012 of hematite ranges from 0.17 to 0.67°2θ and from 0.07 to 0.47°2θ, respectively.

Genetic (parent material, pedobioclimatic conditions, xanthization process) implications of iron oxides in Oxisol taxonomy are discussed. Suggestions on the use of iron oxide mineralogy to distinguish hematite (red) and goethitic (yellow) Oxisols are considered.

Oxisols comprise soils in advanced weathering stages with consequent concentration of 1:1 clay minerals and oxides (including oxyhydroxides and hydroxides). The formative element, *ox*, Oxisol (Soil Survey Staff 1975) is derived from F. *oxide*, stressing the importance of these mineral compounds in that order. Among the pedogenic oxides the more common and frequent ones are the oxides goethite (α - FeOOH) indicated by yellowish colors (2.5Y - 10YR) in the absence of hematite, and hematite (α - Fe_2O_3), with reddish colors (2.5YR - 5R), even if in very minor amounts; less frequent is maghemite (γ - Fe_2O_3) having reddish-brown color (5YR - 2.5YR) and magnetic properties (Resende 1976; Fasolo 1978; Rauen 1980; Kämpf 1981; Curi 1983; Santana 1984; Schwertmann and Kämpf 1985; Resende, Santana, and Resende 1986; Kämpf, Klamt, and Scheider 1986; Dick 1986). Due to the significance of the iron compounds in terms of Oxisols genesis, mineralogy, use, and management, more attention should be given to the characterization of the Fe-oxide phases and their inclusion in soil classification systems.

The contributions of this paper are: (1) to survey the information on amounts, types, isomorphous substitution, and crystallinity of iron oxides in Brazilian Oxisols; and (2) to consider some alternatives in the use of iron oxides in Oxisol taxonomy.

Amount, Types, Isomorphous Substitution, and Crystallinity of Iron Oxides

Iron Amount

Although Oxisols originate under conditions which favor concentration of iron oxides, the iron amount in these soils can vary from extremely low to extremely high. The total iron amount Fe(H_2SO_4) determined by H_2SO_4 extraction ranges from 44 percent Fe in itabirite-derived Acrorthoxs (EMBRAPA 1984; Curi and Franzmeier, in press) to 0.7 percent Fe in yellow Oxisols developed from poorly graded kaolinitic Tertiary continental deposits (e.g., the Barreiras group). According to Dick (1986) the extraction of iron with 6N HCl has the same efficiency of the H_2SO_4 method.

Iron oxide minerals tend to concentrate in the clay fraction (Eswaran and Sys 1970) except when they occur in nodules or concretions. The values of citrate-bicarbonate-dithionite(CBD)-extractable iron Fe(CBD) (Mehra and Jackson 1960) and Fe(HCl) registered for the clay fraction of

[1] Departamento de Solos, Faculdade de Agronomia - UFRGS. Caixa Postal 776. CEP 90.001 - Porto Alegre, RS, Brazil. CNPq Fellow.
[2] Departamento de Solos, Universidade Federal de Viçosa. CEP 36570 - Viçosa, MG, Brazil.
[3] Departamento de Ciência do Solos, Escola Superior de Agricultura de Lavras. Caixa Postal 37. CEP 37.200 - Lavras, MG, Brazil. CNPq Fellow.

Oxisols vary from 2 to 58 percent, with a range similar to that recorded for the whole-soil fraction (Kämpf 1981; Curi 1983; Santana 1984; Dick 1986).

The high Fe(CBD)/Fe(H_2SO_4) ratio observed in the fine-earth fraction (< 2 mm) of most Oxisols indicates that 80 to 100 percent of the iron is in the form of free iron oxides—goethite, hematite, and maghemite; the rest comprises the iron present in magnetite, ilmenite, and clay minerals (Vettori 1976; Resende 1976; Kämpf 1981; Dick 1986). The difference between Fe(CBD) and Fe(H_2SO_4), or Fe(HCl), increases in Oxisols derived from basic rocks, due to the presence of the primary mineral magnetite and ilmenite, which are not dissolved by the CBD-extraction. In the clay fraction Fe(CBD) and Fe(H_2SO_4) or Fe(HCl) are more similar (Dick 1986) due to the concentration of magnetite and ilmenite in the coarser fractions.

Iron Oxide Types

Goethite (Gt) and hematite (Hm) are the dominant phases in Oxisols and their proportions range from solely goethite (Hm/Hm+Gt ratio = 0.0) to the dominance of hematite (Hm/Hm+Gt ratio = 0.97). Among the hematitic Oxisols there are those with high amounts of maghemite which generally are developed from mafic and itabiritic rocks (Resende 1976; Fasolo 1978; Rauen 1980; Kämpf 1981, 1986; Curi 1983; Santana 1984; Dick 1986; Kämpf, Klamt, and Schneider 1986). Examples of x-ray diffractograms of iron oxides in Bo horizons of Oxisols are given in Figure 1. The treatment of soil samples with boiling 5M NaOH (Kämpf and Schwertmann 1982a) concentrates the

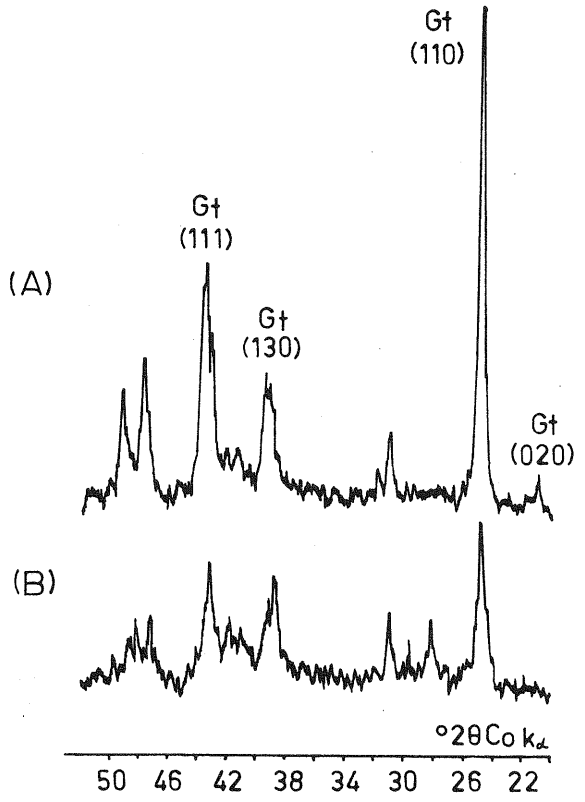


Fig. 1a. X-ray diffractogram of 5M-NaOH treated clay fractions of Bo horizons of (A) goethitic Typic Acrustox (Hm/Hm+Gt = 0.00); and (B) goethitic Haplohumox (Hm/Hm+Gt = 0.93. (Data from Kampf 1981; and Schwertmann & Kampf,1985).

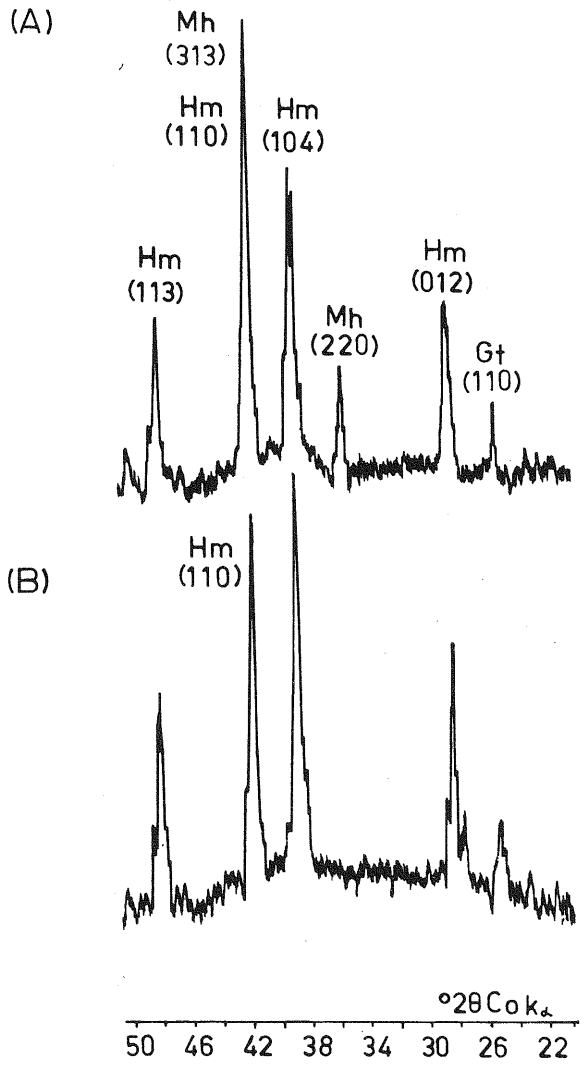


Fig. 1b. X-ray diffractogram of 5M-NaOH treated clay fractions of Bo horizons of (A) hematitic-maghemitic Typic Acrustox (Hm/Hm+Gt = 0.97); and (B) hematitic Typic Haplorthox (Hm/Hm+Gt = 0.85) (Data from Kämpf 1981 and Kämpf, Klamt, and Schneider *et al.* 1986).

iron oxides and allows their quantification by x-ray diffraction (Kämpf and Schwertmann 1982b).

As in other soils, the red, brown, and yellow colors of Oxisols are due to the proportion of geothite and hematite, and in red Oxisols developed from basic rocks also to hematite and maghemite. The relationship of Hm/Hm+Gt ratios and hematite amount to soil color and color indexes has been demonstrated by many authors (Kämpf and Schwertmann 1983a; Curi 1983; Santana 1984; Kämpf, Klamt, and Schneider 1986). Figure 2 shows the significant relationship (r^2= 0.94) of the Hm/Hm+Gt ratio and the moist hue of oxic horizons from Oxisols of southern and southeastern Brazil.

The range of the goethite and hematite proportion is generally associated with the soil's environmental conditions (Schwertmann 1985), but in comparisons among Oxisols that is not always very clear. According to Resende (1976) isohyperthermic Ustox may present regionally a wide variation of the goethite and hematite proportions which may be related to the amount of iron in the parent material and to present or past bioclimatic and drainage conditions. Data of regional soil surveys give support to these observations (Goiás 1976). However, landscape position influences locally the proportion of goethite and hematite, as described by Curi (1983) in a toposequence of isohyperthermic Acrustoxs developed from basalt, which graded progressively downslope from 2.5YR with a Gt/Gt+Hm ratio of 0.19 to 10YR with solely goethite. A similar trend was observed on tuffite where the Hm/Hm + Gt ratio ranged from 0.79 to 0.42 and the color ranged from 10R to 7.5YR downhill (Santana 1984).

In Oxisols under udic transitional to perudic moisture regimes and thermic transitional to mesic temperature regimes, the proportion of goethite and hematite is more clearly related to the present climate. In altitudinal climosequences of southern Brazil (Kämpf and Schwertmann 1983a), hematitic Haplorthox grade progressively to goethitic Haplohumox as the temperature decreases, with increasing rainfall and accumulation of organic compounds The cooler and humid conditions favor geothite formation, whereas in warmer areas hematite is widespread (Fig. 3).

Depth functions of hematite and goethite ratios can be relatively constant in isohyperthermic red Ustox, and in udic and thermic Orthox. However, as the rain increases in udic to perudic regimes, and under thermic to mesic regimes, as observed in southern Brazil, the organic compounds accumulation in red Humox imparts more goethite in upper horizons and more hematite in lower horizons, even if in the presence of high amounts of iron. This results in a goethite/hematite depth gradient in the soil profiles. As the rains and low temperatures increase further, goethite dominates throughout Haplohumox profiles (Kämpf 1981; Pötter and Kämpf 1981). Kaolinitic-hematitic (red) Oxisols over gibbsitic-goethitic (yellow) saprolites (bauxite) found in southern Brazil are evidence of lithological discontinuities and not due to a transformation of goethite in hematite (Kämpf 1981).

Information about iron oxide minerals in Aquox are very scarce; under aquic moisture regimes the iron oxides tend to be segregated in mottles, nodules, and concretions and in placic horizons, while the gray bleached portions are depleted of iron oxides. In a Plinthaquox (Kämpf 1986) the yellow mottles had only goethite whereas the red mottles had mainly goethite but with some hematite; the placic horizon also had only goethite but with a better crystallinity than the goethite of the yellow mottles.

Similar to what happens in the fine-earth fraction, the nodules and concretions can also have a huge variation of the goethite and hematite proportions (Fontes et al. 1985). Yellow

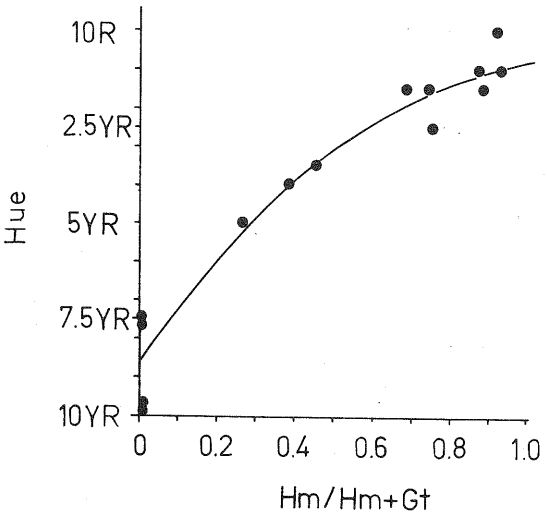


Fig. 2. Relationship of Hm/Hm+Gt ratio and moist Hue of Bo horizons from Oxisols of southeastern and southern Brazil. (Data from Kämpf, Klamt, and Schneider 1986.)

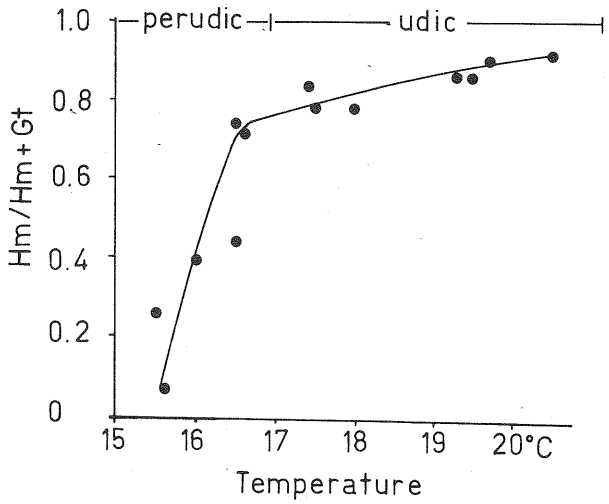


Fig. 3. Relationship of Hm/Hm+Gt ratio of Bo horizons and mean annual air temperature in climosequences under udic and perudic moisture regimes (Kämpf 1981 and unpublished data).

concretions are goethitic; goethitic (yellow) Oxisols may contain hematitic (red) nodules; petroferric material of goethitic Acrustox may have dominance of hematite, whereas hematitic Oxisols may contain goethitic nodules; concretions from itabirite-derived Acrorthoxs have mainly hematite and maghemite, and may have some goethite.

Maghemite is commonly present in significant amounts in hematitic Oxisols developed from mafic and itabiritic rocks, but is virtually absent in goethitic (yellow) Oxisols developed from the first ones (Resende 1976; Fasolo 1978; Rauen 1980; Curi 1983; Santana 1984; Kämpf, Klamt, and Schneider 1986; Dick 1986). In hematitic Oxisols from mafic rocks the maghemite content ranges from 1 to 8 percent (Resende, in press; Dick 1986). Hematite-maghemite association in these soils can be due to magnetite oxidation, while the maghemite absence in goethitic Oxisols (which have more water influx) could be due to maghemite dissolution (Curi 1983; Santana 1984; Resende et al., in Coey, in press). Other possibilities would be an inhibition of maghemite formation in environments that favor goethite. Thus, the cause of presence or absence of maghemite under specific situations is not sufficiently established (Schwertmann 1985), but in Brazilian Oxisols it seems to be always related to magnetite-rich parent materials. Its reddish-brown color (5YR - 2.5YR) presents some overlapping with that of hematite (2.5YR - 5R), which causes difficulties in terms of visual distinction of these minerals in the field.

Magnetite ($Fe_2^{3+}Fe^{2+}O_4$), a nonpedogenic iron oxide, has magnetic behavior similar to maghemite, but is distinguished by dark color and by occurring mainly as a residue in the sand and silt fractions of Oxisols originated from mafic and itabiritic rocks (Kämpf 1981; Curi 1983). Magnetite from Oxisols developed from basaltic rocks shows mostly intergrowth with ilmenite (Resende 1976; L.L. Antonello, per. comm.). According to Curi (1983) in these Oxisols magnetite is richer in trace elements (Co, Cu, Zn, Mo) than it is in Oxisols from other kinds of rocks. Thus, as magnetite is weathered these elements would be slowly released to the soil solution; this fact helps to explain the different crop productivities of the mafic-rock-derived Oxisols (Curi and Franzmeier, in press). More details about magnetic properties of Oxisols are given by Resende et al.(this workshop). Residual ilmenite ($FeTiO_3$) is also common in the coarse fractions of these Oxisols.

Lepidocrocite (α - FeOOH) and ferrihydrite ($5Fe_2O_3 \cdot 9H_20$) have been observed in hydromorphic environments near Acrustoxs, Haplustoxs, and Haplorthoxs, but not in them (Schwertmann and Kämpf 1983).

Isomorphous Substitution

In a manner somewhat similar to other soils, goethite and hematite from Oxisols present aluminum in their structure. In goethite the quantities generally range from 15 to 36 mole% Al, while in hematite the registered range is from 4 to 17 mole% Al (Resende 1976; Bigham et al. 1978; Kämpf 1981; Curi 1983; Schwertmann and Kämpf 1985; Dick 1986).

In average the magnitude of Al substitution seems to be related to the desilication intensity of Oxisols (Schwertmann and Kämpf 1985; Dick 1986). Among the Acrustoxs, the yellower ones may have greater substitution (Bigham et al. 1978; Curi and Franzmeier 1984; Gualberto 1984). However, Resende (1980) registered only 2 mole% Al in goethite from a gibbsitic Oxisol. In this case feldspar weathered to gibbsite and primary iron-rich minerals in a ocellated spotted distribution weathered to hematite and goethite in an environment with low available aluminum. Goethites of petroferric and concretionary materials may have lower Al substitution than goethites from the clay fraction of the same soil (Kämpf 1986). This is evidence of the polygenetic nature of Oxisols. Thus, the Al substitution in goethite is a useful parameter to characterize the soil environment in which iron oxides form (Fitzpatrick and Schwertmann 1982) even in highly weathered soil systems as Oxisols.

There is some evidence that the amount of Al in goethite increases toward the surface horizons of some Oxisol systems. This has been observed by Resende (1980) in gneiss-derived Oxisols from southeastern Brazil, and by Fabris et al. (1986) in an Oxisol originated from a pellitic rock.

Schwertmann and Fechter (1984) mentioned the presence of Al in maghemite structure, and Fitzpatrick and LeRoux (1975) and Resende et al., in Coey (in press) registered the presence of titanomaghemite.

Crystallinity

The concept of crystallinity as used here comprises structural perfection and particle size, both affecting the specific surface area (SSA) of iron compounds. The low Fe(Ox)/Fe(CBD) (where Fe(Ox) = ammonium oxalate-extractable iron, Schwertmann 1964) ratio with values <0.03 in Oxisols (Kämpf 1981; Santana 1984) indicates that the crystalline forms by far predominate and that presence of ferrihydrite is of little significance in these soil systems. However, the iron oxides' crystallinity is generally worse than their corresponding ones in ores or parent rocks. So, in Oxisols developed from itabirite, the hematite in the fine-earth fraction appears to have crystallinity inferior to the rock hematite.

Under the transmission electronic microscope (TEM) Oxisol goethites reveal serrated crystals without the typical acicular form of well-crystallized goethites; also hematites from Oxisols diverge from the hexagonal plate morphology showing granular crystals (Schwertmann and Kämpf 1985).

The examination of 45 oxic horizons from different physiographic regions of Brazil showed for the WHH_{110} of goethites a range from 0.17 to 0.67°2θ and for the WHH_{012} of hematites a range from 0.07 to 0.47°2θ (Dick 1986). A similar range for the WHH_{110} of goethites (0.10 to 0.60°2θ) was found in the VIIIth ISCW pedons (Kämpf 1986). The wide range in crystallinity of these minerals should affect their SSA and consequently their anion adsorption capacities (Jones 1981; Gualberto 1984; Correa 1984; Dick 1986).

According to XRD estimates in Oxisols the SSA for goethites (66-170m^2g^{-1}) are generally higher than for hematites (40- 75m^2g^{-1}) although some overlapping occurs (Schwertmann and Kämpf 1985); this confirms the observation that the SSA of goethitic Oxisols is generally higher than those of hematitic

Oxisols (Bigham et al. 1978; Curi 1983) within the same physiographic region. However, the goethite crystallite size may vary from soil to soil in the same physiographic region or from one region to the other: the range of WHH_{110} was 0.17 to 0.27 for Amazon Oxisols, 0.17 to 0.47 for Oxisols from the Brazilian central plateau, and 0.17 to 0.67°2θ for Oxisols from southern Brazil (Dick 1986). Gualberto (1984) found a bigger crystallite size for goethite from a goethitic Oxisol in the Brazilian Amazon region in comparison with a goethite from a goethitic Oxisol of the Brazilian central plateau. These data indicate that the variability in goethite types imposes caution on the generalizations about the behavior of one or the other form of these iron compounds. Correa (1984), working with Oxisols from southeastern Brazil, reached the same conclusion.

Genetic Implications of Iron Oxides

Besides being an important compositional phase, iron oxides in Oxisols are related to morphological features such as soil color and structure, and chemical properties as content of trace elements, anion adsorption (Bigham et al. 1978; Bahia Filho 1982; Curi 1983; Gualberto 1984; Souza 1985; Dick 1986), and so on, and reflect in their amount and/or types and arrangement the influence of parent rocks, and the present or past pedobioclimatic features (Resende 1976; Almeida 1979; Kämpf and Schwertmann 1983a; Curi 1983). That is, information on the nature of the parent material and the pedobioclimatic conditions are registered through the iron oxides. Thus, iron oxides represent one of the best environmental indicators in the soil profile. The best expression of this is the fact that Oxisols, depending on parent rock and pedobioclimatic conditions (including paleohydrological conditions), may have magnetic properties, tend to be yellower toward the surface, present mottling under aquic regimes, and so forth.

The influence of parent material can sometimes be pursued even in very old Oxisols. The use of a hand magnet has been used consistently in Brazil to detect the Oxisols developed from iron-rich rocks with considerable amounts of magnetite (basalt, tuffites, itabirite). It should be mentioned that the influence of the parent material being detected in this particular case affects both the sand + silt (magnetite) and clay fraction (maghemite).

In many Oxisols there is a clear trend of yellowing (xanthization) toward the soil surface. Exceptions are some red Oxisols in which the hematite is inherited from the parent material, or in those cases where the amount of hematite is high enough and or the pedobioclimatic conditions that favor goethite are relatively weak as in warmer and drier areas.

Xanthization is suggested as the process that leads to the expression of yellow colors by way of the destruction of hematite (leaving goethite) or to the formation of goethite in the absence of hematite. It is being suggested that xanthization be considered when the soil is goethitic (yellower than 6YR) in any part of the Bo horizon. The process can affect all the color control section or only the upper part, producing in this case a bichromic Oxisol.

Oxisols are mostly polygenetic, that is, they are developed under a nonuniform environmental condition. Consequently, the present pedoclimatic condition loses some of its power as related to covarying properties. That is, high water table in the past, producing strong xanthization, formation of mottles or concretions, or iron removal as identified by high value and relatively low chroma, explains what the present bioclimatic conditions often cannot do.

It seems reasonable then that iron oxides (amount and type) reflecting the result of interaction of parent material and pedobioclimatic conditions should have a large amount of covarying properties, thus having merit of their own for use in high categorical levels in soil classification systems.

Iron Oxides in Oxisol Taxonomy

As implied by the very name, the use of iron oxides in the Oxisol taxonomy would be as natural as the mollic epipedon in the Mollisols or the vertic characteristics in the Vertisols. Apparently, this has not been the case for historical and practical reasons.

Except for their removal to "clean" the silicates, iron oxides of Oxisols have been studied more thoroughly only in recent years (one or two decades at most). These facts have apparently led to an absence of reflection on the possible genetic-taxonomical importance of including iron oxides in the order that bears its name, the root *ox*, from oxide.

The crystallinity of goethite and hematite in Oxisols makes their quantification relatively easy by XRD after a concentration process (Kämpf and Schwertmann, 1982a,b) or by DXRD using selective dissolution (Bryant et al. 1983; Curi 1983; Santana 1984).

Despite this advantage, in *Soil Taxonomy* the mineralogical differentiation of Oxisols at the family level is based upon chemical analysis which measures only the total amount of iron oxide present (CBD-extraction) to define the oxidic and ferritic mineralogical classes. The authors believe that more attention should be given to the characterization of the Fe oxide phases in addition to the chemical extractions now being considered.

An early proposition to separate red from yellow Ustoxs was felt necessary in a soil survey of the Mato Grosso Goiano region in the central plateau of Brazil (Goiás 1976): Ustox with moist hues 2.5YR or redder were defined as Rhodustox, and those with 5YR or yellower hues as Xanthustox.

Due to the significant correlation of goethite and hematite proportion with the color of Oxisols (Kämpf 1981; Curi 1983; Santana 1984; Kämpf, Klamt, and Schneider 1986), goethitic and hematitic mineralogical classes have been proposed, aiming to differentiate the Oxisols.

Kämpf and Schwertmann (1983a) suggested a subdivision of the kaolinitic mineralogical class into a kaolinitic-goethitic and a kaolinitic-hematitic class, using a Gt/Gt+Hm ratio of 0.60 (which corresponds to Munsell hue-dry = 6.25YR and - moist = 3.75YR) as the limit.

Curi and Franzmeier (1984) proposed the distinction of hematitic Oxisols with colors redder than 5YR, at the great group level as Rhodustox, which would be listed early in the key of Ustox; Haplustox would be listed later to include the 5YR or yellower Oxisols that did not meet the requirements of some of the other great groups. Similar classification changes would

seem appropriate in Orthox and other suborders. As reflected in the Brazilian system of soil classification, this grouping of soils recognizes that soil color is associated with some very important properties.

More recently, based on the correlation of Oxisol hues with the Hm/Hm+Gt ratios, Kämpf, Klamt, and Schneider (1986) proposed the following classes for differentiation of Oxisols: goethitic with Hm/Hm+Gt < 0.2 and moist hues 6YR or yellower (= xanthic Oxisols); hematitic with Hm/Hm+Gt > 0.6 and moist hues 2.5YR or redder (= rhodic Oxisols); and criptogoethitic with Hm/Hm+Gt of 0.6 to 0.2 and moist hues yellower than 2.5YR and redder than 6YR (= rhodo-xanthic Oxisols). Due to the occurrence of hematitic Oxisols with reasonable amounts of maghemite, a hematitic-maghemitic class could be added, based upon color and magnetic susceptibility (Resende, Allan, and Coey, in press), since the maghemite quantification by XRD is still difficult.

It is worthwhile to keep in mind that these suggestions are to be discussed and further analyzed in order to pursue a common feeling.

References

Almeida, J.R. 1979. Cromossequência de solos originários de rochas pelíticas do Grupo Bambuí. M.S. thesis. Univ. Federal de Viçosa. 150 p.

Bahia Filho, A.F.C. 1982. Indices de disponibilidade de fósforo em Latossolos do Planalto Central com diferentes características texturais e mineralógicas. Ph.D. thesis. Univ. Federal de Viçosa. 179 p.

Bigham, J.M., D.C. Golden, S.W. Buol, S.B. Weed, and L.H. Bowen. 1978. Iron oxide mineralogy of well-drained Ultisols and Oxisols. II. Influence on color, surface area, and phosphate retention. *Soil Sci. Soc. Amer. J.* 42:825-830.

Bryant, R.B., N. Curi, C.B. Roth and D.P. Franzmeier. 1983. Use of an internal standard with differential x-ray diffraction analysis for iron oxides. *Soil Sci. Soc. Amer. J.* 47:168-173.

Coey, J.M.D. In press. Magnetic properties of iron in soil oxides and clay minerals. *In* J.W. Stucki, B.A. Goodman, and U. Schwertmann (eds.). Iron in soils and clay minerals. Reidel.

Correa, G.F. 1984. Modelo de evolução e mineralogia da fração argila de solos do planalto de Viçosa, MG. M.S. thesis. Univ. Federal de Viçosa. 87 p.

Curi, N. 1983. Lithosequence adn toposequence of Oxisols from Goiás and Minas Gerais states, Brazil. Ph.D: thesis. Purdue Univ., Lafayette, Ind. 158 p.

Curi, N., and D.P. Franzmeier. 1984. Toposequence of Oxisols from the central plateau of Brazil. *Soil Sci. Soc. Amer. J.* 48:341-346.

———. In press. Effect of parent rocks on chemical and mineralogical properties of some Oxisols in Brazil. *Soil Sci. Soc. Amer. J.* 50

Dick, D.P. 1986. Iron oxides characterization and P sorption in the clay fraction of latossolic B horizons. M.S. thesis. UFRGS, Porto Alegre. 196 p. (In Portuguese).

EMBRAPA. Serviço Nacia=onal de Levantamento e Conservação de Solos. 1984. Guia de excursão de estudos de solos nos Estados de Minas Gerais, Rio de Janeiro, São Paulo e Paraná. Ministério da Agricultura, Rio de Janeiro, Brazil. 104 p.

Eswaran, H. and C. Sys. 1970. An evaluation of the free iron in tropical basaltic soils. *Pedologie* 20:62-85.

Fabris, J.D., M. Resende, J.E.M. Allan, and J.M.D. Coey. In press. Mössbauer analysis of Brazilian Oxisols.

Fasolo, P.J. 1978. Mineralogical identification of four igneous extrusive rock derived Oxisols from the State of Paraná, Brazil. M.S. thesis. Purdue Univ., Lafayette, Ind. 109 p.

Fitzpatrick, R.W., and J. Le Roux. 1975. Pedogenic and solid solution studies on iron-titanium minerals. Proc. of the Intern. Clay Conf. Pp.585-599.

Fitzpatrick, R.W., and U. Schwertmann. 1982. Al-substituted goethite an indicator of pedogenic and other weathering evironments in South Africa. *Geoderma* 27:335-347.

Fontes, M.R., J.D. Fabris, M. Resende, and E. Galvão da Silva. 1985. Concreções ferruginosas de alguns solos brasileiros. II. Caracterização mineralógica. *R. Bras. Ci. Solo* 9:199-123.

Goiás. 1976. Secretaria da Agricultura. Levantamento de Reconhecimento dos Solos da Microregião do Mato Grosso Goiano. Volume I. Goiânia. 215 p.

Gualberto, V. 1984. Caracterização física, química e mineralógica de alguns latossolos, com altos teores de ferro, da Amazônia e do Planalto Central. M.S. thesis. Univ. Federal de Viçosa. 67 p.

Jones, R.C. 1981. X-ray diffraction line profile analysis vs. phosphorus sorption by 11 Puerto Rican soils. *Soil Sci. Soc. Amer. J.* 45:818-825.

Kämpf, N. 1981. Die Eisenoxidmineralogie einer Klimasequenz von Böden aus Eruptiva in Rio Grande do Sul, Brasilien. Ph.D. thesis. Tech. Univ., München, F.R.G. 217 p.

———. 1986. X-ray diffraction of iron oxides in selected samples from the VIII ESCW pedons. Proc. VIIIth Intern. Soil Class. Work.

Kämpf, N., and U. Schwertmann. 1982a. The 5-M-NaOH concentration treatment for iron oxides in soils. *Clays Clay Miner.* 30:401-408.

———. 1982b. Quantitative determination of goethite and hematite in kaolinitic soils by x-ray diffraction. *Clays Clay Miner.* 17:359-363.

———. 1983a. Relations between iron oxides and soil colour in kaolinitic soils of soil of southern Brazil. *R. Bras. Ci. Solo* 7:27-31. (In Portuguese).

———. 1983b. Goethite and hematite in a climosequence in southern Brazil and their application in classification of kaolinitic soils. *Geoderma* 29:27-39.

Kämpf, N., E. Klamt, and P. Schneider. In press. Iron oxides in latossols of Southeastern and South Brazil. Anais da III Reunião de Classificação, Correlação de Solos e Interpretação da Aptidão Agrícola. September 1984. EMBRAPA/SNLCS Rio de Janeiro (In Portuguese).

Mehra, O.P., and M.L. Jackson. 1960. Iron oxide removal from soils and clays by a dithionite-citrate system buffered with sodium bicarbonate. *Clays Clay Miner.* 7:317-327.

Pötter, R.O., and N. Kämpf. 1981. Argilo-minerais e óxidos de ferro em Cambissolos e Latossolos sob regime climático térmico údico no Rio Grande do Sul. *R. Bras. Ci. Solo* 5:153-159. (In Portuguese).

Rauen, M.J. 1980. Mineralogical identificaiotn of a toposequence of soils from basaltic rocks in the State of Paraná, Brazil. M.S. thesis. Purdue Univ., Lafayette, Ind. 161 p.

Resende, M. 1976. Mineralogy, chemistry, morphology and geomorphology of some soils of the central plateau of Brazil. Ph.D. thesis. Purdue Univ., Lafayette, Ind. 237 p.

Resende, M., J.E.M. Allan, and J.M.D. Coey. In press. The magnetic soils of Brazil.

Resende, M., D.P. Santana, and S.B. Rezende. 1986. Susceptibilidade magnética em Latossolos do sudeste e sul do Brasil. Anais da III Reunião de Classificação, Correlação de Solos e Interpretação da Aptisão Agrícola. September 1984. EMBRAPA/SNLCS. Rio de Janeiro. (In Portuguese).

Rezende, S.B. 1980. Geomorphology, mineralogy and genesis of four soils on gneiss in southeastern Brazil. Ph.D. thesis. Purdue Univ., Lafayette, Ind. 143 p.

Santana, D.P. 1984. Soil formation in a toposequence of Oxisols from Patos de Minas Region, Minas Gerais State. Brazil. Ph.D. thesis. Purdue Univ., Lafayette, Ind. 129 p.

Schwertmann, U. 1964. Differenzierung der Eisenoxyde des Bodens durch Extraktion mit Ammoniumoxalat-Lösung. *Z. Pflanzenernähr. Bodenkd.* 105:195-202.

———. In press. Some properties of soils and synthetic iron oxides. *In* J.W. Stucki, B.A. Goodman, and U. Schwertmann (eds.). Iron in soils and clay minerals.

———. In press. Occurrence and formation of iron oxides in various pedoenvironments. *In* J.W. Stucki, B.A. Goodmann and U. Schwertmann (eds.). Iron in soils and clay minerals.

Schwertmann, U., and H. Fechter. 1984. The influence of aluminum on iron oxides. XI. Aluminum - substituted maghemite in soils and its formation. *Soil Sci. Soc. Amer. J.* 48:1462-1463.

Schwertmann, U., and N. Kämpf. 1983. Young iron oxides in Brazilian pedogenic environments. *R. Bras. Ci. Solo* 7:251-255. (In Portuguese).

———. 1985. Properties of goethite and hematite in kaolinitic soils of southern and central Brazil. *Soil Sci.* 139:344-350.

Soil Survey Staff, SCS, USDA. Soil taxonomy: A basic system of soil classification for making and interpreting soil surveys. Agric. Handb. no. 436. USDA. U.S. Govt. Printing Office, Washington, D.C. 754 p.

Souza, J.A. 1985. Relações entre formas de ferro e sorção de fósforo em Latossolo sob cerrado do Planalto Central. M.S. thesis. Escola Superior de Agricultura de Lavras.

Vettori, L. 1976. Ferro "livre" por cálculo. Anais do XV Congresso Brasileiro de Ciência do Solo. Pp. 127-128.

MAGNETIC PROPERTIES OF BRAZILIAN OXISOLS

M. Resende,[1] D.P. Santana,[2] D.P. Franzmeier,[3] J.M.D. Coey[4]

Abstract

Soil surveyors in Brazil use a field test—attracting soil material by a hand magnet—as a method of judging the nature of the parent material. In recent years there has been a gradual emergence of interest in magnetic susceptibility for classification of Brazilian Oxisols. Spontaneous magnetization, M_s, has been shown to be a better mineralogical parameter than magnetic susceptibility, but a good linear relationship has been established between M_s and the susceptibility obtained at relatively high field (0.5 Tesla) by using a modified analytical balance. Magnetization values for some reference iron minerals show a wide variation, which can be explained by covarying the amounts for isomorphous substitution of Ti and Al for Fe. The use of units related to magnetic measurements has not been uniform and these are discussed. Magnetization data for Brazilian Oxisols are related to both iron content and color. Magnetization of the clay fraction of oxisols is higher in redder soils and in those richer in iron; it decreases markedly when soils are yellower in color and is less pronounced with reduced iron content. The magnetic Oxisols so far are related to parent material as magnetization in the clay fraction is high only in soil derived from mafic, tuffitic, and itabiritic rocks and is always related to coarser fractions with quite strong magnetization due to magnetite or maghemite. Since magnetite is often very rich in trace elements, magnetization can indicate richer pedosystems. Magnetization and color, although relate to each other, provide complementary information. They are expressions of mineralogy which are more sensitive than most mineralogical characteristics. Particularly in Oxisols, by their polygenetic natures, these characteristics might be used at a high taxonomic level. However, iron content and color, if used at a higher level to separate Oxisols, also separate the highly magnetic Oxisols. Thus, magnetization can be used more effectively at a lower taxonomic level.

Over the years, it has been learned that the most effective soil classification criteria are those in which the differentiating characteristics (the properties chosen as the basis for defining classes) are based, to some extent, on properties that covary with the general nature of the parent rock. In general, the younger the soil the greater the influence of parent material on soil properties. However, after long periods of weathering, even small differences in composition of parent material cause significant variation in soil properties. This is very pertinent in Brazil where Oxisols derived from mafic (basic) rocks are separated, in the Brazilian soil classification system, from Oxisols formed from other rock even if they have the same color, the same amount of clay, and the same organic matter content. This separation appears to be well justified in terms of the productivity of the soil, because Oxisols derived from mafic rock have potential for greater agricultural development than those derived from other rocks.

However, in this deeply weathered tropical area, it is not always easy for a soil surveyor to determine the nature of the parent material. Ideally, the nature of the parent material should be determined independently of other soil properties. Soil surveyors in Brazil use a field test—attracting soil material by a hand magnet (Brazil 1960)—as a method of judging the nature of the parent material. In these tests, basic rock-derived soils are strongly attracted. This measurement is only qualitative and it is judged subjectively. In recent years there has been a gradual emergence of interest in the quantification of magnetic susceptibility of Brazilian Oxisols (Resende 1976; Fasolo 1978; Rauen 1980; Resende 1980; Curi 1983; Santana 1984; and Resende, Santana, and Rezende 1985). The idea of using magnetic susceptibility as a classification criteria was discussed by Resende, Santana, and Rezende 1985.

The aim of this paper is to present the magnetic properties of Brazilian Oxisols to discuss the possibility of using soil magnetism to separate Oxisols at a low taxonomic level.

Methodology, Reference Minerals, and Units

Methodology

Before studying magnetism of Oxisols, something should be said about the methodology. Iron soil minerals when subjected to a magnetic field, B_o, in tesla, are magnetized in a relatively irregular way (Fig. 1). The lower linear part of the

[1] Department of Soil, U.F.V. Viçosa, MG, Brazil
[2] EPAMIG, Caixa Postal 515, CEP, 30.000, Belo Horizonte-MG, Brazil.
[3] Department of Agronomy. Purdue University, Indiana.
[4] Department of Pure and Applied Physics, Trinity College, Dublin 2, Ireland.

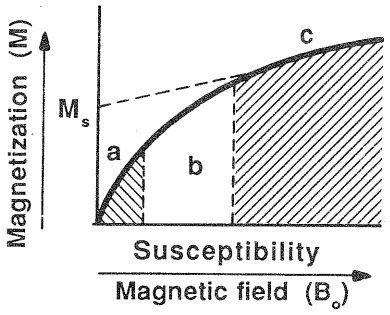


Fig. 1. Magnetization curve showing (a) linear, (b) curvilinear, and (c) linear segments with increase in the magnetic field.

magnetization curve (a) represents the segment where the magnetic susceptibility is measured (Mullins 1977). The susceptibility is usually defined as the slope M/B_o. The upper linear portion (c) of the graph occurs when there is saturation of the spontaneous magnetization M_S; that is, the applied field is strong enough to align the magnetization of the material.

The curve shown in Figure 1 is simplified. The textbook classical example shows a more complex pattern with hysteresis (Fig. 2).

For a demagnetized material, starting from $B_o = 0$ and $M = 0$ the virgin magnetization curve, the inner curve in Figure 2a reaches saturation as shown, but when the magnetic field is decreased the magnetization follows a different path. There is a remnant magnetization (M_r) that remains even when $B_o = 0$, and it is necessary to apply a field of strength, - Bc, in the opposite direction, to reduce M to zero. If the magnetic field is cycled between maximum negative and maximum positive values, the original curve is not recovered but the hysteresis loop is traced out instead. Magnetic materials are classified as hard or soft according to whether the hysteresis loop is broad or narrower (negligible hysteresis).

Hysteresis, Figure 2a, complicates the determination of magnetic susceptibility as pointed out by Mullins (1977), but it is still possible to determine the initial susceptibility by using a weak alternating magnetic field of a few μT. Nevertheless, magnetic susceptibility is not a very useful mineralogical parameter since it depends on size and shape of the magnetic grains. The spontaneous magnetization, M_S (Fig. 2), is a much better parameter (Coey 1986).

A closer look at Figure 2 shows that at a higher value of the magnetic field, the magnetization tends to approach a certain value independent of hysteresis. In other words it is possible to estimate M_S by measuring magnetization in a sufficiently large magnetic field (> $0.3T$). The ratio M/B_o is also sometimes referred to as the magnetic susceptibility, although it is evidently different from the initial susceptibility and depends on the value of the measuring field.

By using data on a series of 20 samples, a calibration curve has been established between what was called magnetic susceptibility, M/B_o, at a field of about $0.5T$, and spontaneous magnetization, M_S, for the clay fraction of Brazilian Oxisols (Fig. 3). Magnetization curves were obtained for the series using a vibrating-sample magnetometer and M_S was extrapolated, as shown in Figure 4. The magnetic susceptibility was simply determined according to Resende, Santana, and Rezende (1985) using an analytical balance by replacing a plastic for a metallic plate. In a hard paper underneath was fixed a U-shaped permanent magnet. The magnetic attraction was measured by the counterweight needed to displace the plate touching the magnet. A calibration curve was plotted using known susceptibility values of $MnSO_4 \cdot H_2O$, $Fe(NH_4)(SO_4)_2 \cdot 6H_2O$ and $CoHg(SCN)_4$, for which M is proportional to B_o in the field used. Figure 3 establishes that the susceptibility in $\approx 0.5T$ provides a consistent measure of the spontaneous magnetization.

The magnetization curves of the Oxisol clays we have studied so far show practically no hysteresis ($B_c \leq 10\ mT$). A typical curve shown in Figure 4 is that of a soft magnetic material (Fig. 2b), like a soft ferrite.

We are not yet sure if all the Oxisol soil magnetic clays are as soft as that shown in Figure 4. This is currently being investigated.

Reference Minerals

The use of reference minerals for soil mineralogical analysis always has been a problem. It has been known for a long time that soil minerals, formed in a pedogenic environment, can be quite different from the reference mineral bearing the same name but formed under quite different conditions. Isomorphous substitutions, degree of crystallinity, and habit of growth are some of the sources of these differences.

The iron oxides are quite variable. They tend to be unstable, so that in the same profile it is possible to find what seems to be, for example, two kinds of goethite, varying for example, in degree of Al-isomorphous substitution and particle size (Rezende 1980; Fabris et al. 1985). Spatial variation in these same properties has also been registered in Oxisols (Resende 1976; Rezende 1980; Kämpf and Schwertmann 1982; Curi 1983; Santana 1984). Hematite, although less studied in this respect, seems to show similar behavior. Among the iron oxides the ferrimagnetic minerals, magnetite and maghemite, are particularly prone to isomorphous substitutions (Nagata and Akimoto 1961; O'Reilly 1984) which have an important influence on the magnetization of the minerals. In Brazil the magnetite of Oxisols developed from basalt is quite different from that developed from itabirite, especially in the amounts of trace elements (Curi and Franzmeier 1984).

Spontaneous magnetization values for some reference iron minerals (Table 1) show a wide variation, illustrating the difficulty of establishing a set of standard minerals. For example soil maghemite in the clay fraction of Oxisols developed from tuffites shows $M_S = 34.5 JT^{-1}kg^{-1}$ ($X = 63650 \times 10^{-8}m^3kg^{-1}$) while pure maghemite should have a value around $M_S = 65 JT^{-1}kg^{-1}$ (Coey 1985) and $X = 110{,}704 \times 10^{-8}m^3kg^{-1}$. Isomorphous substitution of Al and Ti for Fe is presumably the reason for the decrease in magnetization of soil maghemite. The titanomaghemite extracted from the C horizon of a diabase

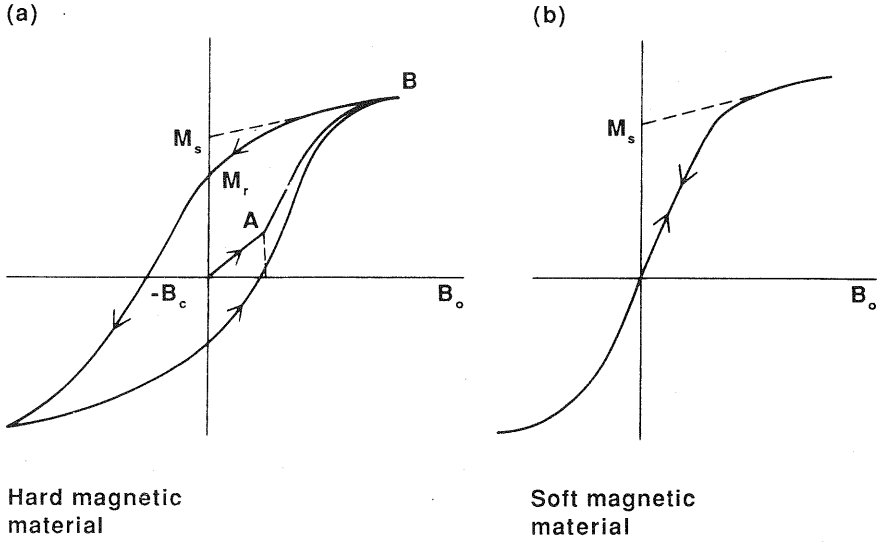


Fig. 2. Magnetization curves showing hysteresis in a hard magnetic material (a) and absence of hysteresis in soft magnetic material (b).

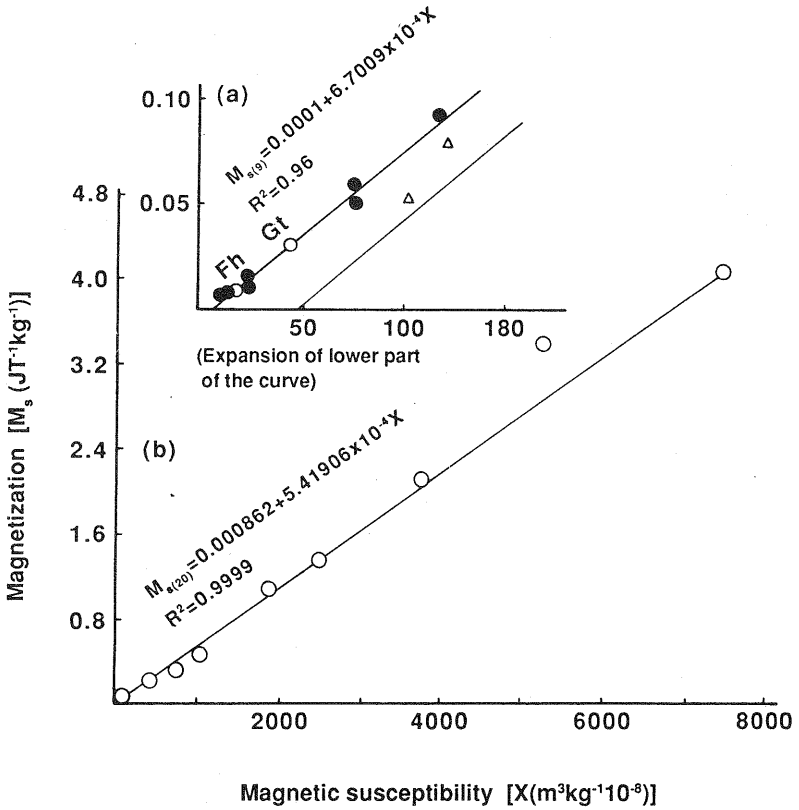


Fig. 3. Relationships between magnetic saturation, M_s, and magnetic susceptibility determined using a modified analytical balance for clay fraction of Brazilian Oxisols (III RCC and G series, see Table 3). (a) using 9 samples with $X < 180$; Gt = Goethite Wards; Fh = Ferrihydrite from West Germany. The lower line is derived from (b) using 20 samples with X up to about 8000.

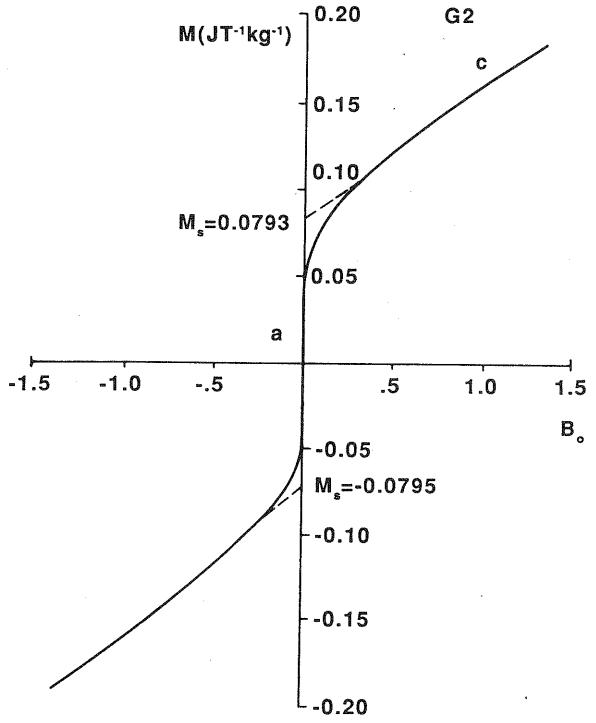


Fig. 4. Magnetization curve of an iron-rich yellow Oxisol (clay fraction).

derived soil also has a much lower magnetization value (M_S = 25.04$JT^{-1}kg^{-1}$) than pure maghemite, Table 1.

Units

The use of units in magnetic measurements has not been uniform. It is particularly confusing when units like mg g^{-1}, relative to magnetite (Matsusaka and Sherman 1961), emucgs, cgs, m^3kg^{-1} (Mullins 1977; Reitz, Milford, and Christy 1980) or $JT^{-2}kg^{-1}$ or Am^2kg^{-1} have all been used. Using the Sommerfield convention $B = B_o + \mu o\, M$, we summarize in Table 2, the units in SI and cgs systems, as well as the conversion factors.

The symbols have the following meaning (Fig. 5).

B = Magnetic flux that is produced in a material as a result of a magnetic field;
B_o = magnetic field, free space induction;
μo = permeability of free space, 4¶ x 10^{-7} T. mA^{-1};
where:
H = field related to B_o by a constant, $H = B_o/\mu o$;
M = magnetization or magnetic moment per unit volume;
σ = magnetization or magnetic moment per unit mass.

What about the unit m^3kg^{-1} used so much for magnetic susceptibility?

This unit used, by Mulay (1963), Mullins (1977), and Reitz, Milford, and Christy (1982), is derived by considering the dimensionless magnetic susceptibility per unit volume.

$$K = \mu o\, M/B_o = M/H.$$

Inspection of Table 2 shows that this is a pure ratio, with no units.

The magnetic susceptibility per unit mass is then obtained by dividing this quantity by the density.

Using symbols of Table 2, $X = K/\rho$.
Since ρ in the SI system is in kg m^{-3}, X_{SI} is in m^3kg^{-1} and X_{cgs} is in cm^3g^{-1} (other units are emu cgs, cgs, emu g^{-1}).

The preferred definition of K is M/B_o. It then has units J/T^2m^{-3} so that $X = K/$ has unit $JT^{-2}kg^{-1}$. To convert from X_{SI} in m^3kg^{-1} to X_{SI} in $JT^{-2}kg^{-1}$ divide by μo.

To convert from X_{SI} in $JT^{-2}kg^{-1}$ to X_{cgs} in emu g^{-1}, divide by 10^4.

Example: X = 45 x $10^{-8}m^3kg^{-1}$ is
45 x 10^{-8}/4¶ x 10^{-7} = 0.36 $JT^{-2}kg^{-1}$ or
0.36/10^4 = 0.36 x 10^{-4} emu g^{-1}

Oxisol Magnetic Data

Bw Horizons

Magnetization data for Brazilian Oxisols, which vary markedly in iron content, color, and bioclimatic environment, are shown in Table 3.

The Oxisols with Fe_2O_3 > 18 percent and color 2.5YR or redder consistently show a higher magnetization in the clay than the ones with an equivalent amount of iron but with color yellower than 2.5YR. Red Oxisols, with a medium amount of iron (8-18 percent Fe_2O_3), can still have a relatively large magnetization when developed from basalt or tuffites; while the yellow ones have much lower X, as do the ones with low amounts or iron < 8 percent, independent of color.

The contribution of the various size fractions to the magnetization is also related somewhat to color (Fig. 6). Reddish soils 1YR, (1.5YR and even 3.5YR 3.5/5) with a high amount of iron derive most of their magnetization from the clay fraction, while the coarse fractions (silt and sand) are more important in the yellower ones (4YR, 5YR). Soil III RCC-1 developed from itabirite is an exception; it shows a large contribution from the sand fraction although its color is 10R. The presence of concretions in the sand fraction is responsible. The magnetization is related to both iron content and color (Fig.7).

The magnetic susceptibility of the clay fraction of Oxisols is higher in the redder and more iron-richer soils. It decreases markedly as the color becomes yellower and iron content is reduced. There is so far an empty space in the region of colors yellower than 2.5YR and of iron oxide content higher than 35 percent. The boundary line, hue = 0.05 + 0.24 Fe_2O_3(A), defines the limit for low susceptibility clays, while the most magnetic clay has Fe_2O_3 higher or equals 18 percent and a hue redder than 2.5YR (B).

Parent Material

The magnetism of Oxisols is related to parent material.

Magnetization in the clay fraction is high only in soils derived from mafic rocks, tuffites, and itabiritic rocks (Table 1), and it is always related to coarser fractions with quite strong magnetization, due probably to magnetite.

Table 1. Magnetization of Ore, Inherited and Pedogenic Iron Materials

Minerals	Spontaneous magnetization ($JT^{-1}kg^{-1}$)	Magnetic susceptibility at $B_o \approx 0.5T$ $m^3kg^{-1} \times 10^{-8}$
Magnetite[a]	≈ 100	(184518)[c]
Magnetite/Ilmenite (Basalt)[b]	(64.4)	118852
Magnetite (Itabirite)	(23.3)	42903
Maghemite	≈ 60	(110704)
Maghemite (Tuffite)	(34.5)	63650
Titanomaghemite (Diabase)	25.0	(46192)
Ilmenite	0	
Ilmenite (Wards)[d]	(0.8)	1472
Hematite (Coey)	(0.07)	116
Hematite (Wards)	(15.6)	28859
Hematite (RD13.RD14)	(0.2)	382
Goethite	0	
Goethite (Wards)	(0.003)	45
Goethite (RD13, RD14)	(0.3)	38
Ferrihydrite	0	
Ferrihydrite (W. Germany)	(0.01)	8.5

[a] Solid underlined samples are synthetic minerals, dashed underlined samples are not soil samples; hematite (Wards) has considerable maghemite as shown also be DXRD.
[b] > 53 μm, isolated magnetically from an Oxisol Bw horizon developed from basalt.
[c] The numbers in parenthesis are estimated by using equation $M_s = 0.00862 + 5.41906 \times 10^{-4} X$ (Fig. 3).
[d] > 88 μm.

Table 2. Quantities and Units Related to Magnetic Measurements

Quantity	SI units	cgs units	Conversion factor SI —> cgs multiply by
B_o, B	Tesla	Gauss	10^4
H	Am^{-1}	Oersted 0.01257	(4¶/1000)
m	$JT^{-1} = Am^2$	erg/oe	10^3
M^*	$JT^{-1}m^{-3} = Am^{-1}$	emu/cc	10^3
σ	$JT^{-1}\,kg^{-1} = Am^2\,kg^{-1}$	emu/g	1
K^{**}	$JT^{-2}\,m^{-3}$ or none	emu/cc	10^{-7}
X^{**}	$JT^{-2}\,kg^{-1}$ or $m^3\,kg^{-1}$	emu/g	10^{-4}
X_m	$JT^{-2}\,mol^{-1}$	emu/mol	10^{-1}

[*] Although M is properly defined as the magnetization per unit volume, this same symbol is sometimes used instead of σ for magnetization per unit mass, which is the quantity directly measured by experiment.
[**] Depending on the definition of $K = M/B_o$ ($JT^{-2}m^{-3}$), or $K = M/H$ (no units), $X = K/\rho$ will be in $JT^{-2}kg^{-1}$ or m^3kg^{-1}, respectively.

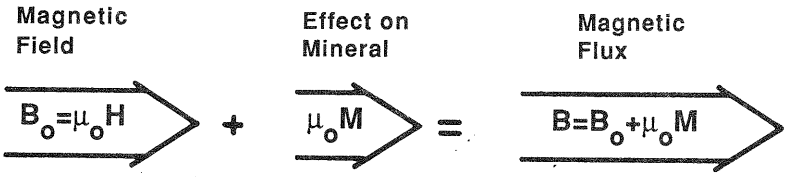


Fig. 5. Scheme showing that the magnetic flux B results from the sum of magnetic field (free space induction) plus the effect of this field in the mineral.

These parent materials themselves contain variable amounts of magnetic minerals. For example, itabiritic and related materials (Fig. 8) show quite a variation of X, independent of the amount of iron oxide; tuffite, although varying in color, shows generally a high, although quite variable susceptibility (Fig. 9). There is no clear relation between color (dry hue) and magnetic susceptibility. This indicates that magnetic behavior is giving information not detected by color alone in both parent materials and soils. The large range of X values, from about 200 to almost 15000 m^3kg^{-1}, gives and indication of the large variation of X of tuffite and also the very great sensitivity of this measurement for characterizing earth materials.

The clear relationship between magnetization of the clay fraction and parent material establishes that the source of the magnetization of Oxisols is not maghemite formed from other iron oxides by burning of organic matter. When samples are heated at various temperatures an increase in magnetization is observed around 500°C (Figs. 10, 11), which is related to the amount of organic matter, but between 500°C and 750°C the magnetization of all horizons drops to almost zero.

The absence of any clear increase in magnetization toward the surface (Fig. 12) in a soil with a considerable amount of organic matter, under *cerrado* vegetation sampled by Sans (1986) in an area very prone to burning, does indicate that formation of maghemite by burning (Le Borgne 1955, 1960) can only play a very minor role in Oxisol maghemite genesis in Brazil.

Particle Size

The magnetic material in the clay-size fractions, which may generally be maghemite, is related to nonclay parent minerals. The magnetization of the material in the coarser fractions is quite variable with particle size. Usually the larger-size particles have higher magnetization in the soils influenced by basaltic parent materials (Fig. 13). The tuffitic material, on the other hand, shows higher X in the silt, fine, and coarse sands, in this order. The clay fraction has a much lower magnetization while the clay fraction of the Oxisol Bw horizon, developed from tuffite, has a much higher magnetization (Fig. 14).

Topo- and Climosequence

The magnetization of the clay fraction is high only in the redder iron rich soils. So, the conditions that tend to develop a yellow color also tend to decrease the maghemite content.

There are two major regimes of yellowing (xantization): along a climosequence and following a toposequence. The magnetization of the clay fraction for Oxisols developed from basalt, for example, decreases from warmer and drier sites at lower altitudes to cooler and moisture conditions at higher altitudes (Fig. 15).

There is much evidence in Brazilian landscapes of paleohydrological conditions leading to reduction in Oxisol iron content, ranging from cases of bleaching with almost complete deferrification to xantization, without much reduction in iron content. Besides those situations where there are conspicuous color changes there are toposequences without much change in color but with a variation in hematite/goethite ratio and a very distinct sequential change in magnetization (Fig. 16).

Across the landscape (Fig. 16) the major difference is a downslope decrease in magnetization. There also are two trends with depth: in profiles 7, 8, and 9 magnetization increases with depth and then decreases; in soils of lower elevation, 1-3, the magnetization is largest closest to the surface and decreases markedly with depth. Apparently, organic matter close to the surface and poor drainage in the lower portions of the landscape each reduce the magnetization, but poor drainage seems relatively more efficient in decreasing the amount of maghemite. Closer to the talweg, the decrease in the amount of maghemite can be registered (by the magnetization) before any color variation is detected (Fig. 17).

This supports the idea that magnetization and color, although related to each other, are not measuring the same thing. That is, they give complementary but not identical information.

The magnetization of the fine earth (Fig. 18) is much higher than the magnetization of the clay fraction (Fig. 16), but presents similarly shaped isolines. This gives an indication that maghemite is derived from the coarser fractions and also that in this particular landscape, although dominated by red colors, the magnetic susceptibility of the clay fraction is relatively low. This fact seems to be related to the concretions registered in the profiles (Santana 1984).

The magnetization of the clay fraction seems to indicate hydrological conditions not registered by color but supported by the concretions.

Quantification of Maghemite

Magnetization has been used to quantify magnetite (Sauk 1972) and might well be used to quantify soil maghemite.

In the toposequence studied by Santana (1984), the amounts of maghemite were determined by differential x-ray diffraction, DXRD (Table 4). Using these data, the susceptibility of soil maghemite should be 63663 m^3kg^{-1} x 10^{-8} (506.6 $JT^{-2}kg^{-1}$) and the spontaneous magnetization, M_s = 34.5 $JT^{-1}kg^{-1}$.

Table 3. Magentization ($m^3kg^{-1} \times 10^{-8}$) of Fine Earth (<2 mm), Sand (2-0.05 mm), Silt (50-2 mm) and Clay-Size (<2 Mn) Particles of Oxisols

Soil	Altitude (m)	Natural vegetation	Rock substrate	Moist color	Clay (%)	Fe_2O_3 (%)	Fe_2O_3 / Clay	TiO_2 (%)	Magnetization $m^3kg^{-1} \times 10^{-8}$ < 2 mm	2-0.05	50-2 µm	< 2	Source**
				High Iron (>18%) Red Colors (≤ 2.5YR)									
III RCC-1	1200	Cerrado	Itabirite	10R 3/6	58	55.8	0.96	2.16	7353	12970	4,078	2535	a
MQ	~1200	Cerrado	Itabirite	10R 3/4	27	63.3	2.34	0.32	28327		12389	13271	e,f,c
Go20	690	Cerrado	Basalt	10R 3/5	62	25.5	0.41	5.52	5040				b,s
33	567	Cerrado	Basalt	2.5YR 3/4	53	29.4	0.55	8.08	3974			3210	b
G6	500	Cerrado	Basalt	2.5YR 3/4	71	26.3	0.37	3.55	4016		2713	2805	c,f,g
III RCC-7	760	SD Forest*	Basalt	1.5YR 3/4	75	34.2	0.46	4.87	7296	9932	12797	2885	a
43	588	SD Forest	Basalt	10R 3/4	62	29.9	0.48	6.81	5951			5296	b
4M1	568	SD Forest	Basalt	10R 3/4	68	30.6	0.45	6.93	4507				b
4M2	567	SD Forest	Basalt	2.5YR 3/4	66	25.2	0.38	6.98	3458				b
RS16	680	ST Pines	Basalt	2.5YR 3/6	82	22.3	0.27	4.18	905				b,q
MT11	350	SE Forest	Basalt	10R 3/4	79	27.0	0.34	3.77	5205				b,q
F7	860	Cerrado	Tuffite	"	58	20.3	0.35	2.25	1845	4990	3419	2247	c,h
F9	882	Cerrado	Tuffite	2.5YR 3/4	45	23.1	0.51	3.65	3612	4365	15848	2356	c,h
PR 61	470	SE Forest	Basalt	10R 3/5	83	27.0	0.33	3.93	61573				k
DE 3			Tuffite	2.5YR 4/6	49	25.4		10.80				354	c
PR 4	700	ST Pines	Basalt	2.5YR 3/4	580	28.2	0.35		18095				k
DB O	910	Cerrado	Tuffite	2.5YR 4/6	74	18.0	0.24	2.60				463	c
DB1	960	Cerrado	Tuffite	2.5YR 3/6	71	21.5	0.30	2.50	647			529	c
DB2	915	Cerrado	Tuffite	2.5YR 3/6	75	23.1	0.31	4.00	1498			1176	c
DB3	960	Cerrado	Tuffite	2.5YR4/6	79	25.0	0.32	6.60				51	c
DB4	980	Cerrado	Tuffite	10R 3/4	65	32.7	0.50	6.80	5406			2,939	c
8ISCW-7	660	SD Forest	Basalt	10R 3/5	76	32.1	0.42	6.52		17471	12438	4238	c,o
8ISCW-8	610	SD Forest	Basalt	10R 3/5	73	31.0	0.42	7.04		5344	9318	4202	c,o
8ISCW-14	480	SD Cerrado	Basalt	1.5YR 3/3	72	26.1	0.36	6.46		4113	8251	5084	c,o
				High Iron (>18% Fe_2O_3) Yellow Colors (>2.5YR)									
BA 4	205	Evergreen	Granulite	7.5YR 4.5/6	67	21.6	0.32	2.6	63		132	41	b,t
PT4-4	220	SE Equat.	Vulc. tuff.	2.5Y 4/4	61	22.5	0.37	1.83				22	c,j
III RCC-6	645	SD Cerrado	Basalt	4YR 4/4	53	30.0	0.57	6.73	5886	14465	2546	1046	a
4M3	550	SD Forest	Basalt	5 YR 3/4	60	21.8	0.36	7.16	889				b
4M4	548	Cerrado	Basalt	3.75YR 3/4	44	33.8		7.47	1976				b
4M5	548	Cerrado	Basalt	5YR 3/4	43	34.9	0.81	7.31	3334			659	b
III RCC-11	920	ST Moist	Basalt	3.5YR 5/5	85	23.1	0.27	3.44	803	4525	2222	458	a
III RCC-12	1100	ST Moist	Basalt	5YR 3.5/5	79	24.0	0.30	6.69	653	5971	2430		a

Soil	Altitude (m)	Natural vegetation	Rock substrate	Moist color	Clay (%)	Fe_2O_3 (%)	Fe_2O_3 / Clay	TiO_2 (%)	Magnetization $m^3kg^{-1} \times 10^{-8}$ < 2 mm	2-0.05 mm	50-2 µm	< 2 µm	Source**
G1	500	Cerrado	Basalt	10YR 4/4	58	17.9	0.31	3.25	212		410	165	c,g,j
G2	500	Cerrado	Basalt	7.5 YR 4/6	67	16.6	0.25	3.31	232		337	185	c,g,j
G3	500	Cerrado	Basalt	7.5YR 4/4	62	20.2	0.33	3.24	347		428	382	c,g,j
G4	500	Cerrado	Basalt	5YR 4/4	66	20.9	0.32	3.38	601		612	603	c,g,j
G5	500	Cerrado	Basalt	5YR 3/4	61	23.5	0.39	3.36	946		810	904	c,g,j
PR-18	550	Cerrado	Basalt	3.5YR 3/4	81	19.1	0.24	4.30	15205				k
DC1	1140	SE Forest	Tuffite		87	19.3		5.60				243	c
				Medium Iron (8-18% Fe_2O_3) Red Colors (<2.5YR)									
III RCC-5		SD Forest	Claystone	2.5YR 3/7	59	11.1	0.19	2.54	565	573	448	642	a
F2	849	Cerrado	Tuffite	2.5YR 3/6	64	14.2	0.22	1.82	816	3129	1093	1034	c,h
F3	851	Cerrado	Tuffite	2.5YR 3/6	64	14.6	0.23	1.75	1064	2981	1633	1577	c,h
F4	852	Cerrado	Tuffite	2.5YR 3/6	61	15.9	0.26	1.92	1332	2952	1810	1624	c,h
F5	853	Cerrado	Tuffite	2.5YR 3/6	64	16.1	0.25	1.87	1359	3822	2232	1839	c,h
F6	854	Cerrado	Tuffite	2.5YR 3/6	62	17.1	0.28	1.93	1494	4707	2359	1901	c,h
13	632	SD Forest	Sandstone	10 R 3/4	24	8.9	0.37	2.49	610			1158	b
23	720	Cerrado	Sandstone	2.5 YR 3/4	27	9.5	0.35	3.80	1156			1098	b
63	900	Cerrado	Clayey sed.	2.5 YR 3/6	65	11.4	0.18	1.98	168			85	b
2M2	680	Cerrado	Sandstone	2.5 YR 3/6	31	9.1	0.29	2.47	417				b
5M3	880	Cerrado	Clayey sed.	2.5 YR 3/4	50	10.2	0.20	2.15	419				b
PR39	1100	ST Pines	Andesite	2.5 YR 3.5/6	77	17.9	0.23	4.04	11560				b,b
GF1	570	SE Forest	Gneiss	2.5 YR2.5/5	64	12.7	0.20	2.11				185	c,d
DCO	1120	SE Forest	Tuffite/sed.	2.5YR 4/6	87	17.2	0.20	5.9	278			110	c
R1	600	Cerrado	Slate	2.5YR 4/6	65	8.9	0.14	0.22				514	c,i
8ISCW-4	620	SE Forest	Pellit/Ls	2.5YR 4/6	76	10.4	0.14	1.16		123	243	118	c,o
8ISCW-17	1070	SD Forest	Cryst. rocks	1.5YR 3/6	54	12.7	0.24	2.39		1594	779	190	c,o
8ISCW-20	1240	SD Cerrado	Metapellit.	2.5YR 4/7	80	14.0	0.18	1.24		779	152	59	c,o
				Medium Iron (8-18% Fe_2O_3) Yellow Colors (>2.5 YR)									
III RCC-2	850	Evergreen Forest	Gneiss and acid migmatite	7.5YR 5/8	57	8.1	0.14	0.95	10	27	125	13	a
III RCC-3	950	Evergreen Forest	Charnok migmatite gneiss	7.5YR 4/5	69	14.7	0.21	1.67	48	114	290	23	a

Table continued on next page

Table 3. Continued

Soil	Altitude (m)	Natural vegetation	Rock substrate	Moist color	Clay (%)	Fe_2O_3 (%)	Fe_2O_3 / Clay	TiO_2 (%)	Magnetization $m^3kg^{-1} \times 10^{-8}$				Source**
III RCC-14	860	Moist F. Pines	Migmatite	10 YR 5/8	50	10.4	0.21	1.29	218	946	90	9	a
53	940	Cerrado	Clayey sed.	5 YR 4/6	66	8.8	0.13	1.97	119			74	b
GF5	780	SE Forest	Gneiss	7.5 YR 3.5/4	68	13.4	0.18	2.55				41	c,d
GF4	780	SE Forest	Gneiss	5 YR 3/8	73	13.3	0.18	2.47				41	c,d
GF7	795	SE Forest	Gneiss	10YR 3.5/3	73	9.8	0.13	1.83				30	c,d
GF8	785	SE Forest	Gneiss	5 YR 4/4	69	10.4	0.15	1.93				39	c,d
8ISCW-9	1060	SE Forest	Sedim	7.5YR 5/6	41	8.0	0.20	1.31		230	538	53	c,o
8ISCW-18	1160	SD Forest	Schists	5 YR 5/6	80	14.4	0.18	2.21		1043	193	24	c,o
8ISCW-19	1120	SD Forest	Metapellit	6.5YR 5/6	83	14.3	0.17	1.19		4617	183	15	c,o
				Low Iron (<8% Fe_2O_3) Red Colors (≤2.5 YR)									
III RCC-8		Cerrado	Sandstone	1.5YR 3/6	24	3.4	0.14	0.60	67	71	643	118	a
III RCC-13	910	Moist pines	Acid. met.	1.5YR 4/8	63	7.7	0.12	1.11	107	62	204	77	a
2 M1	650	Cerrado	Sandstone		26	6.5	0.25	2.32	124				b
8ISCW-3	620	SE Forest	Sandstone	2.5YR 4/5	34	3.8	0.11	0.86		219	461	55	c,o
8ISCW-22	960	SD/SE Cerrado	Pellitic	2.5YR 3.5/6	48	7.2	0.15	0.40		603	249	169	c,o
				Low Iron (<8% Fe_2O_3) Yellow Colors (>2.5 YR)									
III RCC-4	480	SD Forest	Tertiary sed.	10YR 5/6	49		0.11	0.97	11	18	253	23	a
5M1	910	Cerrado	Clayey sed.	7.5YR 6/4	79	3.9	0.05	2.09	55				b
5M2	920	Cerrado	Clayey sed.	7.5YR 5/4	75	6.6	0.09	2.09	74				b
LC-40	1200	Cerrado	Gnaisse	7.5YR 5/8	29	3.6	0.12	0.12				21	c,m
RD2 a-15		SE Forest	Tertiary sed.	10YR 5/6	17	3.7	0.22	0.09				15	c,r
RD1 a-15		SE Forest	Tertiary sed.	10YR 5/6	59	3.5	0.06	0.08			357	18	c,r
RD3 a-15		SE Forest	Tertiary sed.	10YR 5/6	15	3.4	0.23	0.08			141	18	c,r
RD4 a-15		SE Forest	Tertiary sed.	10YR 5/6	54	5.9	0.07	0.08			215	17	c,r
RD5 a-15		SE Forest	Tertiary sed.	10YR 5/6	59	3.7	0.06	0.07			215	18	c,r
RD6 a-15		SE Forest	Tertiary sed.	10YR 5/8	56	4.1	0.07	0.07			364		c,r
R3		Cerrado	Slate	5 YR 5/8	48	6.7	0.14	0.18				66	c,i
RD13		SE Forest	Tertiary sed.									19	c,n
RD14		SE Forest	Tertiary sed.									8	c,n
8ISCW-1	680	SD Forest	Sand/Argill.	7.5YR 5/6	41	4.2	0.10	0.82		60	537	13	c,o
8ISCW-10	970	SE Forest	Sandstone	4 YR 5/6	22	4.0	0.18	1.13		230	538	53	c,o

* SD = semideciduous: ST = subtropical; SE = semievergreen forests.

** (a) Resende, Santana, and Resende 1985; (b) Resende 1976; (c) this work; (d) Correa 1984; (e) Fontes, Resende, and Ribeiro 1985; Fontes et al. 1985; (f) Curi 1983; (g) Curi and Franzmeier 1983; (h) Santana 1984; (i) Almeida 1979; (j) Gualberto 1984; (k) Fasolo 1978 (< 250 μm); (l) Rauen 1986; (m) Rezende 1980; (n) Fabris et al. 1985, 1986; (o) 8 ISCW (Camargo et al. 1986); (p) Brasil 1971; (q) Brasil 1973; (r) Universidade Federal de Viçosa 1984; (s) Brasil 1975, (t) Brasil 1977.

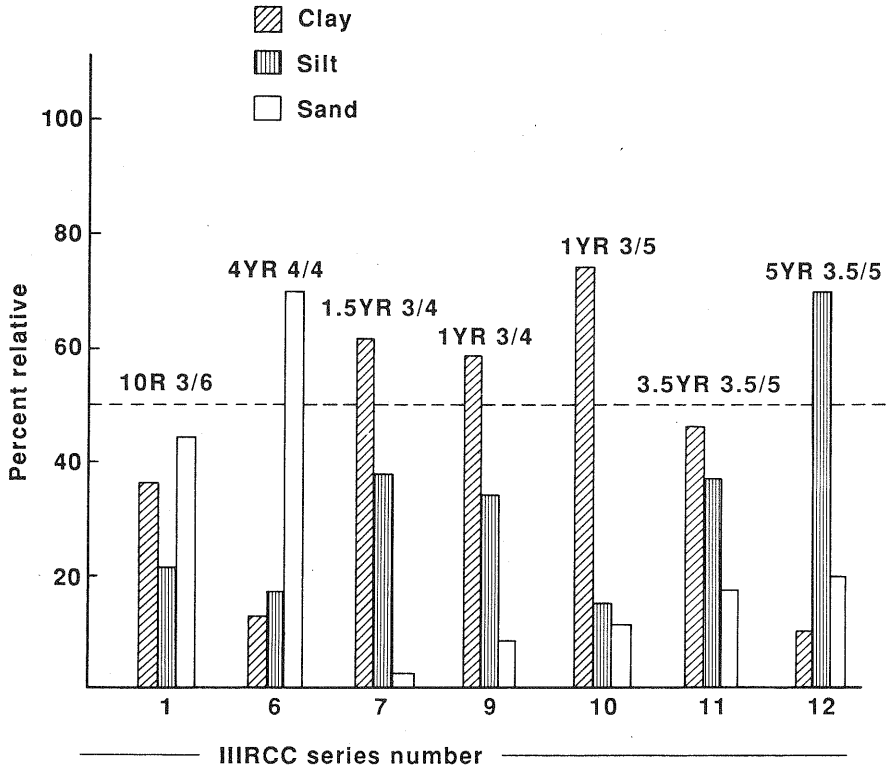


Fig. 6. Magnetic susceptibility of clay, silt and sand fractions of some Oxisols from Brazil, with > 18 percent of Fe_2O_3 from (III RCC) data in Table 3 (Resende, Santana, and Resende 1985).

This value is much smaller than the one for pure maghemite estimated roughly as $X = 115338 \times 10^{-8} m^3 kg^{-1}$ considering $M_S = 65 JT^{-1} kg^{-1}$. Isomorphous substitution by Ti and Al are probably responsible for this difference.

Application of the value $X_{(Mh)} = 63663 \times 10^{-8} m^3 kg^{-1}$ to the series studied by Curi and Franzmeier (1984), Table 5, and the III RCC series Table 6, indicates that the amount of maghemite in the soil can be as high as about 10 percent by weight. Usually there is less maghemite than hematite, but some tends to be present in all soils although in very minor amounts.

From the data by Curi and Franzmeier (1984) and Gualberto (1985) it can be inferred that maghemite is not very important as phosphate adsorbant.

Soil Environment Indicator

As already indicated, soil magnetization is quite sensitive to lithology. In central Brazil the influence of basaltic rocks can be detected quite nicely (Fig. 19) by the large variation in magnetization.

Yellower Oxisols like sample 4M5 (Fig. 19) have low magnetization of the clay fraction relative to the total soil, in line with maghemite destruction under paleohydrological conditions. Resende (1976) has noted the presence of petroplinthic materials indicating a high water table in the past. The magnetization of the iron minerals in the sand fraction, more stable than the maghemite in the clay fraction, still indicates the basaltic influence in the soil parent material in these local conditions.

When the parent materials contrast in amounts of magnetic minerals, the degree of mixing of parent materials can be reasonably inferred by magnetization measurements (Fig. 20). It is very fortunate that a mineral like magnetite can be so easily detected. It is quite resistant under well-drained conditions, and it is very likely the main maghemite parent mineral. Magnetite probably serves as a reservoir of trace elements (Table 7).

Trace elements analysis along a lithosequence of basalt-sandstone (Fig. 20), samples M1, M2, M3, and 14, (Table 8), shows an increase in Cu, Co, and Zn related to the basaltic contribution indicated by the amount of clay, iron, and most strikingly the magnetization. The relationships between magnetization of clay to fine earth is higher for the sample more influenced by sandstone (sample 14 > sample M3). This apparently is in line with the known fact that covering of magnetite grains by clays seem to protect magnetite from weathering. The toposequence studied by Curi and Franzmeier (1984), with profiles varying in color and magnetization, does not show much difference in trace elements. This suggests that magnetization can be used to predict the amount of trace elements only to the extent that it indicates the parent material.

The magnetite intergrowth with ilmenite isolated from sample M3 presents a magnetization of $118852 \times 10^{-8} m^3 kg^{-1}$ ($M_S = 64.4 JT^{-1} kg^{-1}$), being quite rich in trace elements (Table 1).

The very high magnetization of the Oxisol from itabirite, LF (Table 8) with low amounts of trace elements, except Co,

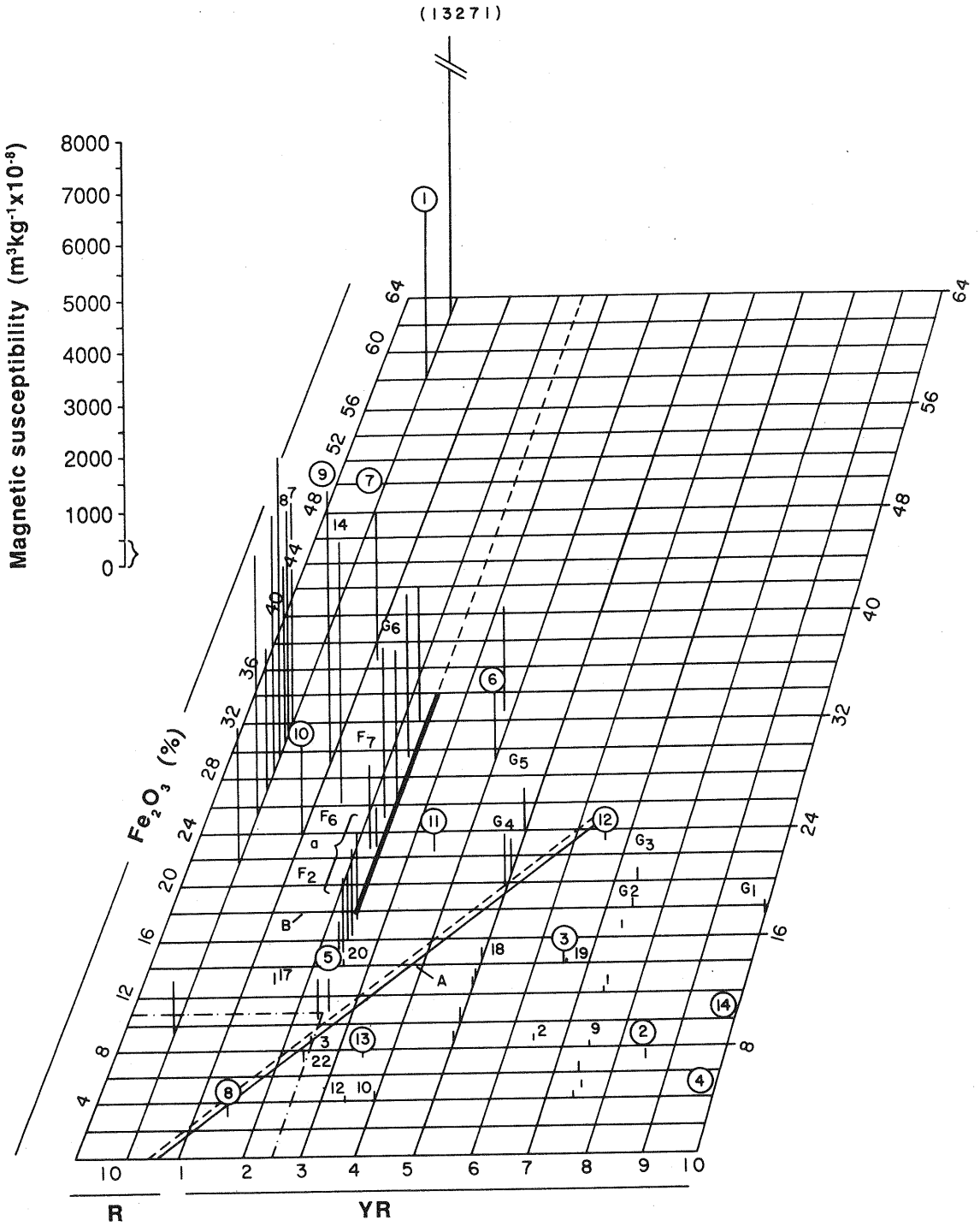


Fig. 7. Magnetic susceptibility of the clay fraction of Oxisols as a function of color hue and amount of iron. Simple numbers 8 ISCW (Camargo et al. 1986); number in parenthesis *X* of MQ (Fontes, Resende, and Ribeiro 1985, Fontes et al. 1985; Curi 1983). Numbers in circles III RCC series (Resende, Santana, and Resende 1985); F series (Santana 1984); G series (Curi 1983), and nonnumbered samples (Resende 1976). For more information on these samples see Table 3.

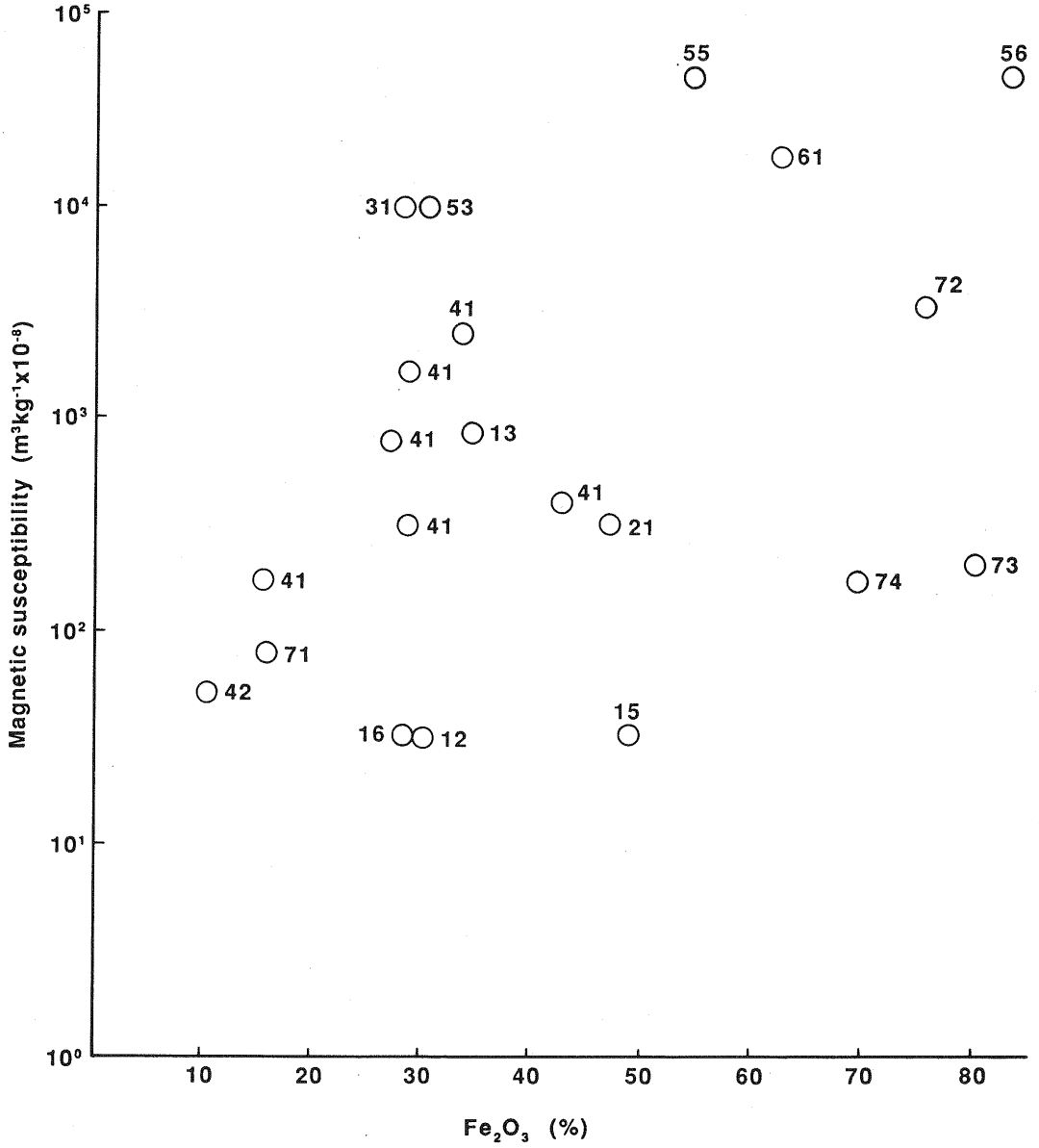


Fig. 8. Magnetic susceptibility of itabirite and associated partially weathered parent materials (Muggler 1985, unpubl. data).

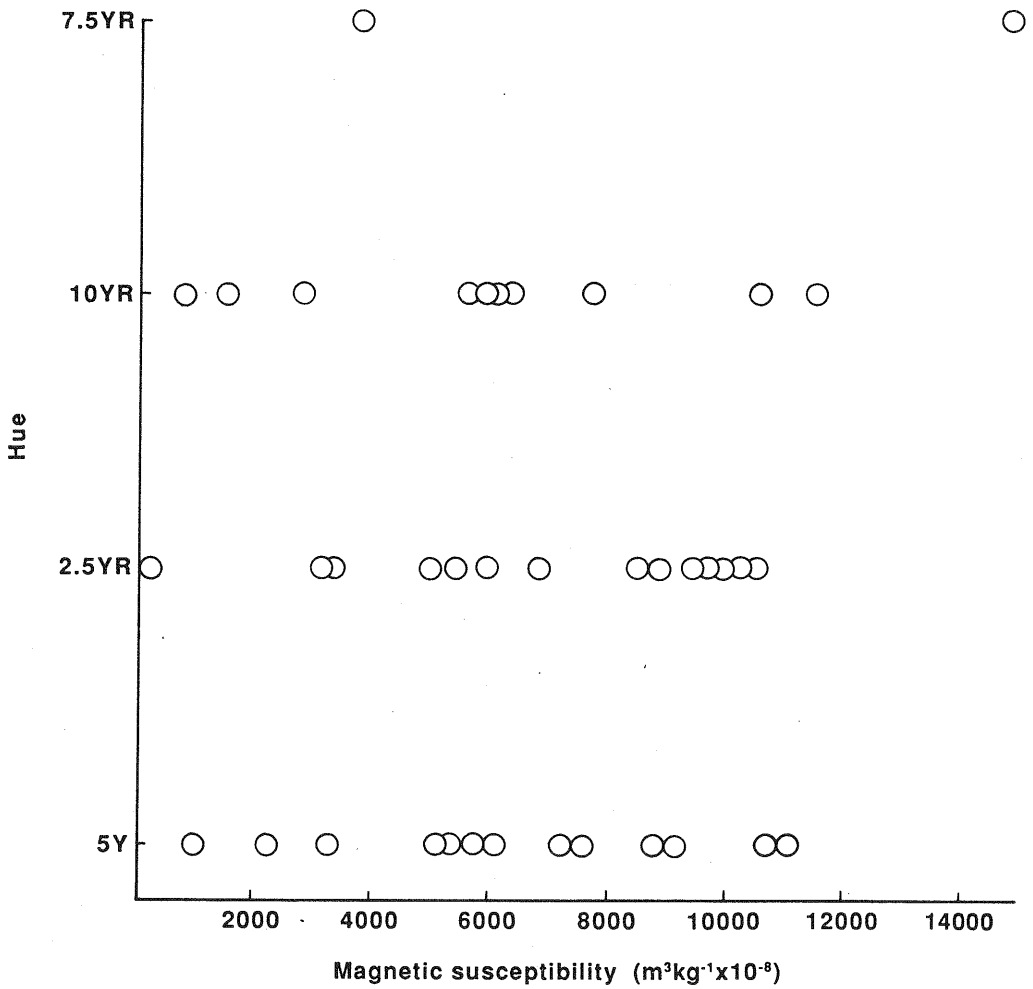


Fig. 9. Magnetic susceptibility and color hue of tuffite parent materials from Dusky Red Latosols.

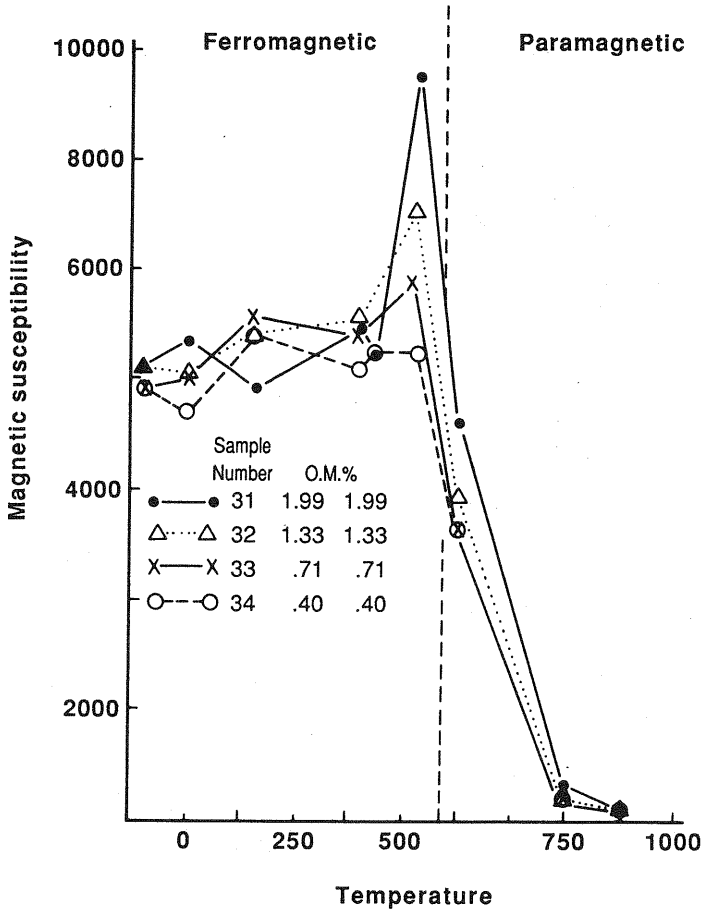


Fig. 10. Magnetization after Oxisol materials with variable amounts of organic carbon were heated at various temperatures. See sample 33 in Table 3 (Resende 1976).

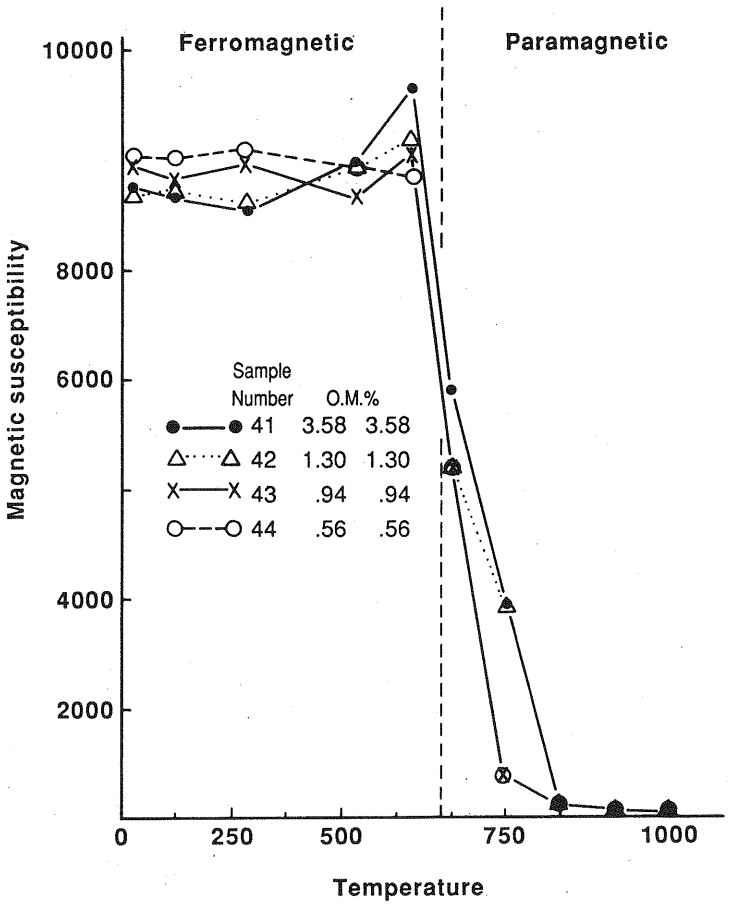


Fig. 11. Magnetization after red Oxisol material rich in iron with variable amounts of organic carbon were heated to various temperatures. See sample 43 in Table 3.

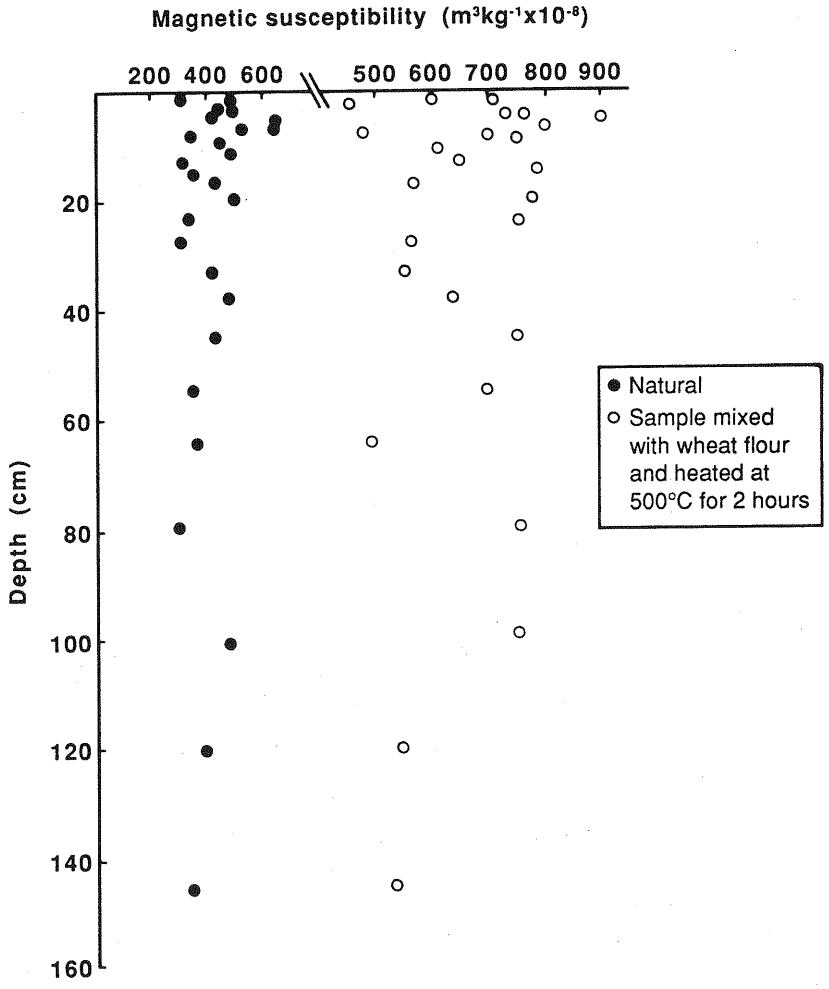


Fig. 12. Magnetization with depth of an Oxisol (fine earth) before and after being heated with wheat flour.

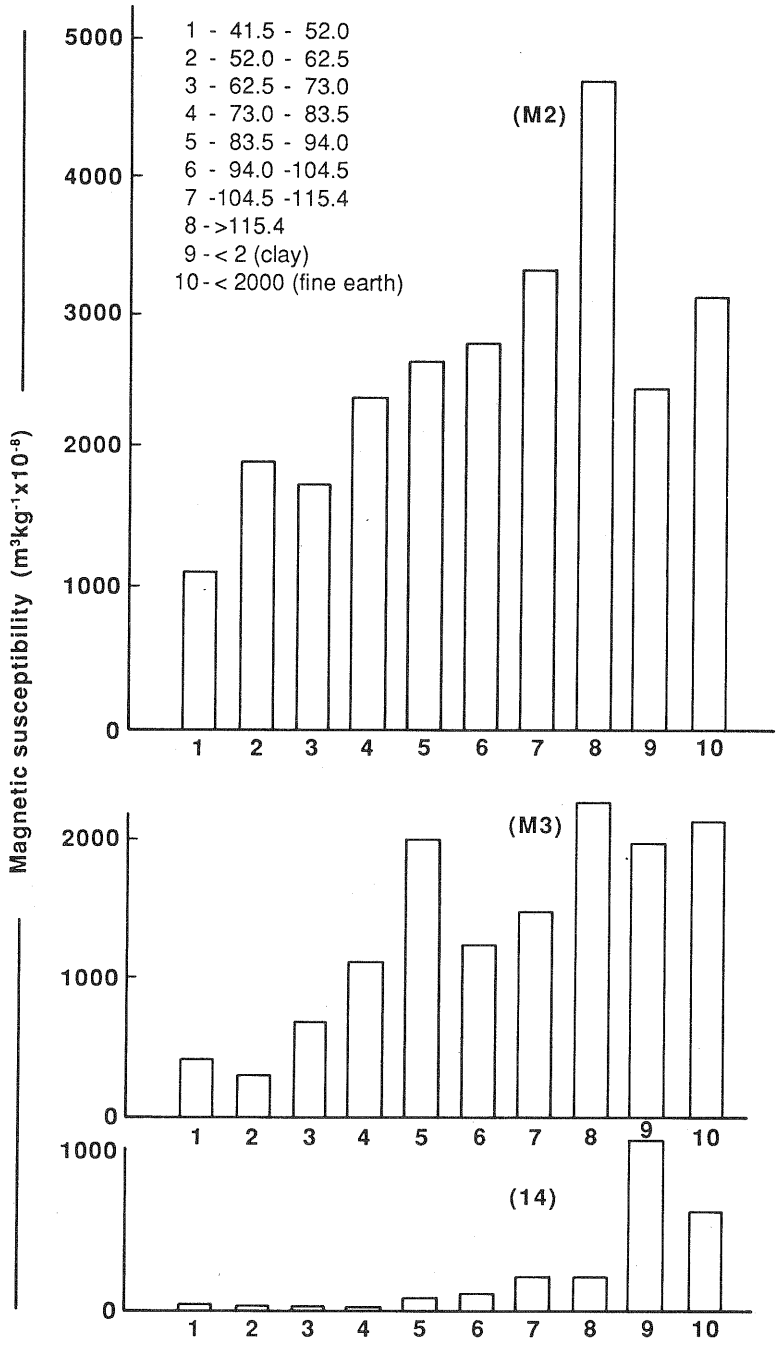


Fig. 13. Magnetic susceptibility of different grain-size classes (upper left) of Oxisol B horizons, influenced from the most (M2) to the least (14) basaltic parent materials. See Figure 19 for location of these samples in the landscape.

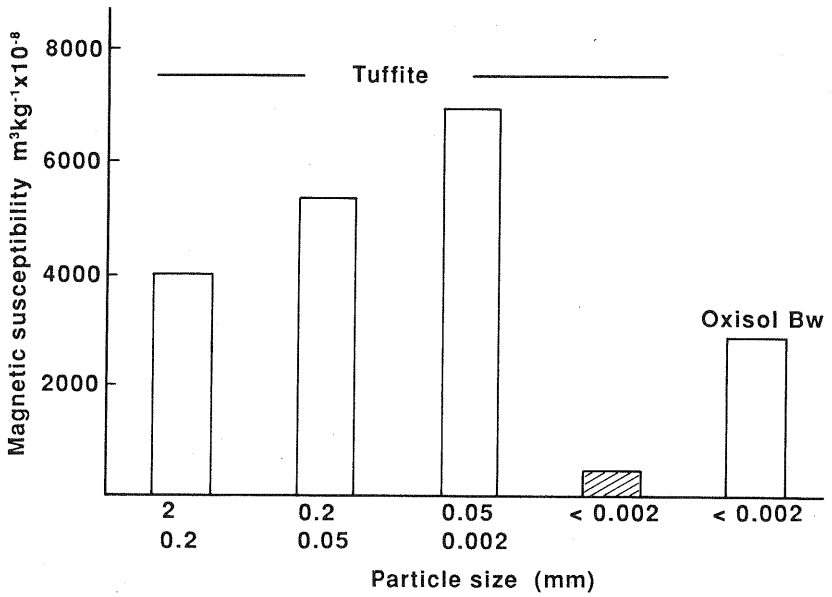


Fig. 14. Magnetic susceptibility of different particle-size fractions of tuffite and of a clay from an Oxisol Bw developed from tuffite.

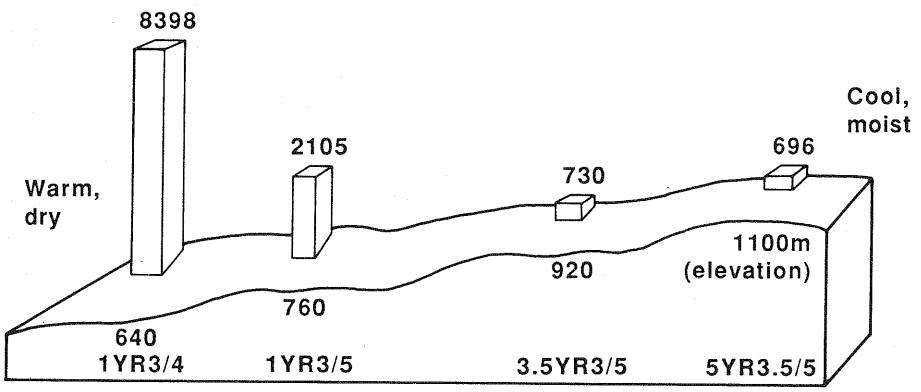


Fig. 15. Magnetic susceptibility in a climosequence of soils developed from basalt in southern Brazil (Resende, Santana, and Resende 1985).

Table 6. Content of Iron Minerals of Clay Fraction and Soil Color of Oxisols from Southern and Southeastern Brazil (data from III CC)

Soil	(Hm/Hm + Gt)	Fed	*X*	Gt	Hm	Mh	Color Munsell
		(%)	($m^3kg^{-1}10^{-8}$)		(%)		
1	0.92	48.9	2535	4.1	43.5	3.70	10R3/6
2	0.00	5.2	13	7.2		0.02	7.5YR5/8
3	0.00	12.4	23	17.0		0.07	7.5YR4/5
4	0.00	3.5	23	3.5		0.03	10YR5/6
5	0.75	8.9	642	2.8	6.1	1.00	2.5YR3/7
6	0.38	19.8	1046	19.0	4.4	1.61	4YR4/4
7	0.88	27.4	3885	3.0	19.8	6.00	15YR3/4
8	0.68	2.9	118	1.3	1.9	0.20	1.5YR3.5/6
9	0.93	23.3	5317	1.2	14.6	8.22	1YR3/4
10	0.87	18.0	1883	2.4	13.8	2.86	1YR3/5
11	0.45	19.1	458	16.9	6.3	0.67	3.5YR3.5/5
12	0.26	15.2	77	18.4	1.7	0.10	4.0YR3.5/5
13	0.74	7.3	77	2.6	5.4	0.09	10YR5/8

Source: Resende, Santana, and Resende (1985).

corroborates the idea that magnetization is a good indicator of trace elements only to the extent that it indicates parent rock. It appears that the TiO_2 content correlates even better than magnetization with the amount of trace element present (Fig. 21).

Minor Pedogenetic Changes

The wide range of values of magnetization in natural materials, probably one of the largest of any measurement, suggests that magnetization might be sensitive to changes in the pedoenvironment not easily detected by other techniques (Fig. 22).

The toposequence studied by Santana (1984), Figure 22, shows almost no variation in the Bw horizon color, and somewhat erratic changes in the amounts of hematite, goethite, kaolinite, and magnemite estimated by DRXD. The amount of gibbsite and especially the magnetization change gradually across the landscape, so, naturally does the amount of maghemite estimated by using the magnetization values.

The soil studied by Curi (1983) along the landscape, Figure 23, shows a more pronounced and sequential variation in color and in kaolinite and gibbsite content, but the variation in goethite is somewhat erratic, and no hematite was detected in samples G_1, G_2, and G_3, by DXRD. Magnetization is still quite high and distinctly sequential, but the amount of maghemite was too small for detection by DXRD except in samples G_6 and G_5.

Nevertheless, estimations of the amount of maghemite by using the magnetization values fit the sequence very nicely.

In fact, many of the trends linked to actual toposequences (Figs. 22, 23) expressing effects of paleohydrological conditions are also detected along distinct bioclimatic sequences (see Fig. 15).

Within the soil profile it is sometimes possible to detect magnetization sequences; apparently due to organic matter, there is a reduction of magnetization closer to the surface similar to the goethitization process (Schwertmann 1971). This effect may or may not be accompanied by a color change (biochromic profiles).

Oxisols which are at present excessively well drained, with or without much color variation, show a distinct magnetization (Table 6, soils 5, 6, and 9).

All these examples suggest the underlying idea that magnetization, for some Oxisol systems, reflects meaningful pedogenic changes better than any other property. It is more sensitive to these changes than soil color for some particular systems.

Importance for Oxisol Taxonomy

After all these considerations, three questions can be raised: Is it justifiable to use magnetization as a taxonomic criterion? How should it be used, and at what levels?

Magnetization as Soil Property

Magnetization is related to soil mineralogy. The main magnetic mineral in coarser size particles, magnetite, has some quite important properties: (1) it is one of the most stable minerals in the Oxisol environment; it is present in considerable amounts in some of the oldest soil landscapes on Earth; (2) the spinel structure encloses a high number of trace elements; (3) magnetite occurs in many soils in minor amounts, but larger

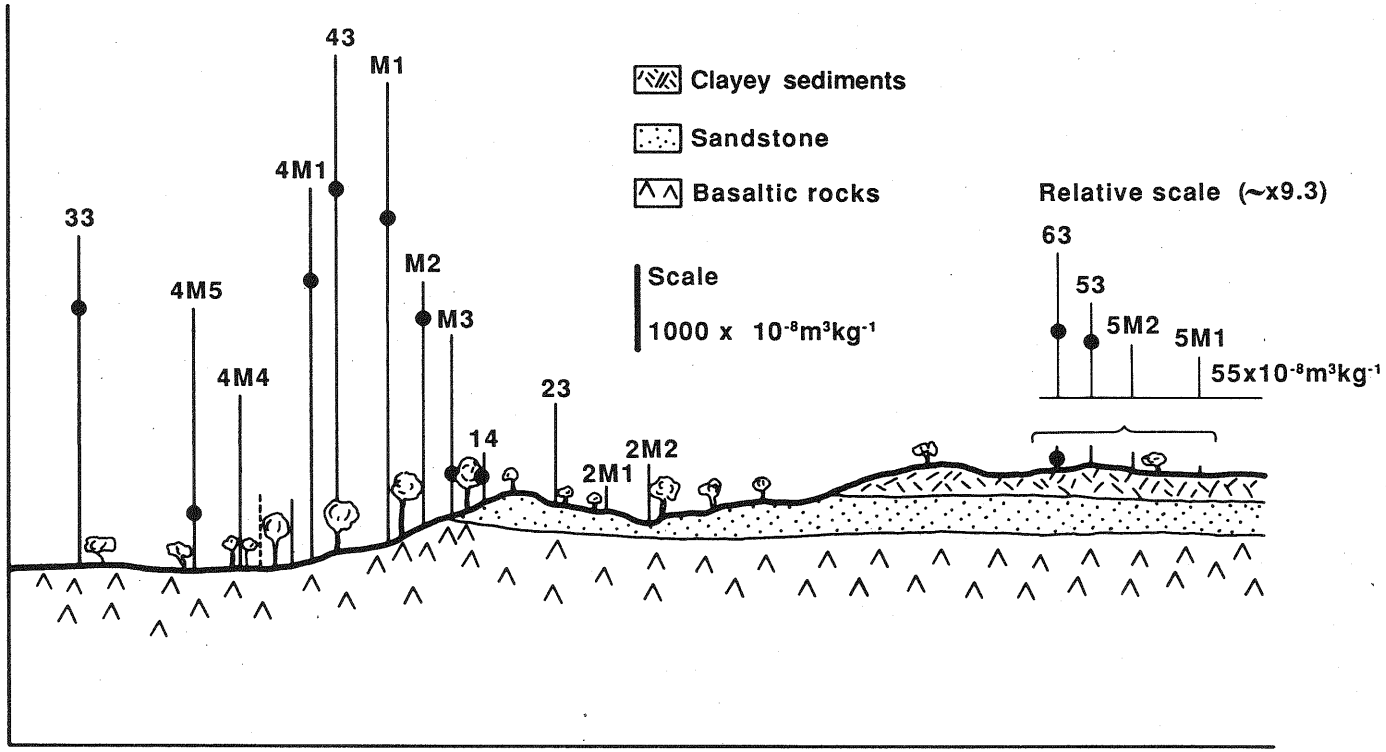


Fig. 19. General landscape of western portion of Minas Gerais showing magnetic susceptibility of clay (dot) and total soil (bar) in relation to lithology and local toposequences. For more information on these samples see Table 3 (Resende 1976).

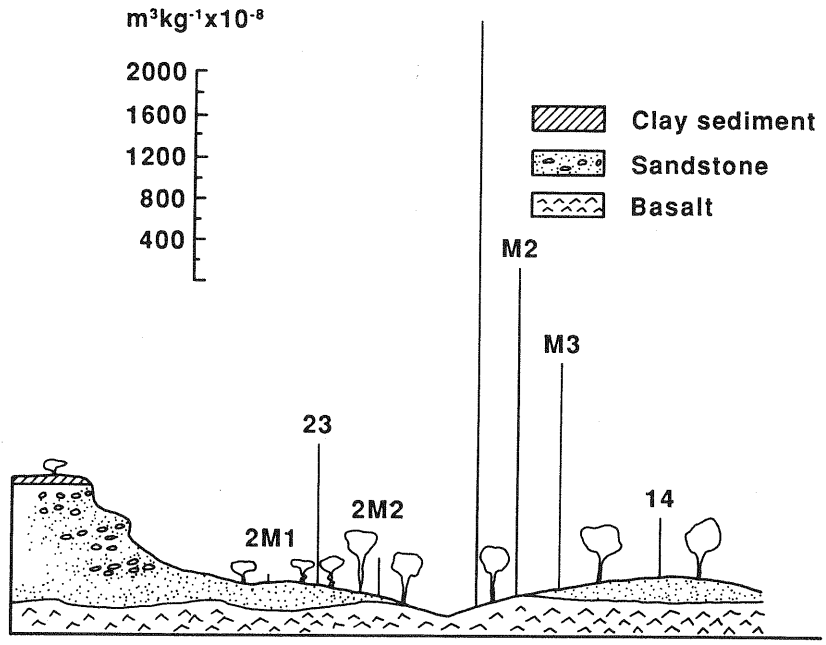


Fig. 20. Magnetic susceptibility of Bw horizons of Oxisols on a basaltic-sandstone landscape (adapted from Resende 1976).

Table 7. Trace Elements in Some Iron-rich Minerals

Mineral	Fe_2O_3 (%)	ΣM[a] mM
Augite	8.21	7.08
Hornblende	20.19	9.42
Olivine	8.64	7.48
Biotite	18.68	8.26
Nontronite	13.10	6.09
Glauconite	23.57	1.22
Goethite	88.69	1.42
Hematite	96.67	1.58
Magnetite	74.36	29.60

[a] ΣM = Sum of Mn, Cr, V, Ni, Co, Cu, and Zn.
Source: Nalovic and Segalen (1973).

Table 8. Trace Elements and Magnetic Susceptibility of Some Materials (fine earth and clay) of Brazilian Oxisols and Some Rocks

	TiO_2	Fe_2O_3	FeO	Cu	Co	Zn	Mo	Total (Cu, Co, Zn, Mo)		Source*
	(%)			(ppm)					($m^3kg^{-1} \times 10^{-8}$)	
				Basalt-Sandstone Lithosequence						
M1 (10R3/4)	9.35	29.68	3.16	225	96	152		473	5597	a
		(18.66)**	(0.00)	(182)	(112)	(78)		(218)	(3870)	a
M3	6.12	15.44	1.24	82	80	56		218	2176	a
		(21.11)	(0.00)	(85)	(96)	(42)			(2033)	a
14 (10R3/4)	2.64	7.04	0.27	30		21		51	684	a
		(23.10)	(0.00)	(70)		(49)			(1504)	a
23 (2.5YR3/4)	3.66	8.4		79	48	53	0.01	180	1156	b
	32.28	41.04	1536	670	160	584		1414	118852	a
				Basalt Toposequence						
G1 (10YR4/4)	7.1	18.0		193	78	86		357	212	b
G2 (7.5YR4/6)	7.15	17.6		203	59	75	0.17	338	232	b
G3 (7.5YR4/4)	7.09	18.3		176	60	80	0.05	316	347	b
G4 (5YR4/4)	7.41	19.7		167	58	84	0.09	309	601	b
G5 (5YR3/4)	7.23	21.6		210	57	107	0.20	374	946	b
G6 (2.5YR3/4)	7.32	21.9		154	105	107	0.21	366	4016	b
				Other Materials						
LF (10R3/6)	0.55	88.0		7	99	71	5.7	177	28327	b
Itabirite	0.018	71.0		4	64	101		109		b
Basalt	3.14	13.143		164	65	112		341		b
LY	1.33	9.61		10	52	46		108		b

a = Resende (unpubl. data); b = Curi (1983).
** Parenthesis = clay.

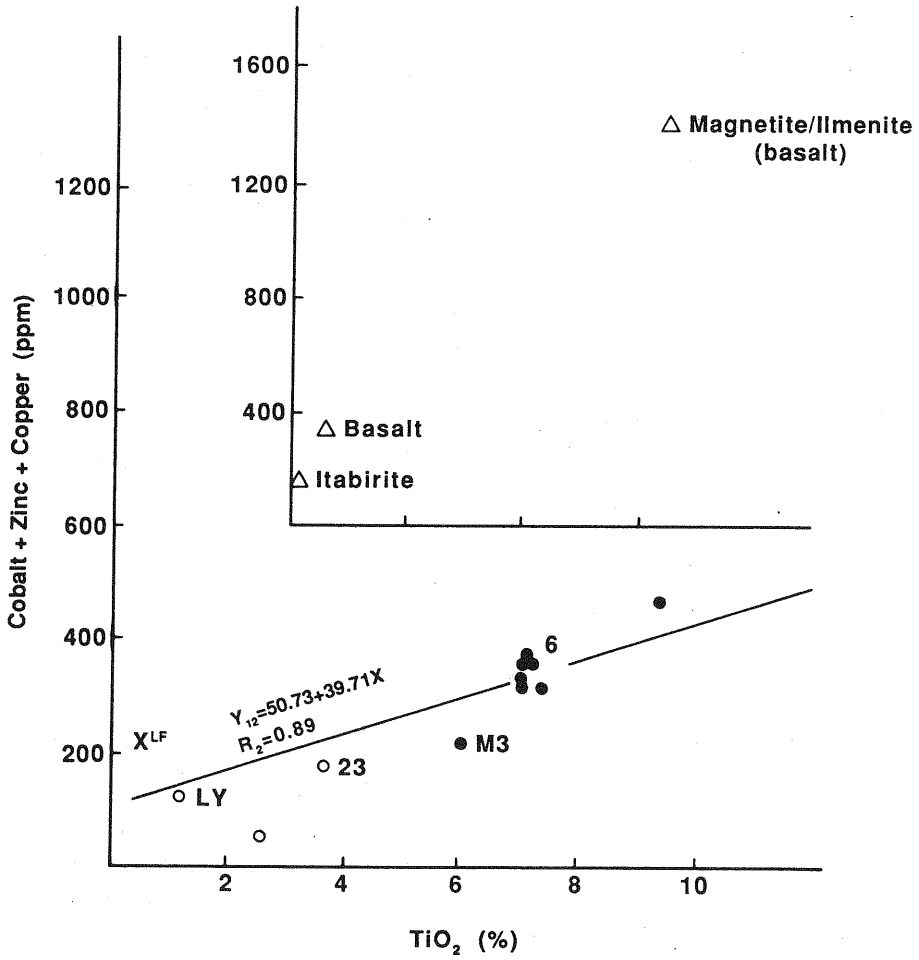
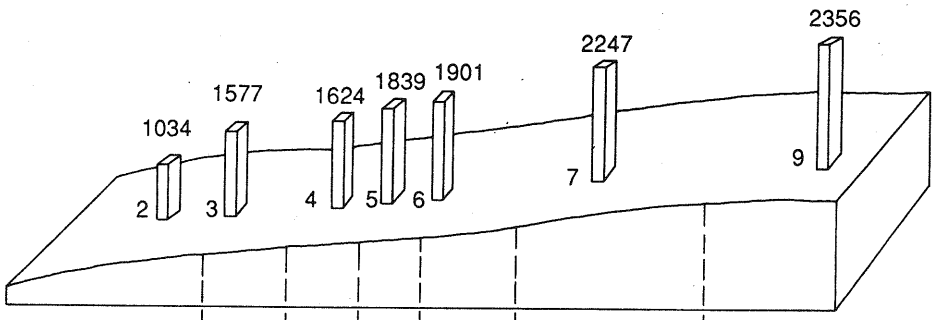
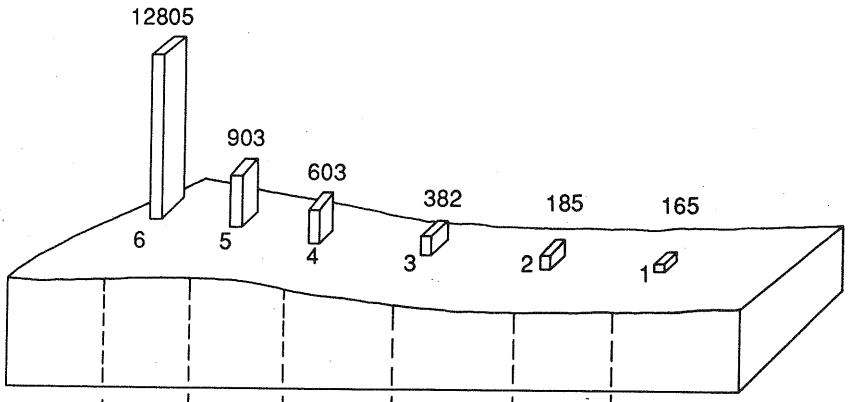


Fig. 21. Sum of cobalt, zinc, and copper as related to titanium content for some Oxisols and related rocks (Resende, Santana, and Resende 1985).



Color		2.5/YR 3/6	3/6	3/6	3/6	3/6	3/4	10R 3/4
Hematite	(%)	5.5	8.2	8.4	9.9	8.7	11.3	14.8
Goethite	(%)	3.8	3.9	4.3	3.5	3.5	4.2	3.9
Kaolinite	(%)	21.0	22.0	26.0	26.0	24.0	25.0	37.0
Gibbsite	(%)	6.0	9.0	16.0	17.0	17.0	19.0	21.0
Maghemite (DRXD)	(%)	1.6	3.9	3.2	3.2	2.8	2.7	3.7
Maghemite (M_s=34.5 X=63663x10^{-8})	(%)	0.8	2.5	2.6	2.9	3.0	3.5	3.5

Fig. 22. Toposequence of Oxisols developed from tuffites (adapted from Santana 1984).



Color		2.5YR 3/4	5YR 3/4	5YR 4/4	7.5YR 4/4	7.5YR	10YR 4/4
Hematite	(%)	16.0	13.1	8.3	-	-	-
Goethite	(%)	2.6	11.1	14.1	24.7	21.1	22.2
Kaolinite	(%)	22.0	29.0	37.0	38.0	44.0	42.0
Gibbsite	(%)	22.0	18.0	12.0	7.0	5.0	6.0
Maghemite (DXRD)	(%)	?	?	-	-	-	-
Maghemite (M_s=34.5 X=63663x10^{-8})	(%)	4.3	1.3	0.9	0.6	0.3	0.2

Fig. 23. Toposequence of Oxisols developed from basalt (adapted from Curi 1983).

amounts are found only in iron-rich soils; (4) its presence in the coarser fraction is related to magnetite minerals in the clay, particularly in the redder soils.

The main magnetic mineral in the clay fraction is maghemite. This clay-grade magnetic mineral has some important properties:

1. Contrary to magnetite, it is fairly unstable under the same conditions that favor the formation of goethite rather than hematite;
2. There is evidence to suggest that titanomaghemite may be responsible for the magnetism of soils derived from mafic rocks (Resende, Allan, and Coey 1986). We have seen that magnetization can apparently be used with advantage to quantify soil maghemite;
3. Maghemite, even in small amounts, is a mineral quite common in Oxisols, but it is expressive only in iron-ric redder soils.

Basic Pedogenic Principles

A useful principal has been that soils should be classified on the basis of their properties and not on their environment. The properties having the largest and most important set of covarying properties are the ideal ones in this context. Thus, there is an intense search for properties that have a clear genetic relation in order to come as close as possible to the taxonomic ideal.

Trying to pursue these goals, and to avoid the previous overemphasis on parent rock, the search for diagnostic criteria has recently been centered almost exclusively around properties linked to bioclimatic conditions. This is somewhat unfortunate because the factors of soil formation in Dockuchaive's original equation (Marshall 1977; Jenny 1980):

$$\Pi = (K, O, Y,)B,$$

place the parent material (Y) in a position comparable to the climatic (K) and organic factors (O).

This would imply that soil results from two main opposing influences: bioclimate and parent rock. Properties like color and magnetization reflect very nicely this balance of forces (Table 9).

It is clear from Table 9 that neither color nor magnetization can be explained by bioclimatic or lithological condition alone but depend on both. Is not this the normal situation?

Oxisols are known to be formed under varying past and present bioclimatic conditions and, more often than not, from a mixture of parent materials. So it is misleading, as far as soil genesis is concerned, to overemphasize present bioclimatic conditions when making a selection of diagnostic properties. On the other hand the mixing of parent material and the inevitable uncertainty in assigning a parent rock to a particular soil suggest that the use of soil criteria sensitive to both factors is more likely to give the best set of covarying characteristics; in this respect soil color and magnetization have an indisputable place in soil classification.

Magnetization as Taxonomic Criteria

Magnetization and color are expressions of mineralogy, but they are, in a sense, more metastable than most mineralogical characteristics. Particularly in Oxisols, because of their polygenetic nature, these characteristics might be used at a high taxonomic level because:

1. They are genetically dependent on the two opposing forces, bioclimate and parent rock.
2. They are both linked to distinctive minerals: goethite-hematite for color and magnetite-maghemite for magnetization.
3. They are easily measured and they have many covarying properties.

Iron content and color, if used at a higher level to separate Oxisols, also separate the highly magnetic Oxisols. Thus, magnetization could be used more effectively at a lower taxonomic level.

References

Almeida, J.R. 1979. Cromossequência de solos originários de rochas pelíticas do Grupo Bambuí. M.S. thesis. Univ. Federal de Viçosa.

Brasil 1960. Serviço Nacional de Pesquisas Agronômicas. Comissão de Solos. Levantamento de reconhemcimento dos solos do Estado de São Paulo. Boletim Técnico 12. Ministério da Agricultura, Rio de Janeiro, Brazil.

———. 1971. Departamento Nacional de Pesquisa Agropecuária. Divisão de Pesquisa Pedológica. Levantamento de reconhecimento dos solos do Sul do Estado de Mato Grosso. Boletim Técnico 18. Ministério da Agricultura, Rio de Janeiro, Brazil. 839 p.

———. 1973. Deaprtamento Nacional de Pesquisa Agroqecuária. Divisão de Pesquisa Pedológica. Levantamento de reconhecimento dos solos do Estado do Rio Grande do Sul. Boletim Técnico 30. Ministério da Agricultura, Rio de Janeiro, Brazil. 413 p.

———. 1975. Empresa Brasileira de Pesquisa Agroqecuária. Devesão de Pesquisa Pedológica. Mapa esquemático dos solos das regiões Norte, Meio-Norte e Centro-Oeste do Brasil. Texto explicativo. Boletim Técnico 17. Ministério da Agricultura, Rio de Janeiro, Brazil. 553 p.

———. 1977. Empresa Braileira de Pesquisa Agropecuária. Serviço Nacional de Lavantamento e Conservação de Solos. Levantamento exploratório - reconhecimento de solos da margem.direita do Rio São Francisco Estado da Bahia. Recife, Ministério da Agricultura. (Boletim Técnico 52; Brasil. SUDENE. Divisão de Resursos Renovávies, Série Recursos de Solos, 10. 737 p.

Camargo, M.N., P. Klinger, F.H. Beinroth, H. Eswaran, C.S. Holzhey, and J. Olmos. 1986. Tour guide. VIIIth Int. Soil Class. Work. Brazil. SMSS/ EMBRAPA/UPR. 285 p.

Coey, J.M.D. 1986. Magnetic properties of iron in soil oxides adn clay minerals. *In* J. Stucke and A. Goodman (eds.). Iron in soils and clay minerals. A NATO Advanced Study Institute—Bad Wndshein, Germany. Pp. 65-84.

Correa, G.F. 1984. Modelo de evolução e minerlogia da fração argila de solos do planalto de Viçosa, MG. M.S. thesis. Univ. Federal de Viçosa.

Curi, N. 1983. Lithosequence and toposequence of Oxisols from Goiás and Minas Gerais States, Brasil. Ph.D. thesis. Purdue Univ., Lafayette, Ind.

Curi, N., and D.P. Franzmeier. 1984. Toposequence of Oxisols from the central plateau of Brazil. *Soil. Sci. Soc. Amer. J.* 48(2):341-346.

Table 9. Soil Properties That Could Be Inferred by Color and Magnetization Measurements

Color	Magnetization	Interpretation
Red	High	High amount of iron, considerable magnetite in the coarse fraction and maghemite in the clay fraction, bioclimatic conditions favoring hematite or hematite parent rock inherited. High trace element content.
Yellow	High	Not detected.
Red	Low	Low amount of iron, small amounts of magnetite and maghemite, bioclimatic conditions favoring hematite or hematite parent rock inherited.
Yellow	Low	Low amounts of iron, magnetite, and maghemite or bioclimatic condition quite unfavorable to hematite.

Fabris, J.D., M. Resende, E. Galvão Da Silva, and J.M.D. Coey. 1985. Iron oxides in two Oxisols from Brazilian coastal plain. *J. Soil Sci.* 36:543-550.

Fabris, J.D., M. Resende, J.E.M. Allan, and J.M.D. Coey. 1986. Mossbauer analysis of Brazilian Oxisols. *Hyperfine Interactions* 29:1093-1096.

Fasolo, P.J. 1978. Mineralogical identification of four igneous extrusive rock derived Oxisols from the state of Parana, Brazil. M.S. thesis. Purdue Univ., Lafayette, Ind.

Fontes, M.R., M. Resende, and A.C. Ribeiro. 1985. Concreções ferruginosas de alguns solos brasileiros. I. Carcterização química. *R. Bras. Ci. Solo* 9:113-117.

Fontes, M.R., J.D. Fabris, M. Resende, and e. Galvão Da Silva. 1985. Concreções ferruginosas de alguns solos brasileiros. II. Caracterização mineralógica. *R. Bras. Ci Solo* 9:119-123.

Gualberto, V. 1984. Caracterização física, química e mineralógica de alguns Latossolos, com altos teores de ferro, da Amazônia e do Planalto Central. M.S. thesis. Univ. Federal de Viçosa. 67 p.

Jenny, H. 1980. The soil resource. Ecological Studies 37. Springer-Verlag, New York. 377 p.

Kämpf, N., and U. Schwertmann. 1982. Quantitative determination of goethite and hematite in kaolinitic soils by x-ray diffraction. *Clays Clay Minerals* 17:359-363.

Le Borgne, E. 1955. Abnormal magnetic susceptibility of the topsoil. *Ann. Geophys.* 11:399-419.

———. 1960. The influence of fire on the magnetic properties of soil, schists and granite. *Ann. Geophys.* 16:159-196.

Marshall, C.E. 1977. The physical chemistry and mineralogy of soils. Vol. II: Soils in place. John Wiley and Sons, New York. 313 p.

Matsusaka, Y., and G.D. Sherman. 1961. Magnetism of iron oxide in Hawaiian soils. *Soil Sci.* 91:239-245.

Mulay, L.N. 1963. Magnetic susceptibility. *In* I.M. Kolthoff and P.J. Elving. Treatise on analytical chemistry, part I, vol. 4, 1751-1883. John Wiley and Sons, New York.

Mullins, C.E. 1977. Magnetic susceptibility of the soil and its significance in soil science - a review. J. Soil Sci. 28:223-246.

Nagata, T., and S. Akimoto. 1961. Magnetic properties of rock forming ferromagnetic minerals. *In* T. Nagato (ed.). Rock magnetism. Maruzen Company Ltd., Tokyo. Pp. 127-146.

Nalovic, and P. Segalen. 1973. Rélations entre le fer et les elements traces de transition dans un certain nombre de mineraux ferrifères. Cah. ORSTOM, série Pedol. II (2): 181-191.

O'Reilly, W. 1984. Rock and mineral magnetism. Blackie, Glasgow. 220 p.

Rauen, M.J. 1980. Mineralogical indentification of a toposequence of soils from basaltic rocks in the state of Parana, Brazil. M.S. thesis. Purdue Univ., Lafayette, Ind.

Reitz, J.R., F.J. Milford, and R.W. Christy. 1982. Foundations of electromagnetic theory. Rio de Janeiro, Editora Campus. (Portuguese translation, 3 ed.). 516 p.

Resende, M. 1976. Mineralogy, chemistry, morphology and geomorphology of some soils of the central plateau of Brazil. Ph.D. thesis. Purdue Univ., Lafayette, Ind.

———. 1980. Geomorphology, mineralogy and genesis of four soils on gneiss in southeastern Brazil. Ph.D. thesis. Purdue Univ., Lafayette, Ind.

Resende, M., J.E.M. Allan, and J.M.D. Coey. 1986. The magnetic soils of Brazil. *Earth and Planetary Sci. Letters* 78:322-326.

Resende, M., D.P. Santana, and S.B. Rezende. 1985. Susceptibilidade magnética em latossolos do Sudeste e Sul do brasil. *In* M.C. Camargo (ed.). Anis da III reunião de correlação e classificação de Solos. EMBRAPA, Rio de Janeiro, Brazil.

Santana, D.P. 1984. Soil formation in a toposequence of Oxisols from Patos de Minas Region, Minas State, Brazil. Ph.D. thesis. Purdue Univ., Lafayette, Ind.

Sauk, W.A. 1972. Magnetic susceptibility and magnetite content. *Economic Geology* 67:383-385.

Schwertmann, U. 1971. Transformation of hematite to goethite in soils. *Nature 232:624-625.*

Sans, L.M. 1986. Estimativa do regime de umidade, pelo método de Newhall, de um Latossolo dVermelho-Escuro Alico da Reião de Sete Lagoas, M.G. Viçosa. D.S. thesis. Univ. Federal de Viçosa. 190 p.

Universidade Federal De Viçosa. 1984. Caracterização de solos e avaliação dos prinicipais sistemas de manejo dos tabuleiros da Bacia do Rio Doce e Região do Norte do Estado do Espírito Santo e sua interpretação para uso agrícola. Viçosa, UFV. 153 p.

MINERALOGY OF THE DEFERRIFIED CLAY FRACTION IN B HORIZON OF PEDONS OF THE VIIITH INTERNATIONAL SOIL CLASSIFICATION WORKSHOP

L. L. Antonello[1]

Abstract

A mineralogical study of the deferrified clay fraction in "B horizons" of 22 pedons located in the Brazilian states of Goiás, São Paulo, Minas Gerais, Rio de Janeiro, and the Federal District was carried out. Most of the samples were taken from the Bo2 and Bto2 horizons. Kaolinite, gibbsite, hydroxy-interlayered vermiculite, and mica are the minerals present. Kaolinite and gibbsite are the dominant ones. Pedons with increasing weathering intensity have gibbsite increase and lower Ki ratios; pedons with decreasing weathering intensity have mica and hydroxy-interlayered vermiculite content increase and higher Ki ratios.

Materials and Methods

Mineralogical analyses were done in the clay fraction of some B horizon of 22 pedons collected in the Brazilian states of Goiás, São Paulo, Minas Gerais, Rio de Janeiro, and the Federal District.

Methods for separation of the clay fraction and the value of the SiO_2/Al_2O_3 molecular ratio (Ki) were carried out according to the procedures described in *Manual de Métodos de Análise de Solo* (Empresa Brasileira de Pesquisa Agropecuária [EMBRAPA] 1979), with some modifications.

The pretreatment for mineralogical analyses—removal of free iron oxides, removal of organic matter, saturation of exchange complex, solvation with glycerol solution—were carried out according to the methods described in Jackson (1974) and Soil Conservation Service (1972), with some modifications.

The x-ray techniques for the clay mineralogy were as follows:

1. Oriented specimens on glass slides were prepared using Mg-saturated samples, also glycerol solvated (glycerol solution of 10 percent in ethanol); K-saturated samples were x-rayed at room temperature (25°C) and afterheating treatments of 150°C, 300°C, and 500°C.
2. X-ray diffraction patterns were obtained for each of the treatments using Rigaku x-ray diffraction equipment Geigerflex System/D max IIA, with the following operating conditions: radiation: Cu Kα; potential: 35 KV; current: 15 mA; goniometric scan speed: 2°(2 θ) per minute; strip-chart drive speed: 10mm/min; time-constant: ls; counting rate: 1000 cps.

The estimate of the amount of mineral present in the sample was evaluated by relative intensities of x-ray diffraction peaks.

Results and Discussion

Data for the clay minerals obtained by XRD in oriented deferrified clay fractions of some B horizon, the estimate of the amount of clay minerals through relative intensities of XRD peaks, and the value of SiO_2/Al_2O_3 molecular ratio (Ki) are shown in Table 1.

Kaolinite with x-ray diffraction peaks in the region of 7.19 Å and gibbsite with the strongest peak of 4.84 Å are the dominant minerals (Figs.1 to 27).

The mineral with basal diffraction peaks in the 14-15 Å region did not expand with Mg saturation and glycerol solvation, and did not collapse on K saturation; subsequent heating at 150°C, 300°C, and 500°C of K-saturated clays resulted in a hydroxy-interlayered vermiculite (HIV). Mica with diffraction peaks in the region of 10 Å is also present.

Taking into consideration the data in Table 1, we see that 7 percent of the horizons studied are dominantly gibbsitic and have low Ki ratios, pedons 11 and 12; about 15 percent of the horizons are dominantly kaolinitic and have high Ki ratios, pedons 2, 22, and 23; about 44 percent of the horizons have dominant kaolinite and small amounts of gibbsite, pedons 1, 3, 4, 5, 6, 10, 13, 15, and 18; 26 percent have dominant kaolinite and large amounts of gibbsite, pedons 7, 8, 9, 14, 16, and 17; and the remaining 7 percent have almost the same amount of gibbsite and kaolinite, pedons 19 and 20.

Hydroxy-interlayered vermiculite is observed in approximately 52 percent of the horizons examined. It is absent or seems to be present in lesser amounts in the horizons with lower Ki ratios. Mica is observed in 30 percent of the horizons, pedons 5, 6, 13, 15, and 16, the ones with the highest Ki ratio.

The movement of Si controls the weathering and the

[1] Serviço Nacional de Levantamento e Conservação de Solos (SNLCS), EMBRAPA, Rua Jardim Botânico 1024. Rio de Janeiro, Brazil 22460.

Table 1. Summary Data of Dominant Mineralogy of Deferrified Clay and Values of SiO_2/Al_2O_3 Molecular Ratio (Ki) in B horizon of 22 Pedons

			Mineralogy of the Clay Fraction				
ISCW Pedon	Horizon	Depth (cm)	Minerals K	G	HIV	Mi	Ki
1	Bo2	-160	xxx	x	x		1.41
2	Bo1	-280	xxx	tr			1.68
3	Bo1	-180	xxx	x	x		1.48
4	Bo2	-255	xxx	x	x		1.50
5	Bto2	-78	xxx	x	x	tr	1.62
5	Bo2	-290	xxx	x	x	tr	1.67
6	Bto2	-60	xxx	x	x	x	1.84
6	Bo2	-225	xxx	x	x	x	1.75
7	Bo2	-280	xxx	xx			0.85
8	Bo2	-235	xxx	xx	tr		1.11
9	Bo1	-225	xxx	xx			0.54
10	Bo2	-240	xxx	x			0.75
11	Bo3	-239	xx	xxx			0.34
12	Bov3	-150	x	xxx			0.44
13	Bo2	-210	xxx	x	x	x	2.01
14	Bo2	-210	xxx	xx	tr		1.17
15	Bto1	-70	xxx	x		x	1.31
16	Bto1	-60	xxx	xx		x	1.09
16	Bo	-177	xxx	xx		x	0.97
17	Bo3	-200	xxx	xx	tr		0.61
18	Bo	-156	xxx	x			0.65
18	Boc2	-290	xxx	x			0.88
19	Boc1	-175	≈	≈			0.39
20	Bo2	-165	≈	≈			0.65
22	Bo1	-150	xxx	tr	x		1.65
23	Bog1	-70	xxx	tr	x		1.79
23	Bcvg	-180	xxx	tr	x		1.77

Note: Estimate of the amount of minerals: xxx = dominant, xx = large amount; x = small amount; tr = trace; ≈ approximately same amount of K and G; Ki = Si_2/Al_2O_3 molecular ratio from H_2SO_4 and NaOH digestion in clay fraction (< 0.002 mm); HIV = hydroxy-interlayered vermiculite; K = kaolinite; G = gibbsite; Mi = mica.

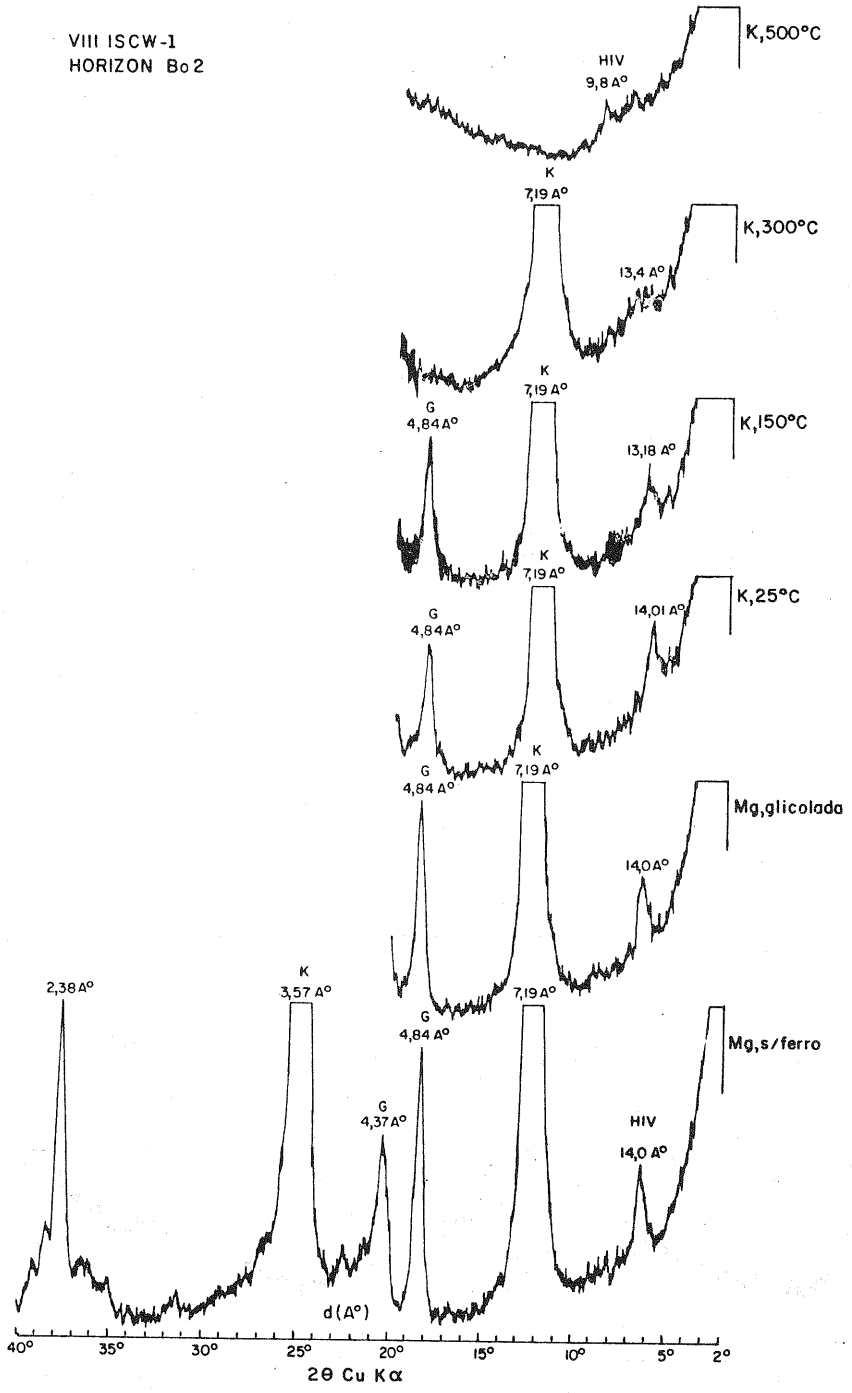


Fig. 1. X-ray diffraction patterns of the deferrified clay from Bo2 horizon of pedon 1 after Mg saturation and glycerol solvation, K saturation at room temperature (K 25° C), heating at 150° C, 300° C, and 500° C. Units of d spacing are in angstrom Å. Hydroxy-interlayered vermiculite (HIV); gibbsite (G); kaolinite (K).

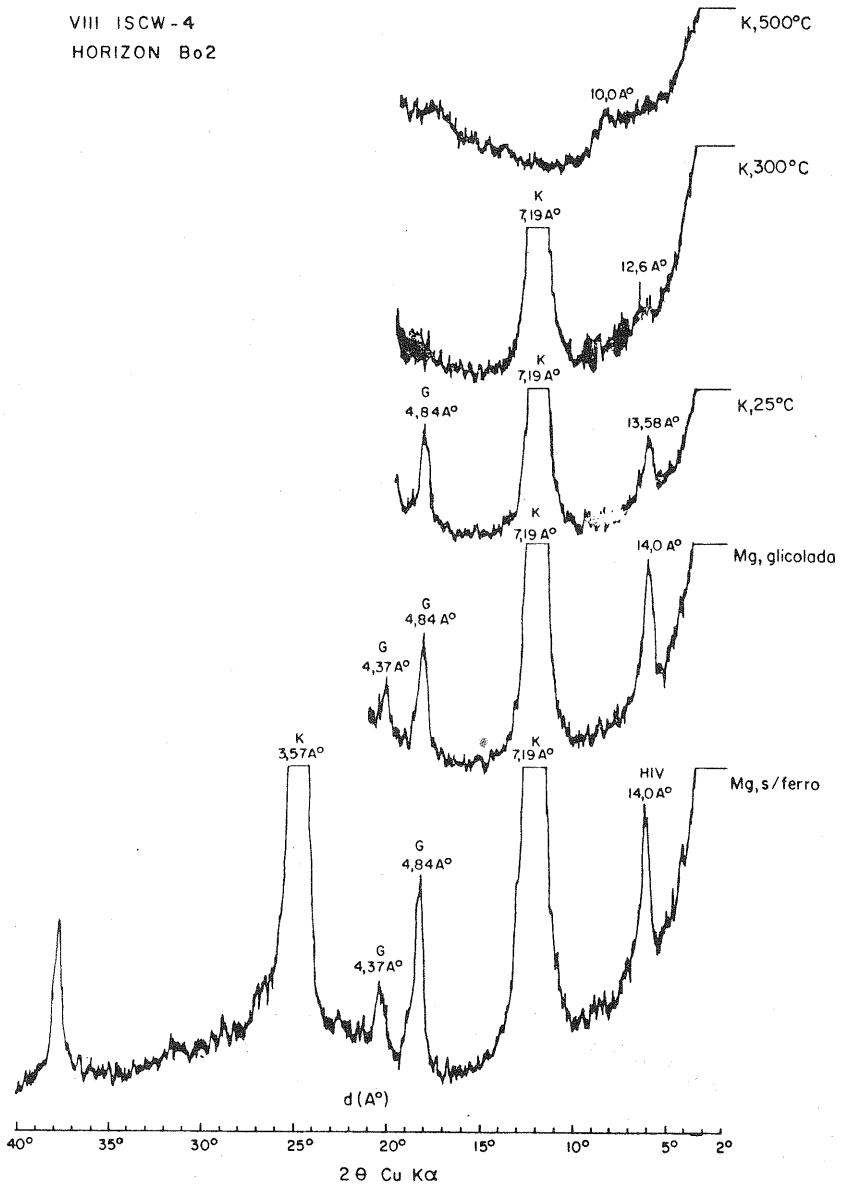


Fig. 4. X-ray diffraction patterns of the deferrified clay from Bo2 horizon of pedon 4 after Mg saturation and glycerol solvation, K saturation at room temperature (K 25°C), heating at 300°C and 500°C. Units of d spacing are in angstrom Å. Hydroxy-interlayered vermiculite (HIV); gibbsite (G); kaolinite (K).

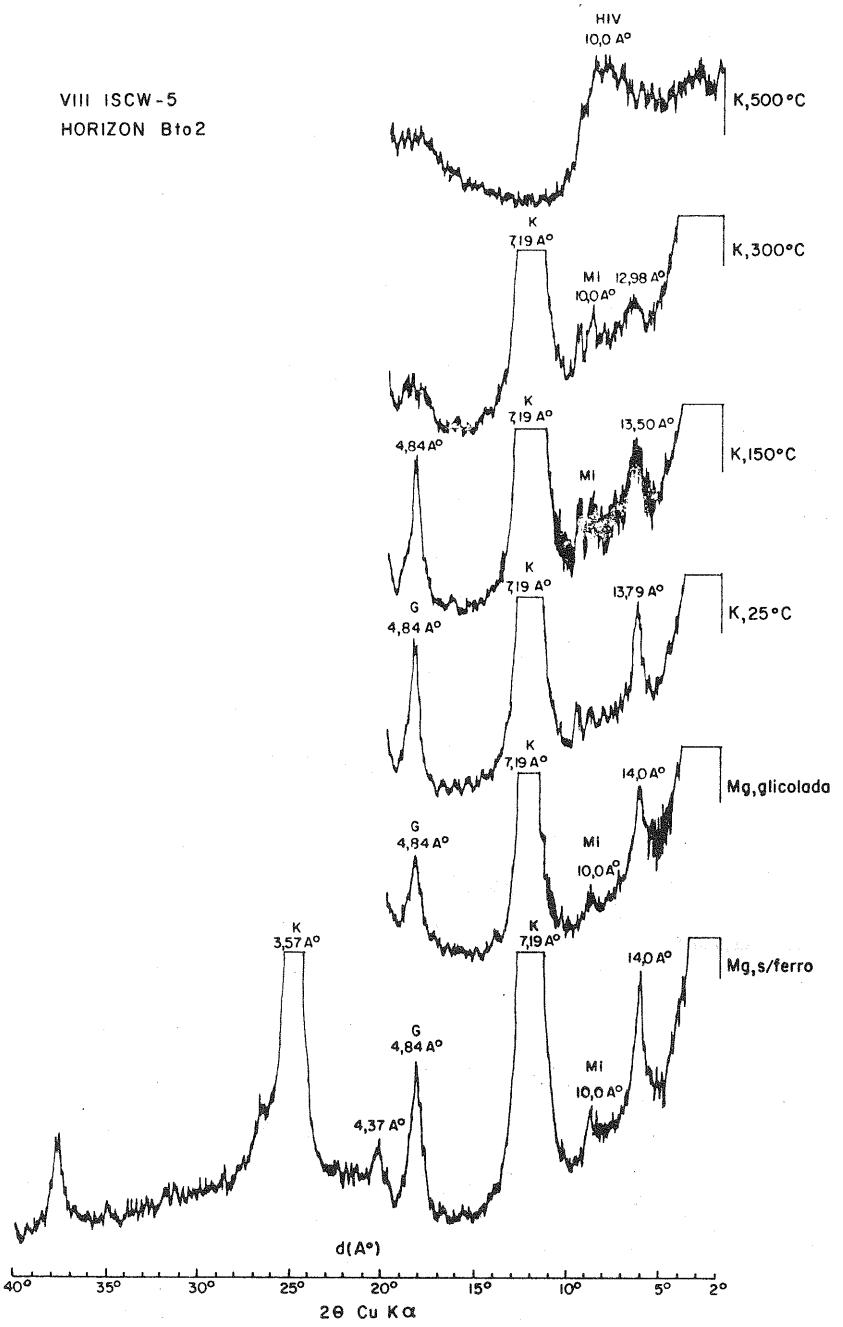


Fig. 5. X-ray diffraction patterns of the deferrified clay from Bto2 horizon of pedon 5 after Mg saturation and glycerol solvation, K saturation at room temperature (K 25°C), heating at 150°C, 300°C, and 500°C. Units of d spacing are in angstrom Å. Kaolinite (K); gibbsite (G); hydroxy-interlayered vermiculite (HIV).

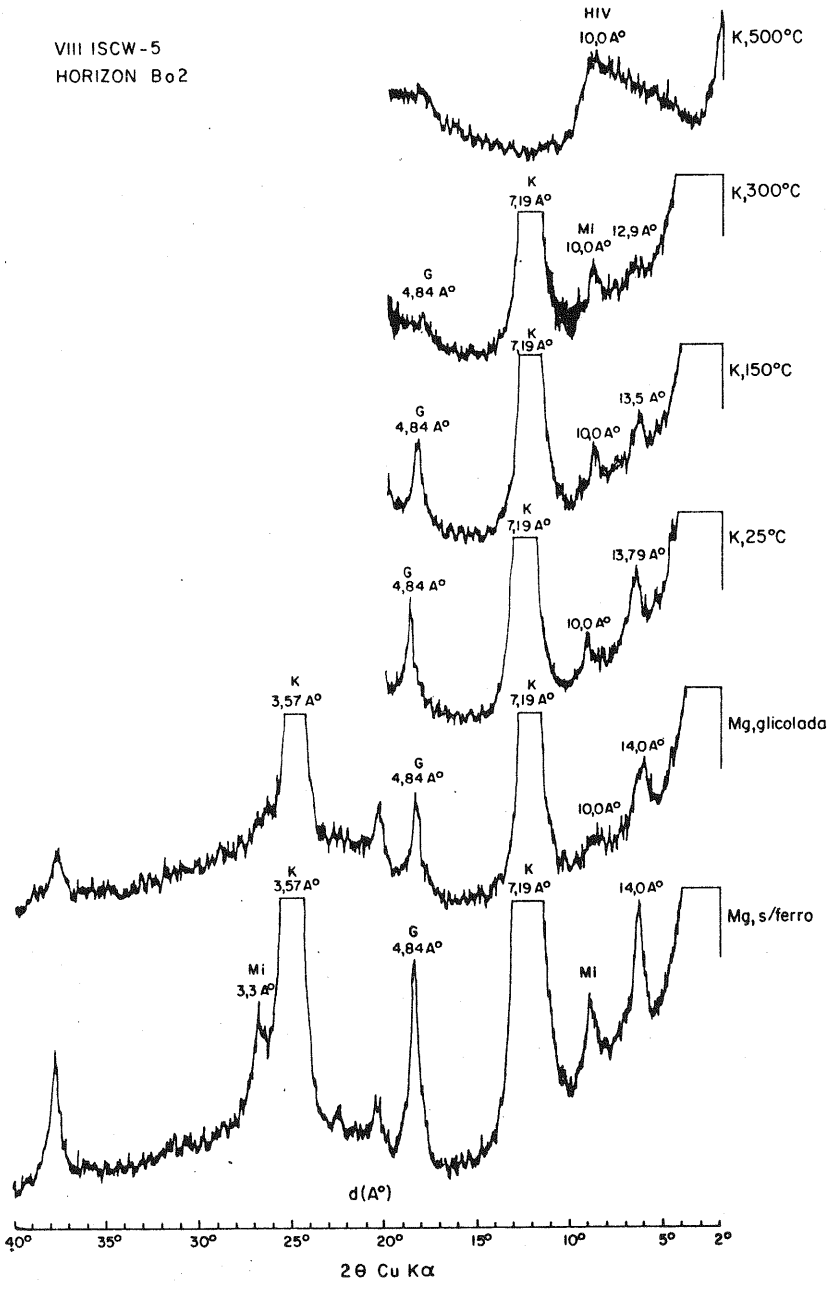


Fig. 6. X-ray diffraction patterns of the deferrified clay from Bo2 horizon of pedon 5 after Mg saturation and glycerol solvation, K saturation at room temperature (K 25°C), heating at 150°C, 300°C, and 500°C. Units of d spacing are in angstrom Å. Kaolinite (K); gibbsite (G); hydroxy-interlayered

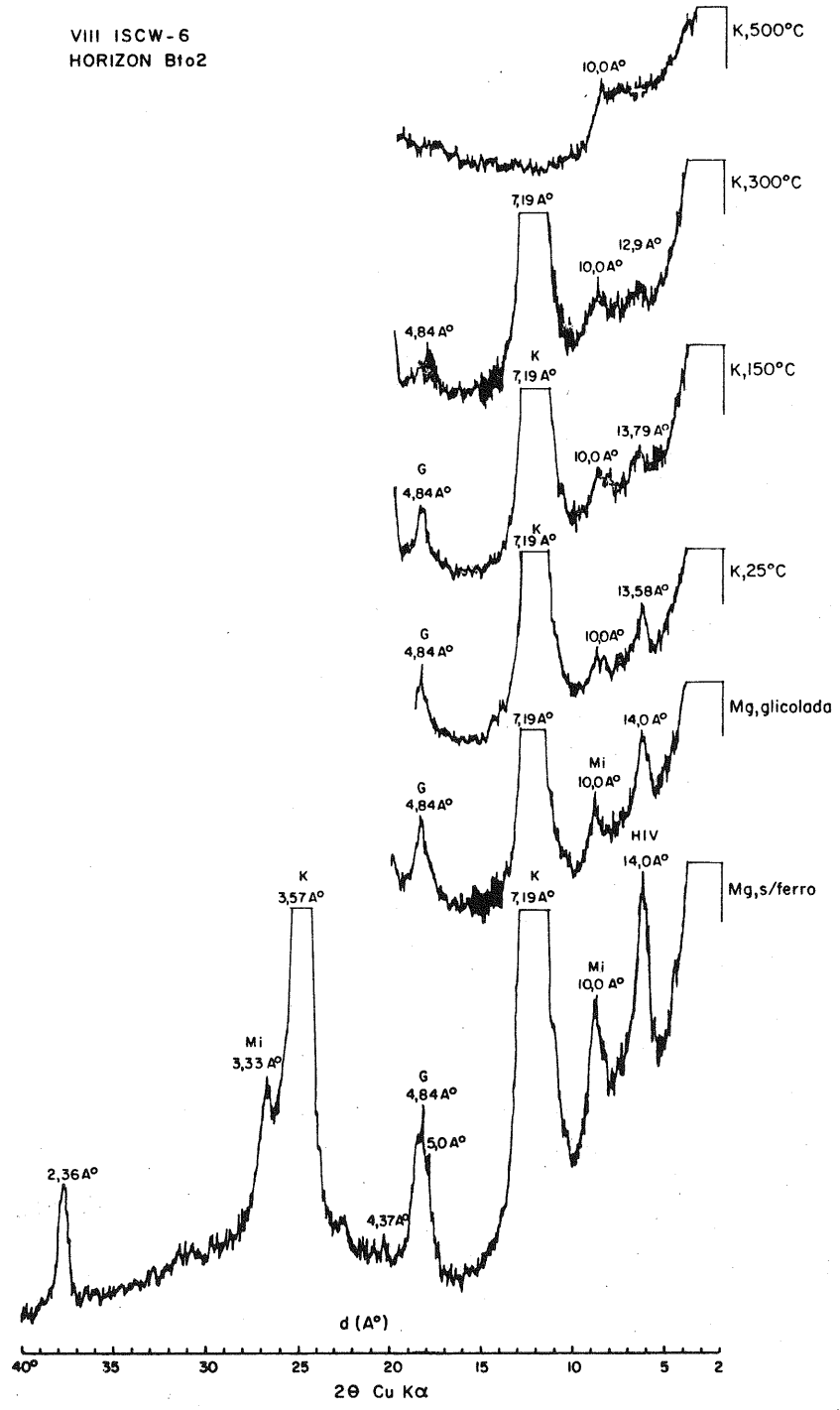


Fig. 7. X-ray diffraction patterns of the deferrified clay from Bto2 horizon of pedon 6 after Mg saturation and glycerol slovation, K saturation at room temperature (K 25°C), heating at 150°C, 300°C, and 500°C. Units of d spacing are in angstrom Å. Kaolinite (K); gibbsite (G); hydroxy-interlayered vermiculite (HIV).

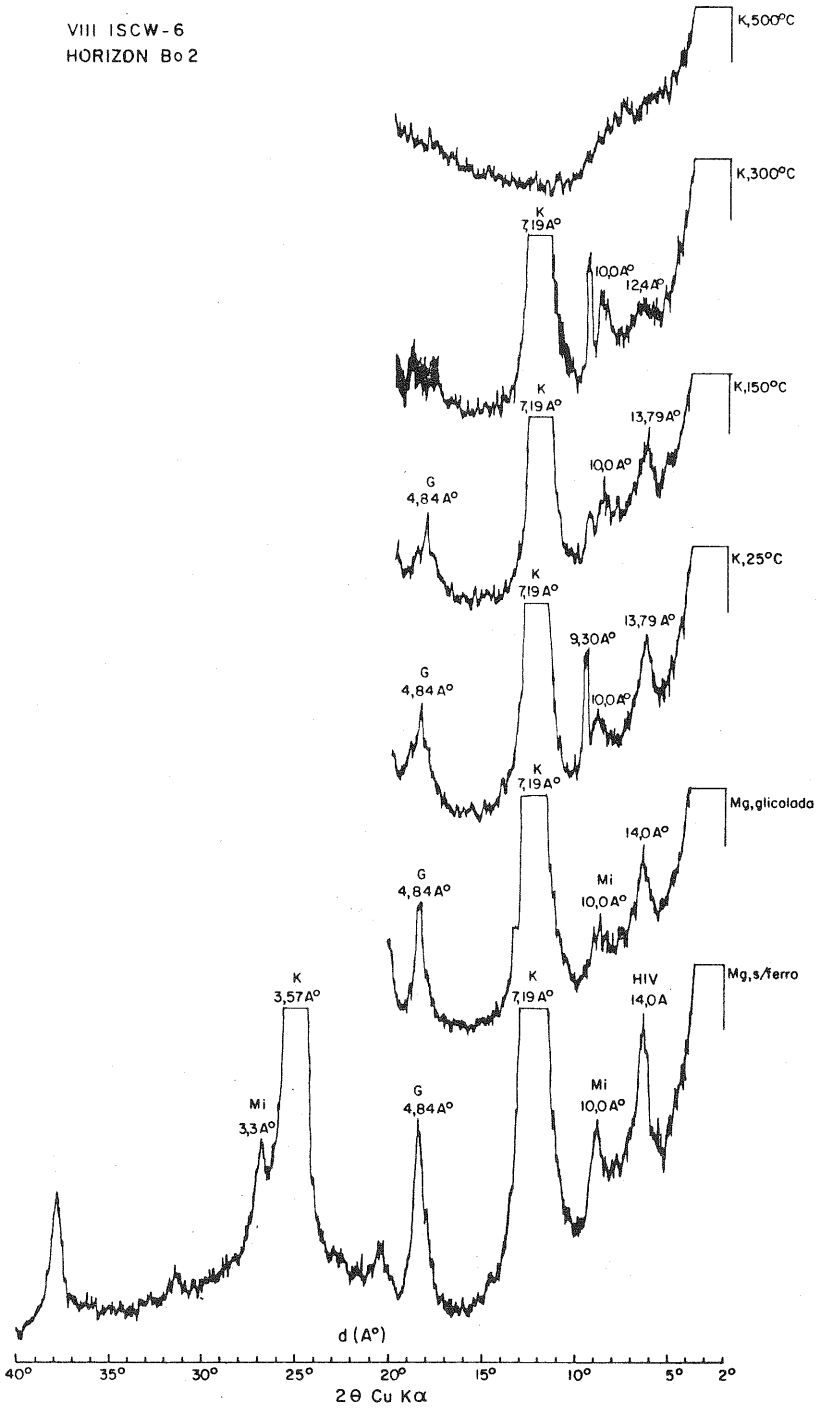


Fig. 8. X-ray diffraction patterns of the deferrified clay from Bo2 horizons of pedon 6 after Mg saturation and glycerol solvation; K saturation at room temperature (K 25°C), heating at 150°C, 300°C, and 500°C. Units of d spacing are in angstrom Å. Hydroxy-interlayered vermiculite (HIV); kaolinite (K); gibbsite(G).

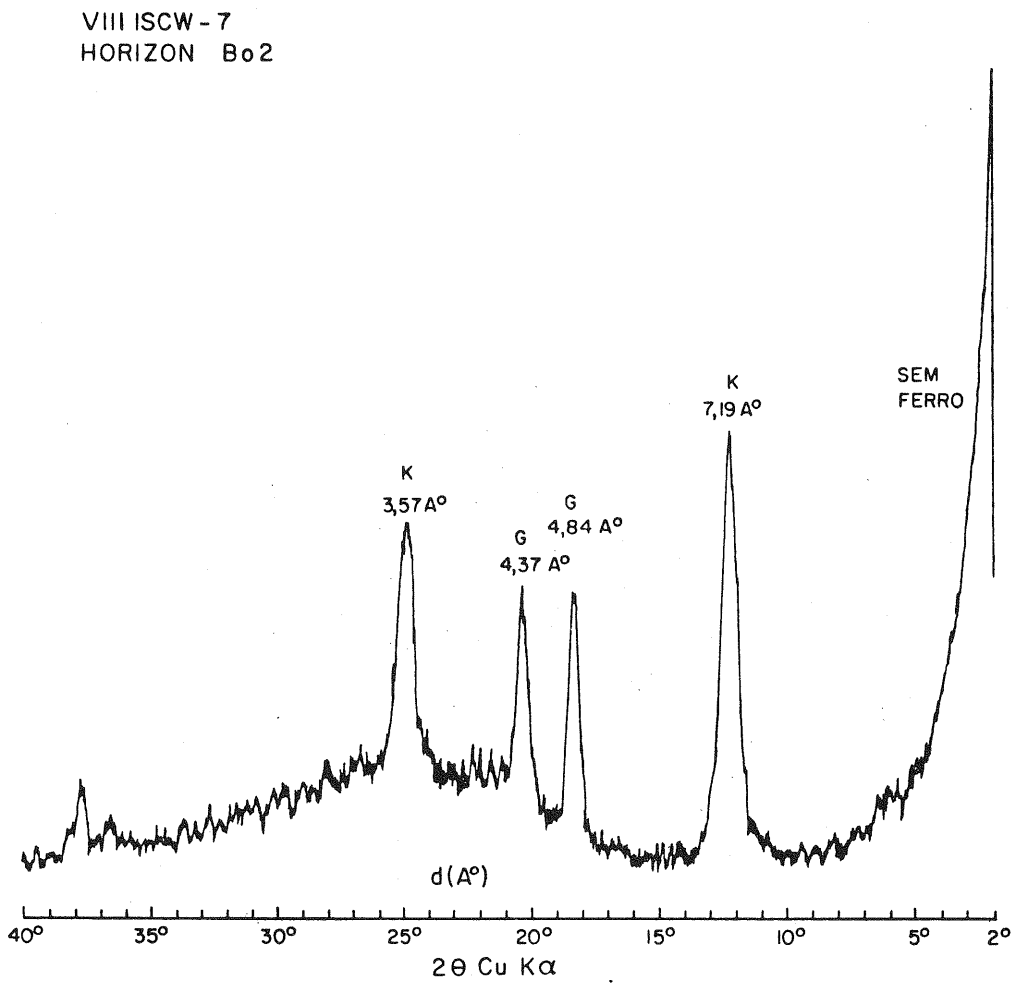


Fig. 9. X-ray diffraction patterns of the deferrified clay from Bo2 horizon of pedon 7. Units of d spacing are in angstrom Å. Kaolinite (K); gibbsite (G).

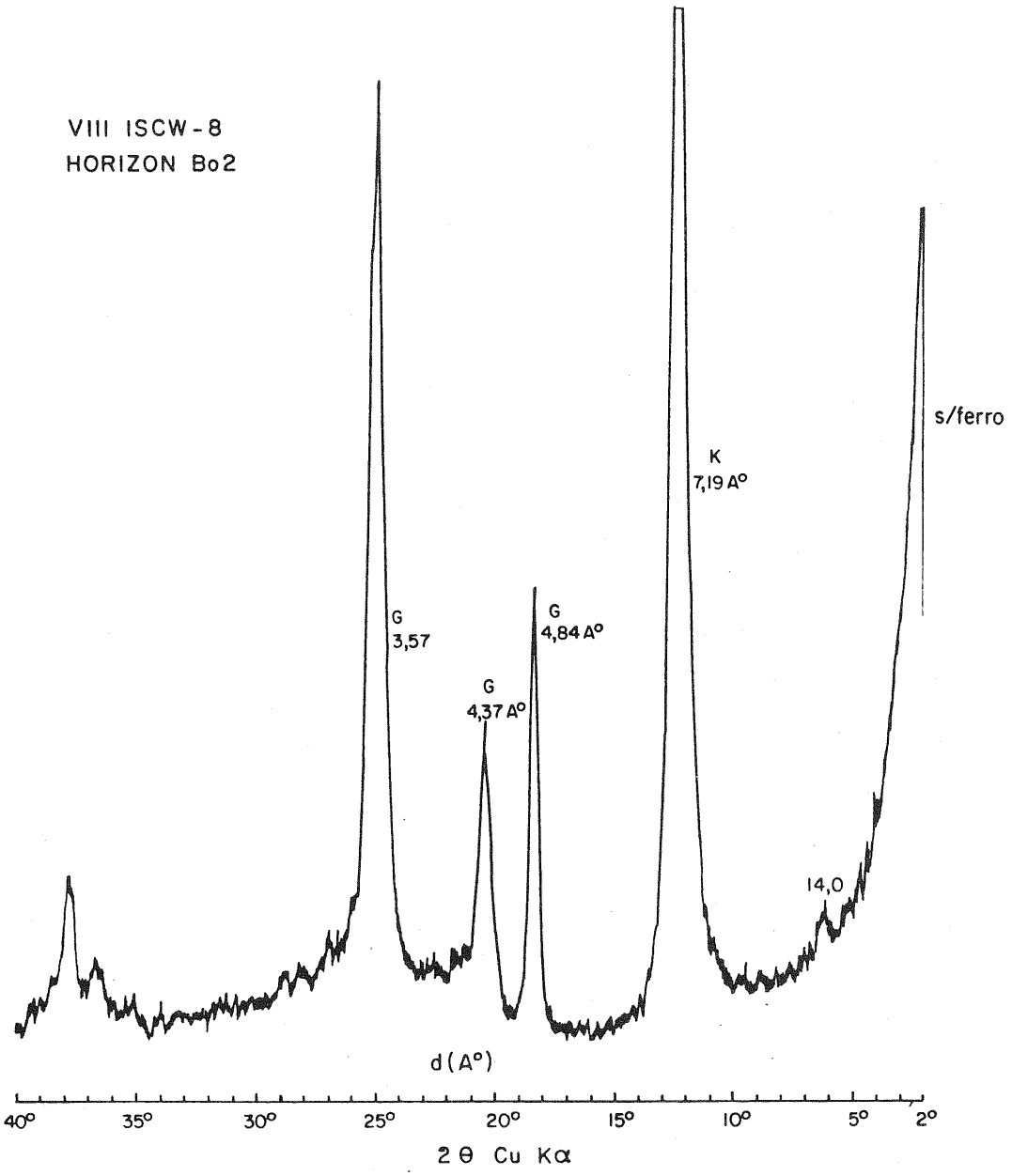


Fig. 10. X-ray diffraction patterns of the deferrified clay from Bo2 horizon of pedon 8. Units of d spacing are in angstrom Å. Kaolinite (K); gibbsite (G).

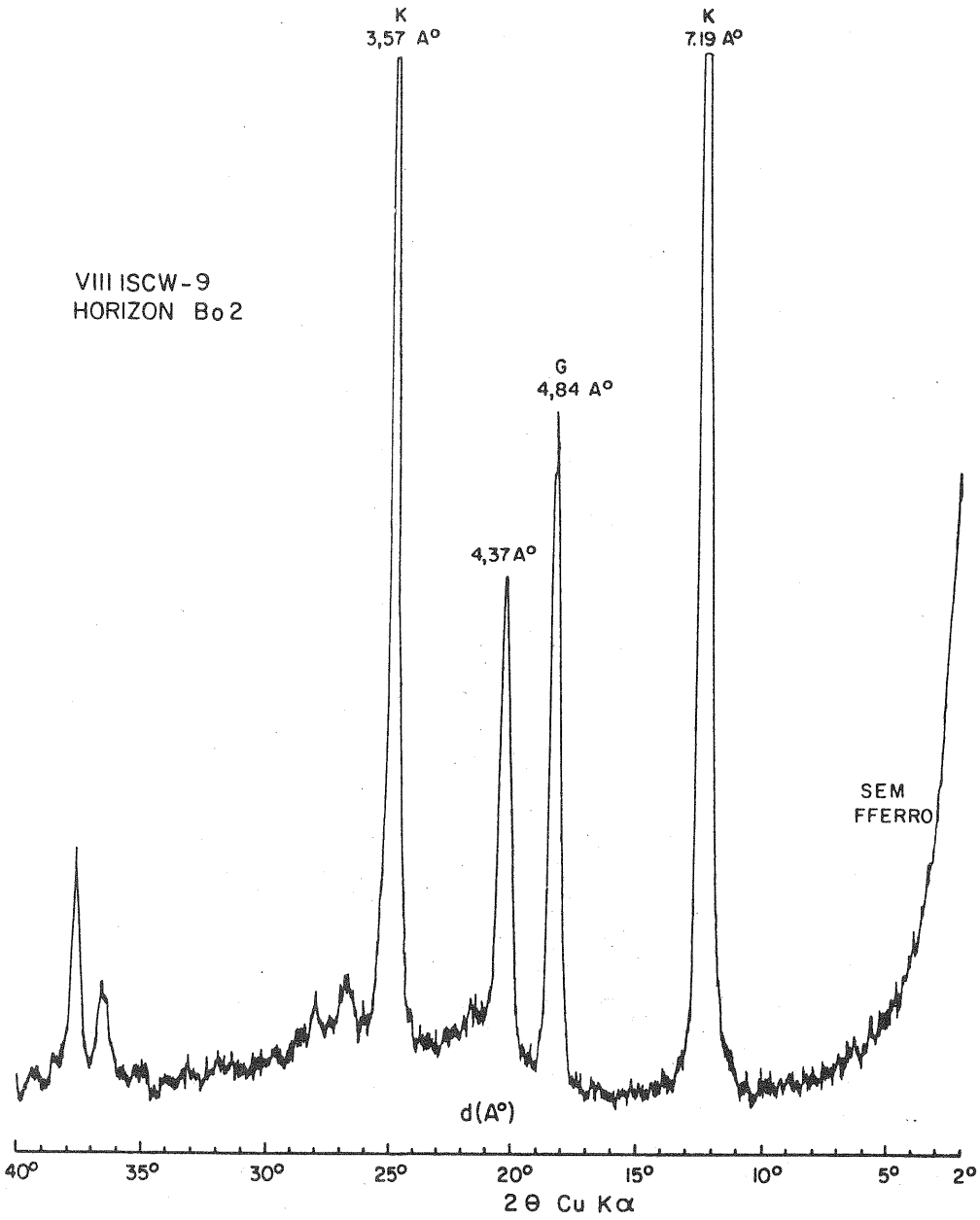


Fig. 11. X-ray diffraction patterns of the deferrified clay from Bo2 horizon of pedon 9. Units of d spacing are in angstrom Å. Kaolinite (K); gibbsite (G).

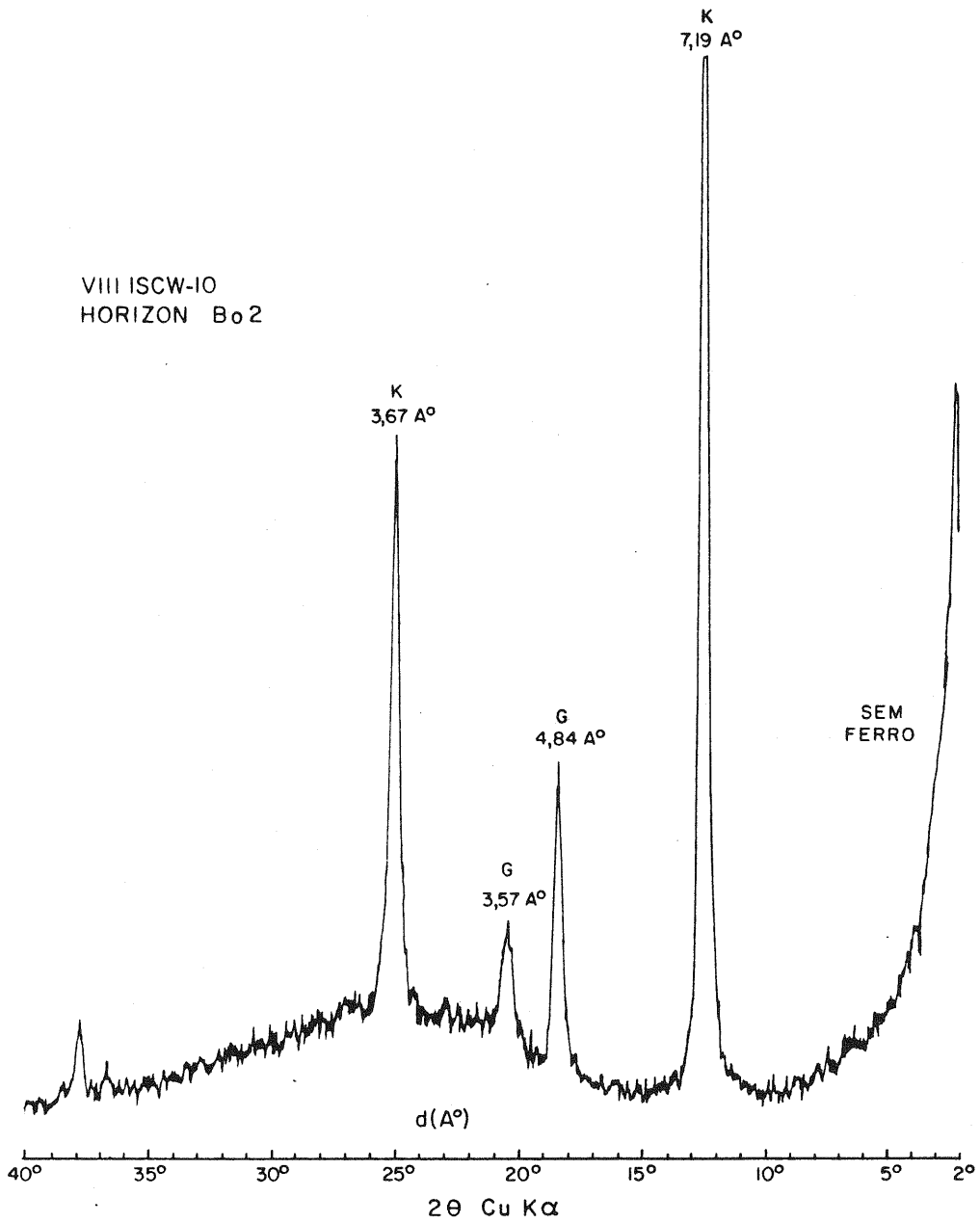


Fig. 12. X-ray diffraction patterns of deferrified clay from Bo2 horizon of pedon 10. Units of d spacing are in angstrom Å. Kaolinite (K); gibbsite (G).

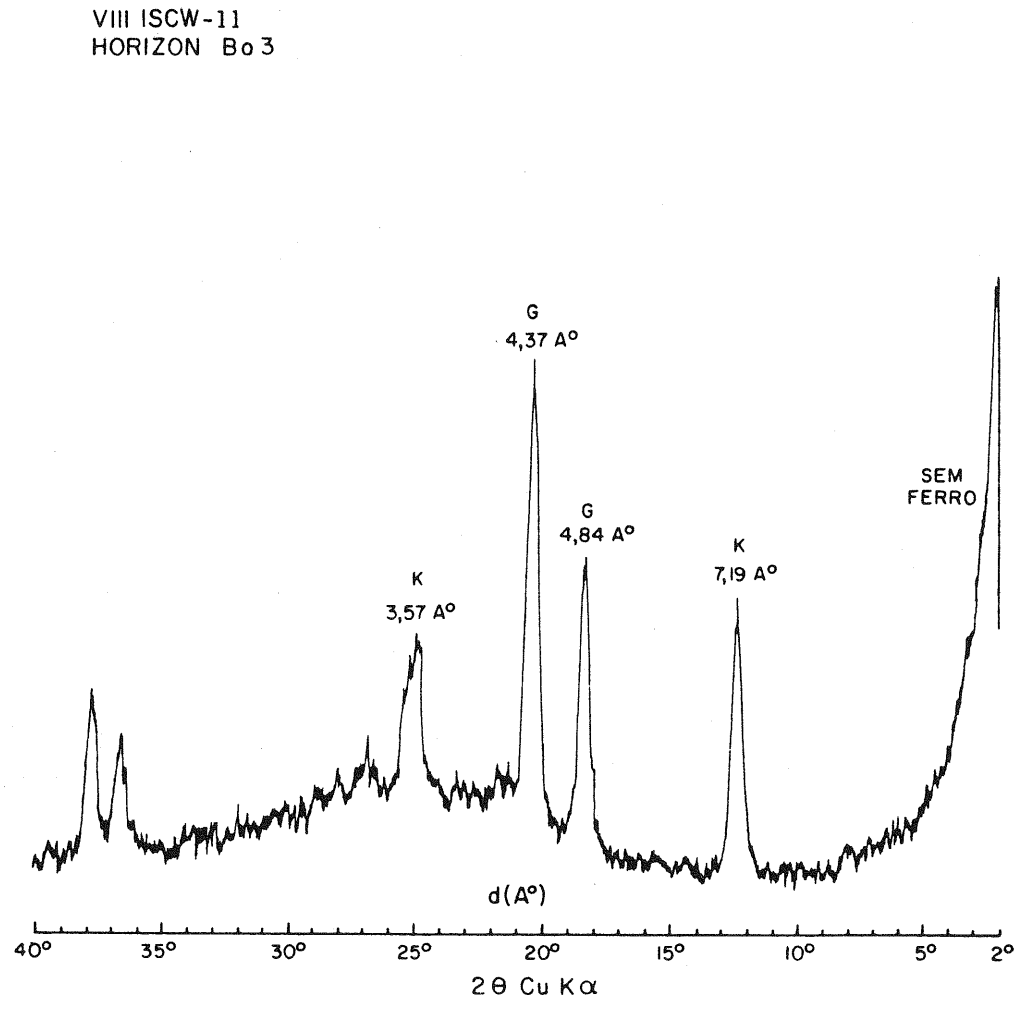


Fig. 13. X-ray diffrection patterns of the deferrified clay from Bo3 horizon of pedon 11. Units of d spacing are in angstrom Å. Kaolinite (K); gibbsite (G).

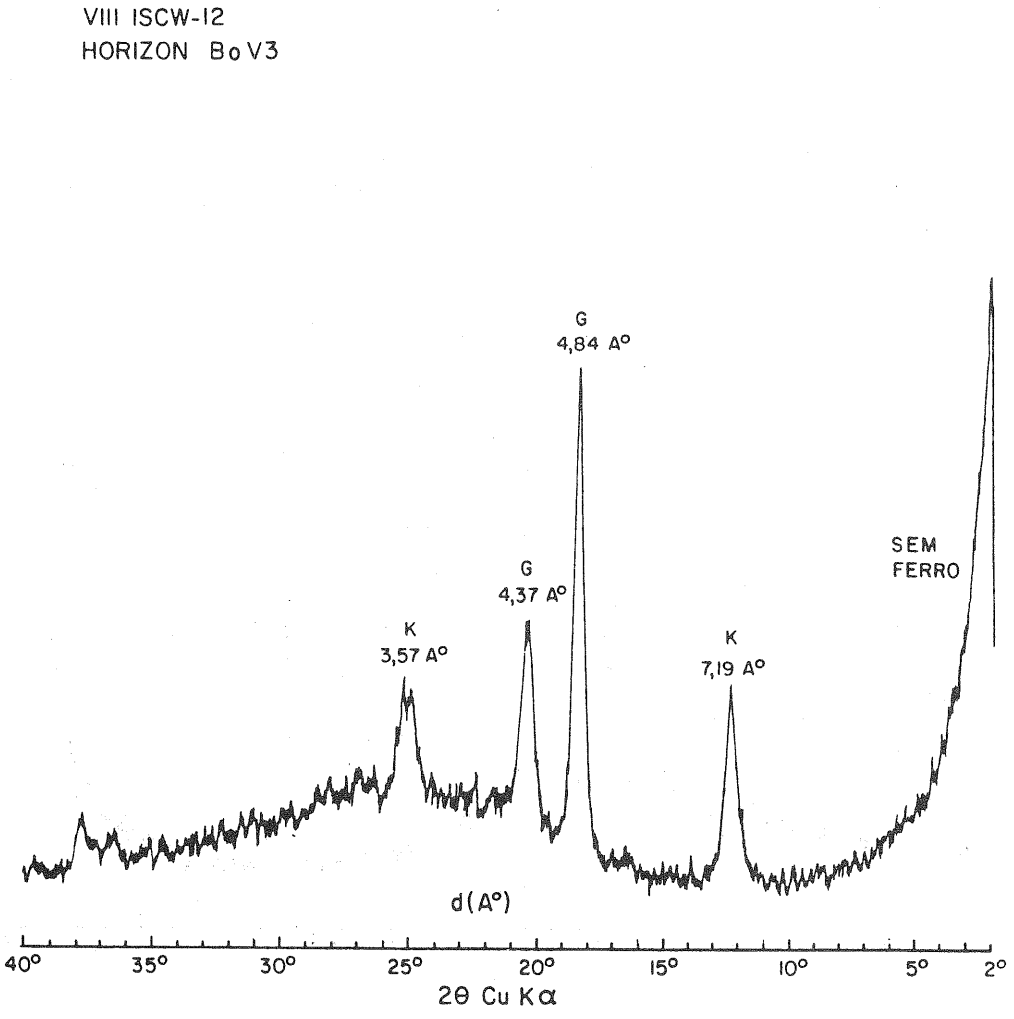


Fig. 14. X-ray diffraction patterns of the deferrified clay from Bov3 horizon of pedon 12. Units of d spacing are in angstrom Å. Kaolinite (K); gibbsite (G).

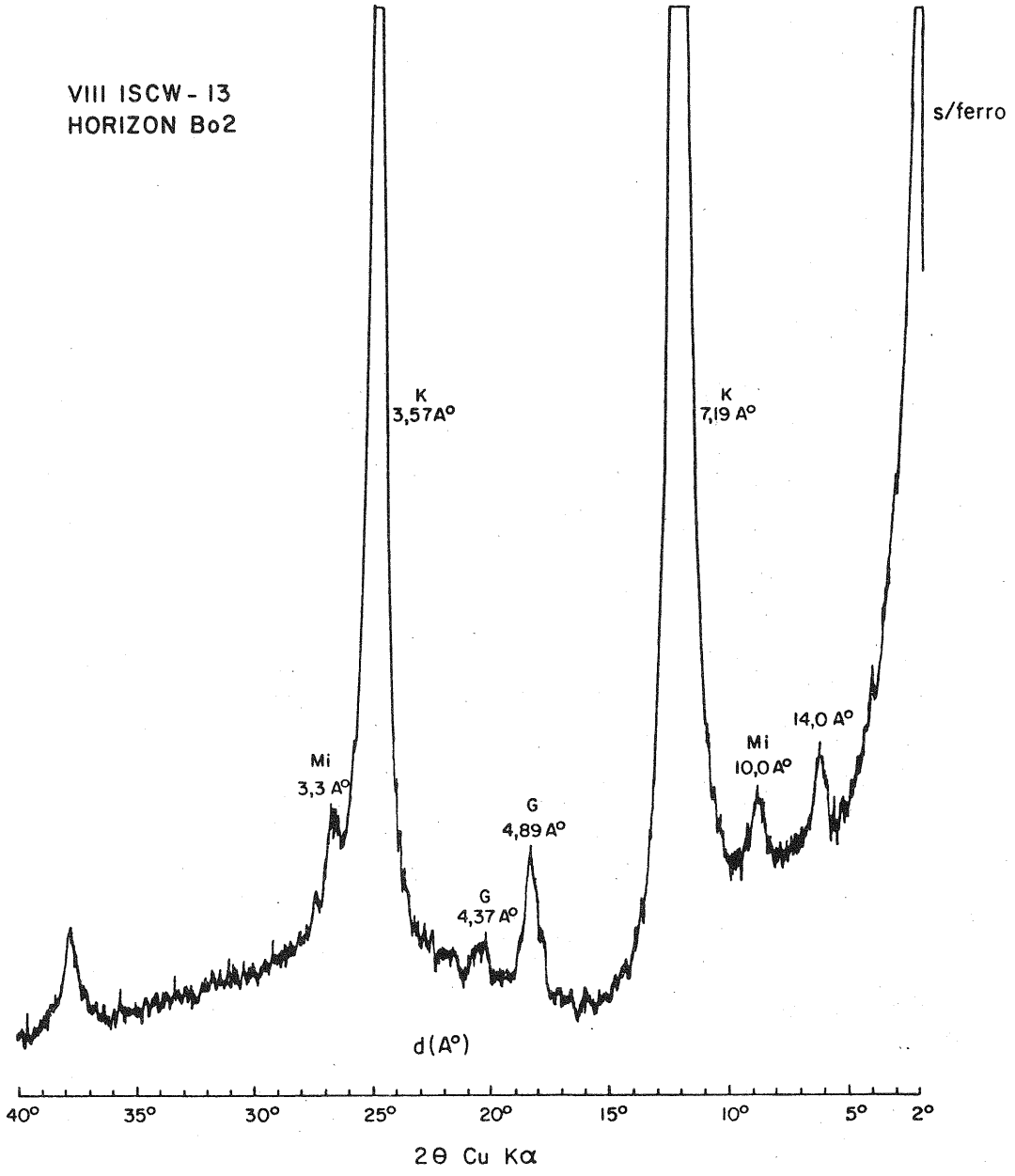


Fig. 15. X-ray diffraction patterns of the deferrified clay from Bo2 horizon of pedon 13. Units of d spacing are in angstrom Å. Kaolinite (K); gibbsite (G); mica (Mi); hydroxy-interlayered vermiculite (HIV).

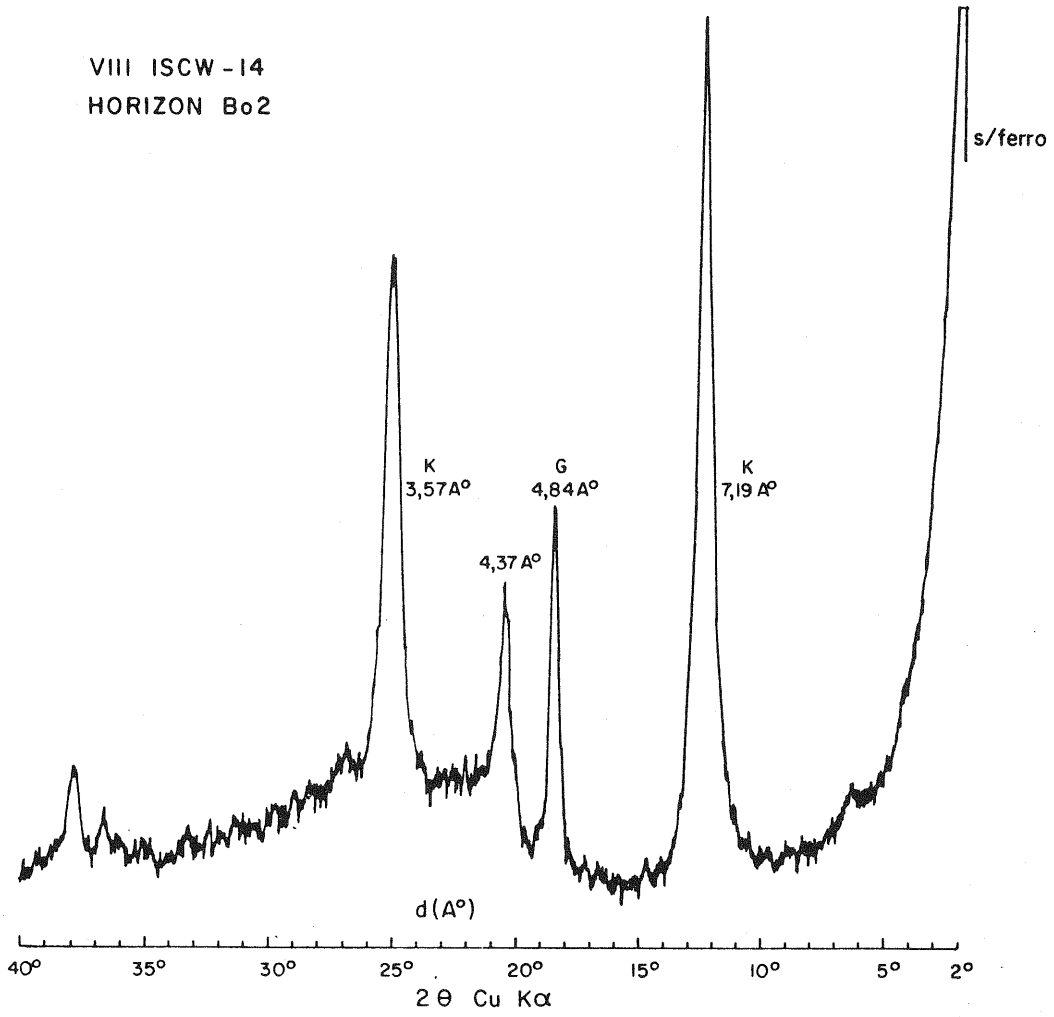


Fig. 16. X-ray diffraction pattern of the deferrified clay from Bo2 horizon of pedon 14. Units of d spacing are in angstrom Å. Kaolinite (K); gibbsite (G).

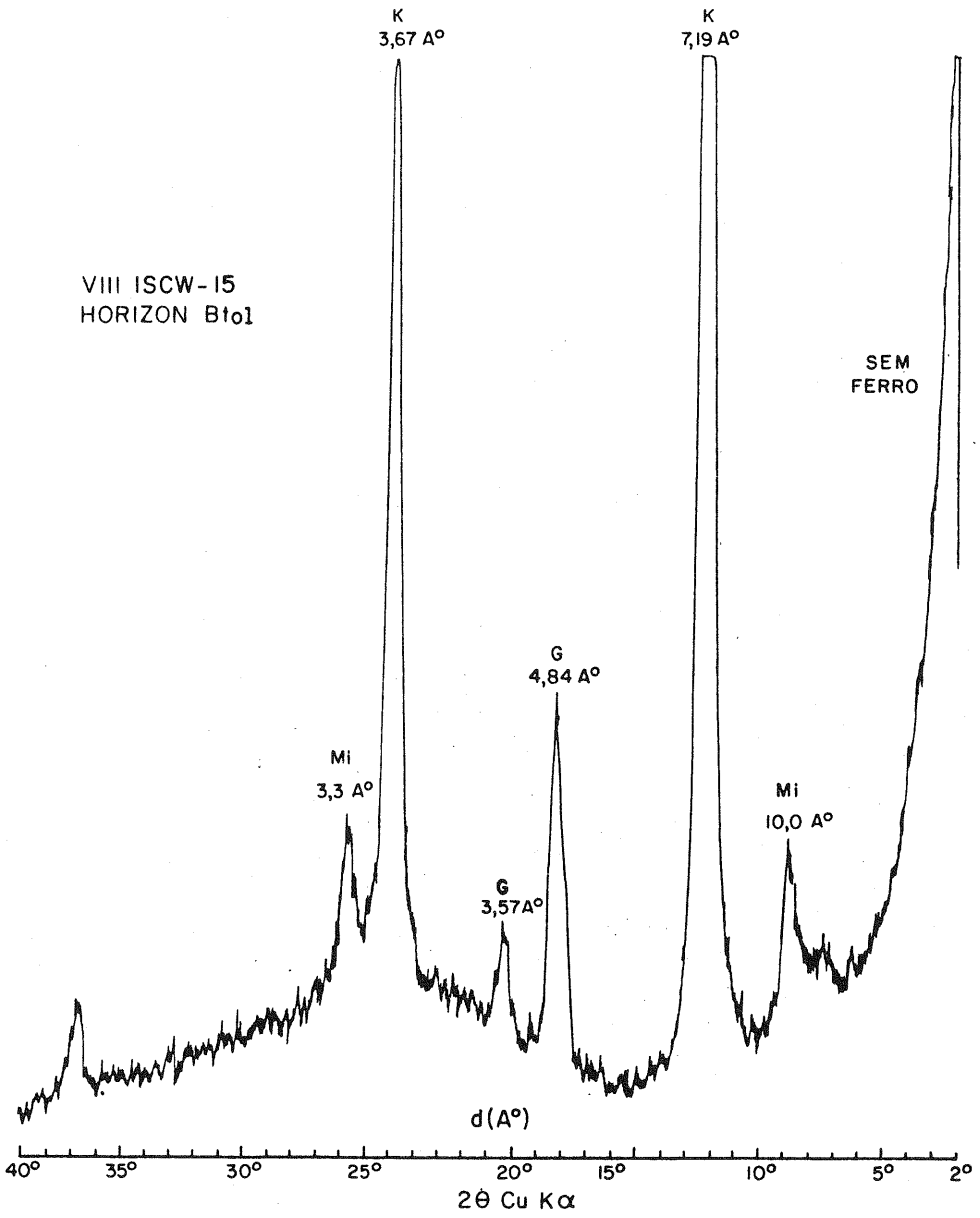


Fig. 17. X-ray diffraction patterns of the deferrified clay from Bto1 horizon of pedon 15. Units of d spacing are in angstrom Å. Kaolinite (K); gibbsite (G); mica (Mi).

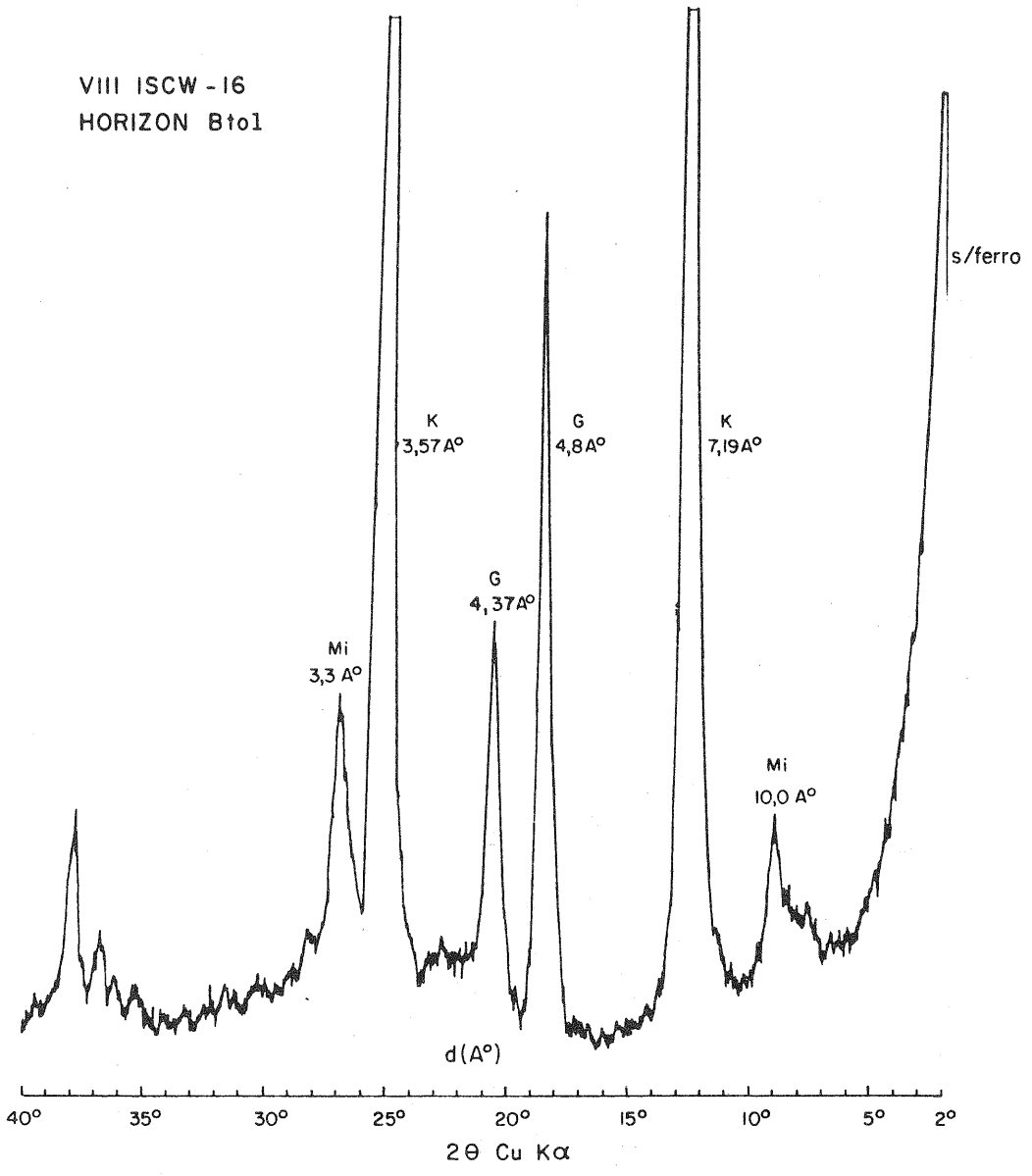


Fig. 18. X-ray diffraction patterns of the deferrified clay from Bto1 horizon of pedon 16. Units of d spacing are in angstrom Å. Kaolinite (K); gibbsite (G); mica (Mi).

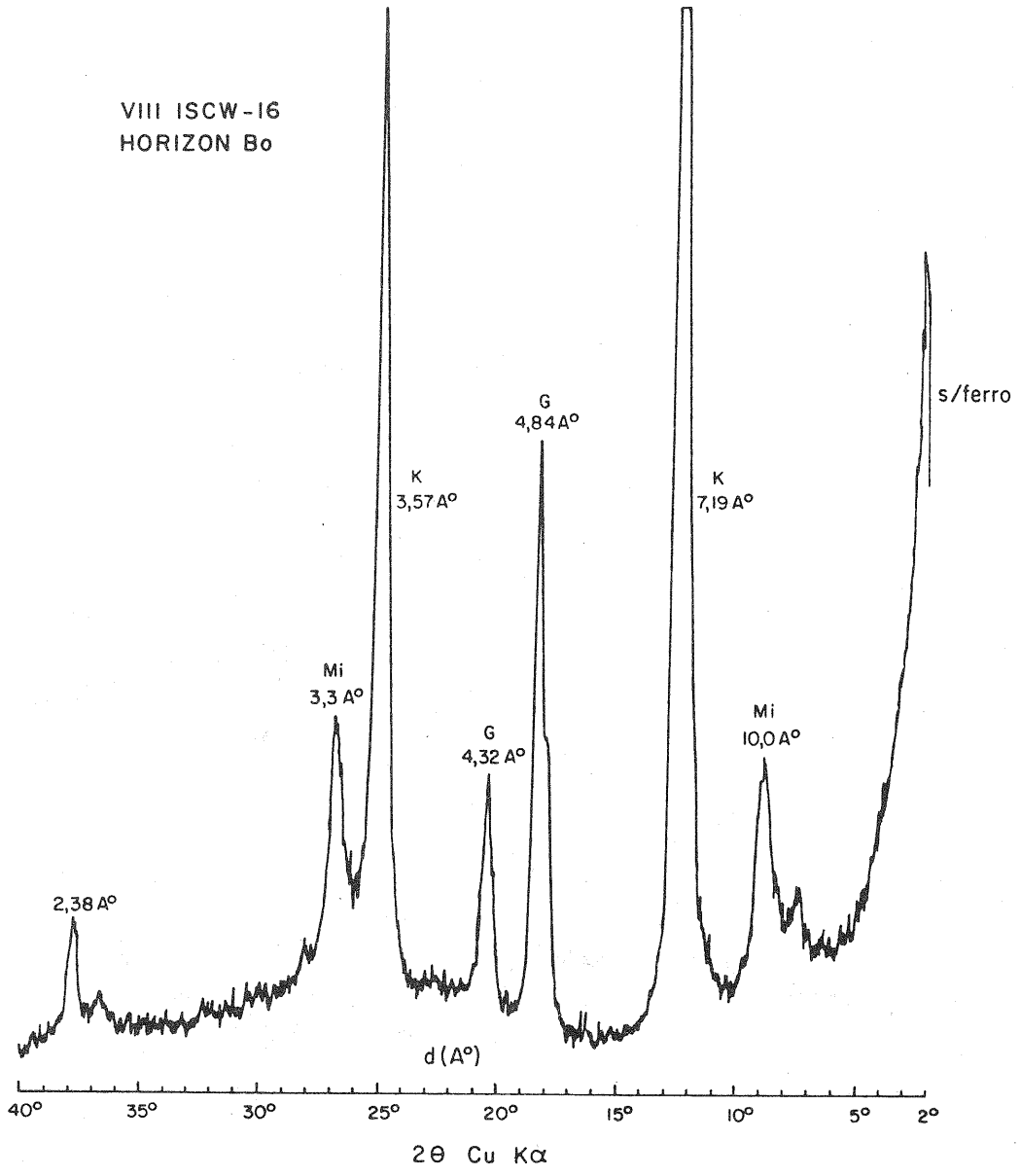


Fig. 19. X-ray diffraction patterns of the deferrified clay from Bo horizon of pedon 16. Units of d spacing are in angstrom Å. Kaolinite (K); gibbsite (G); mica (Mi).

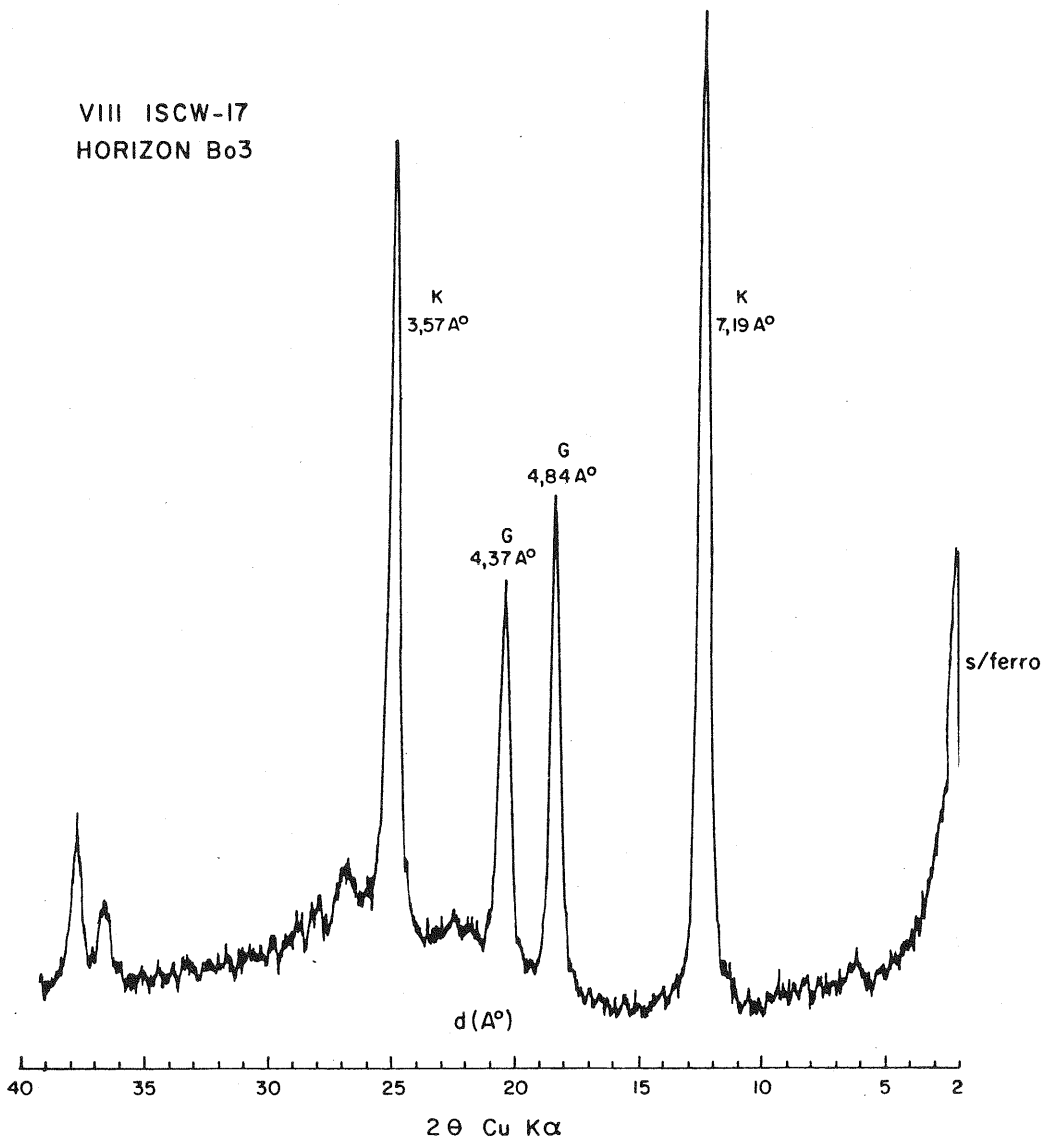


Fig. 20. X-ray diffraction patterns of the deferrified clay from Bo3 horizon of pedon 17. Units of d spacing are in angstrom Å. Kaolinite (K); gibbsite (G).

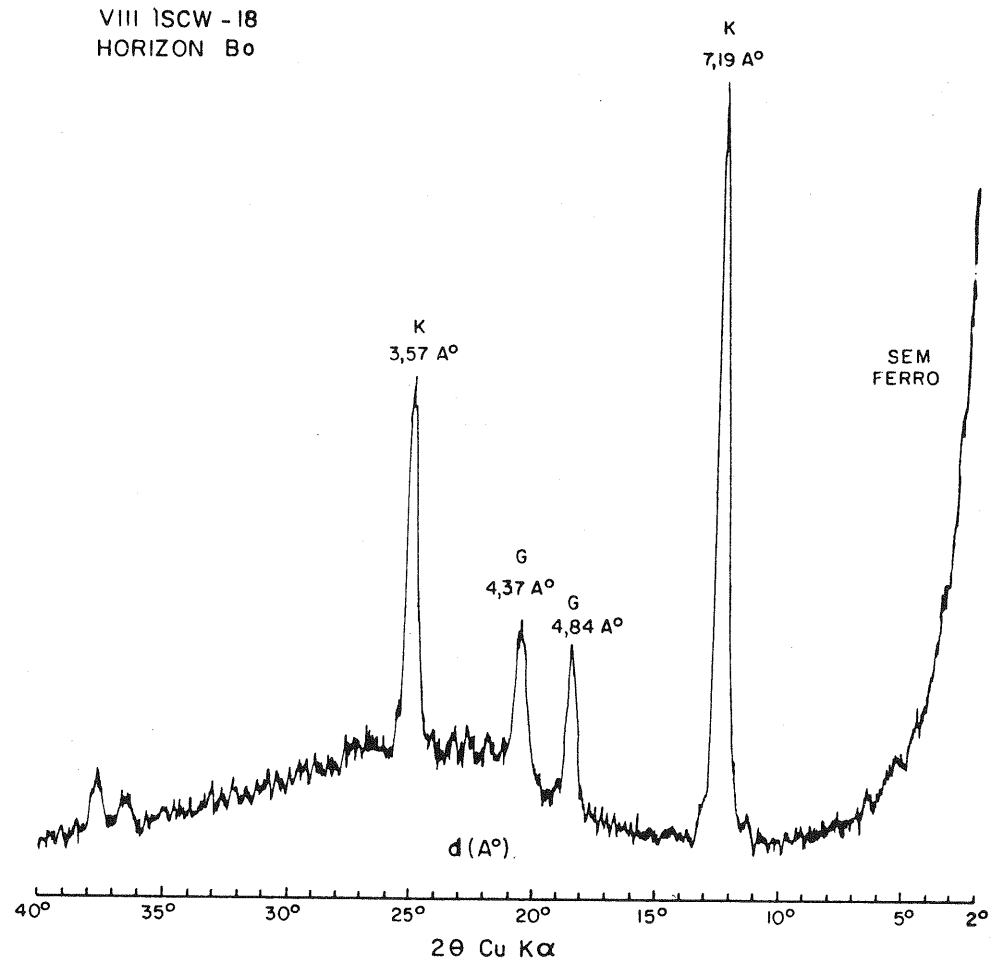


Fig. 21. X-ray diffraction patterns of the deferrified clay from Bo horizon of pedon 18. Units of d spacing are in angstrom Å. Kaolinite (K); gibbsite (G).

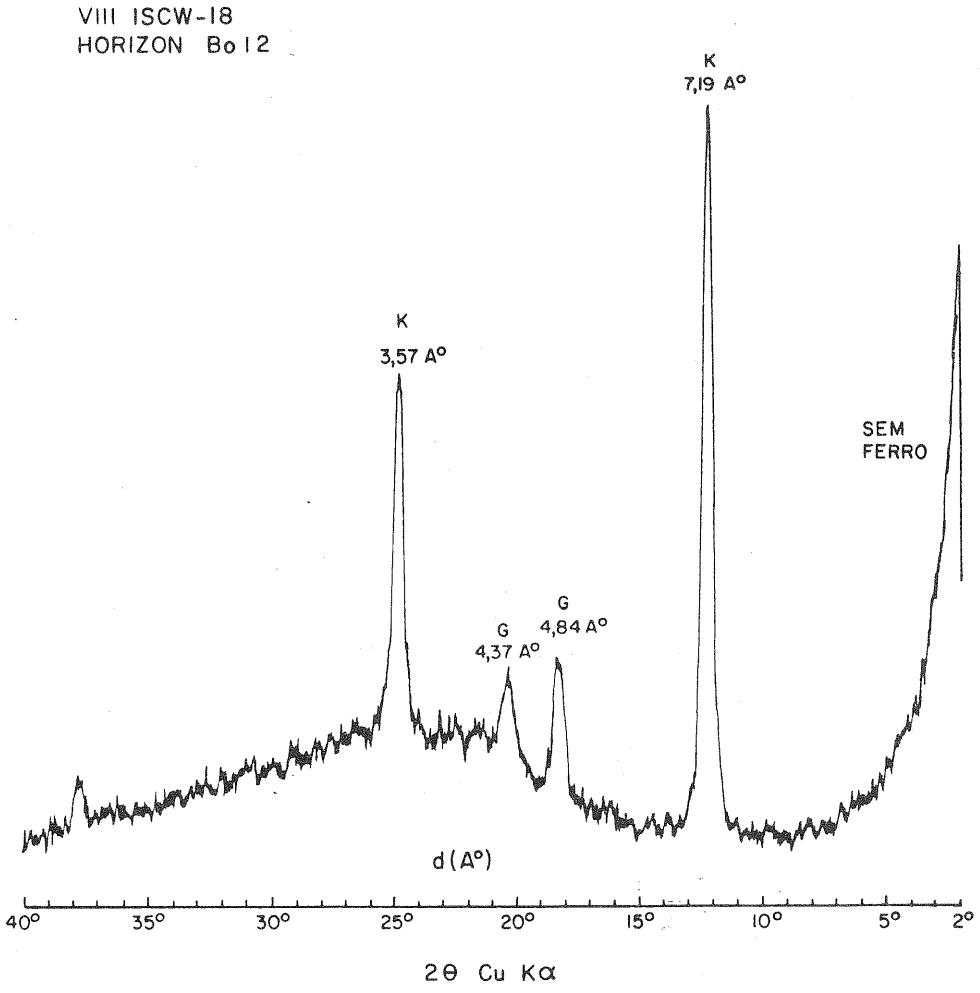


Fig. 22. X-ray diffraction patterns of the deferrified clay from Bo12 horizon of pedon 18. Units of d spacing are in angstrom Å. Kaolinite (K); gibbsite (G).

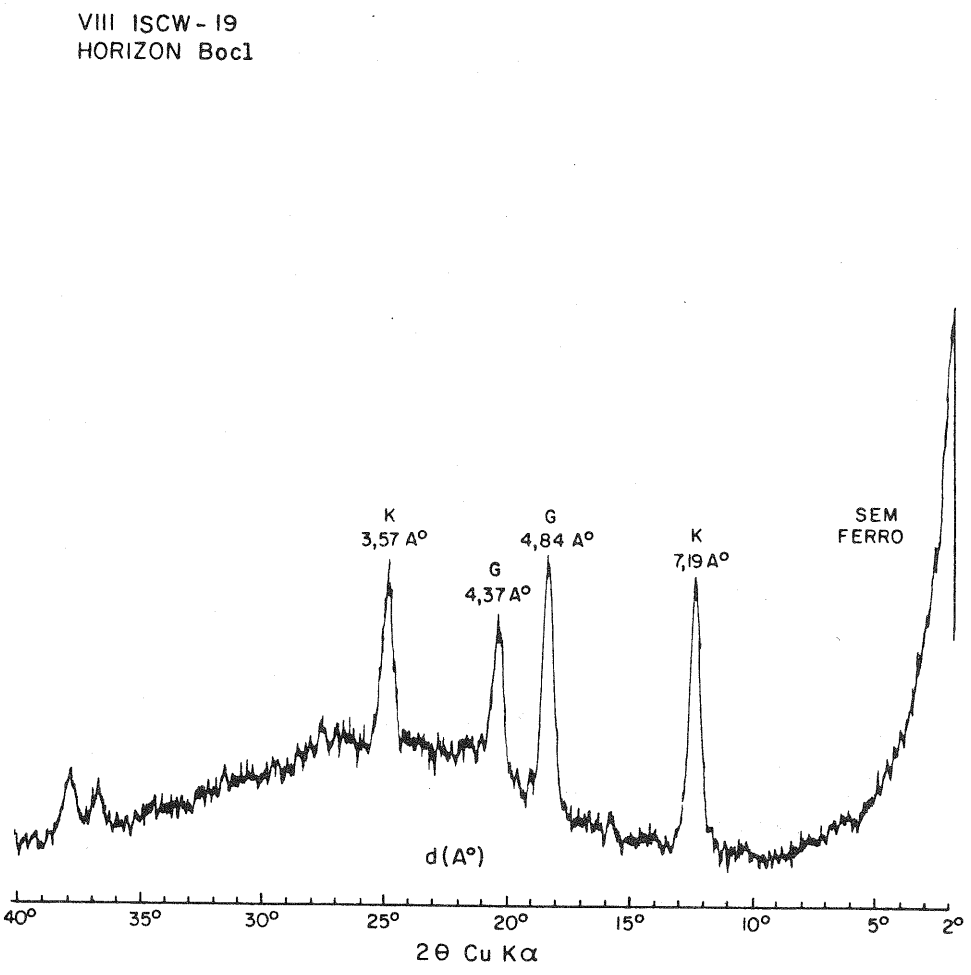


Fig. 23. X-ray diffraction patterns of the deferrified clay from Bocl horizon of pedon 19. Units of d spacing are in angstrom Å. Kaolinite (K); gibbsite (G).

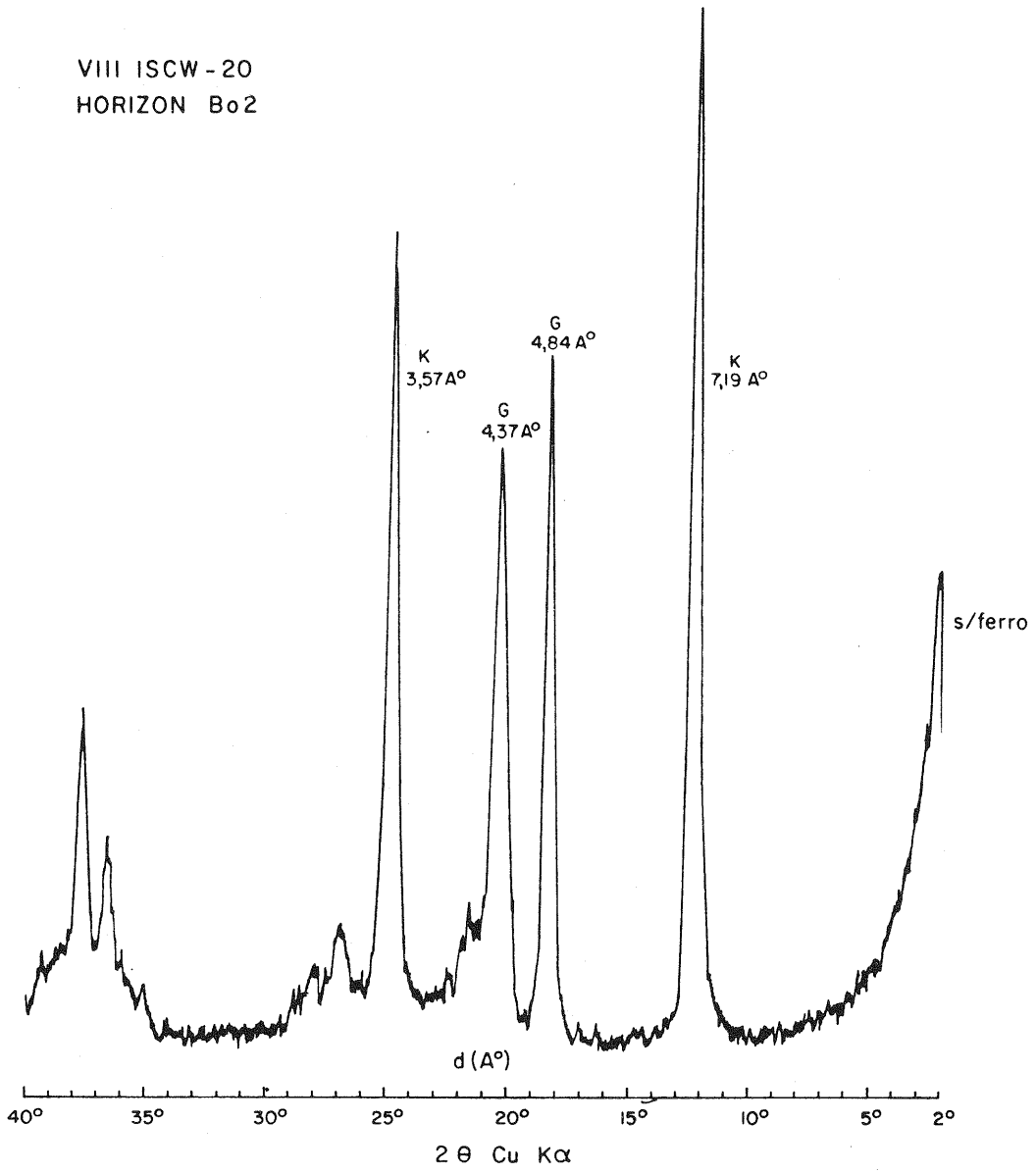


Fig. 24. X-ray diffraction patterns of the deferrified clay from Bo2 horizon of pedon 20. Units of d spacing are in angstrom Å. Kaolinite (K); gibbsite (G).

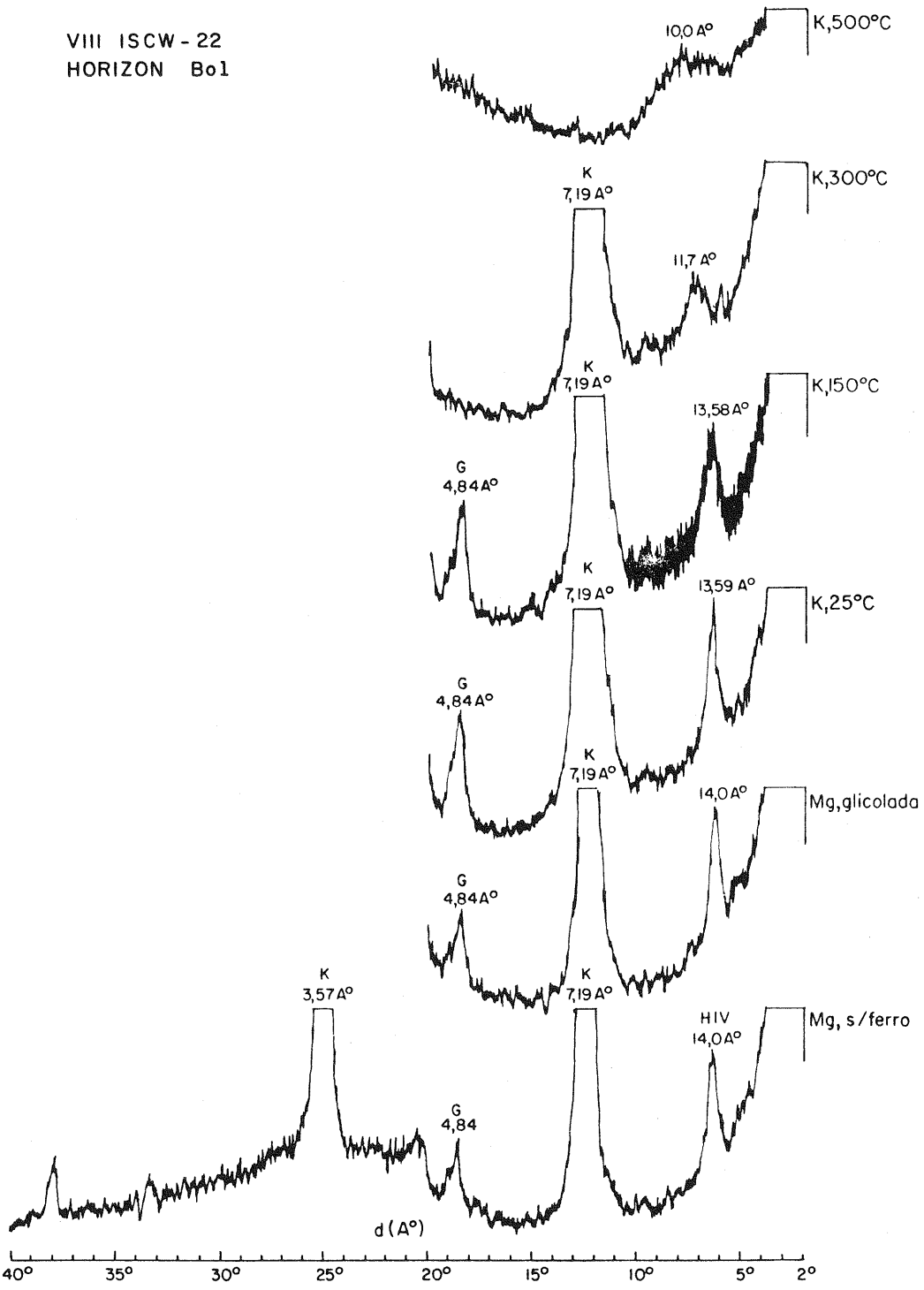


Fig. 25. X-ray diffraction patterns of the deferrified clay from Bo1 horizon of pedon 22 after Mg saturation and glycerol solvation, K saturation at room temperature (K 25°C), heating at 150°C, 300°C, and 500°C. Units of d spacing are in angstrom Å. Kaolinite (K); gibbsite (G); hydroxy-interlayered vermiculite (HIV).

Table 1. Hematite/goethite ratio (Hm/Hm+Gt), Al-substitution of Goethite (Gt) and Hematite (Hm), and width at Half-height (WHH) of Gt and Hm Peaks.

SNLCS Sample No.	Pedon	Horizon	Hm/Hm+Gt	Al-Substitution (mole% Al)		WHH(°2q)			
				Gt	Hm	Gt		Hm	
						110	111	104	110
850610	1	Bo2	0.00	34		0.15	0.38	0.00	0.00
850618	2	Bo1	0.11	23		0.35	0.43		
850625	3	Bo1	0.33	31		0.35	0.38		
850632	4	Bo2	0.46	31	14	0.55			
850636	6	Bto2	0.47	34	10	0.40			
850639	6	Bo2	0.55	36	10	0.55			
850645	5	Bto2	0.42	37	12	0.30			
850647	5	Bo2	0.52	38	12	0.55			
850655	7	Bo2	0.91		15			0.38	0.13
850661	8	Bo2	0.97		15			0.40	0.18
850669	9	Bo1	0.00	31		0.20	0.23		
850676	10	Bo2	Hm<Gt	25		0.20	0.33		
850683	11	Bo2	0.13	27		0.35			
850684	11	Bo3	0.25	29		0.40	0.43		
850690-1	12	Bvm	0.00	14		0.25	0.18		
850690-2	12	Bov1 (a)	0.00	19		0.45	0.23		
850690-4	12	Bov1 (b)	Hm<Gt	14		0.45	0.23		
850092	12	Bov2	0.15	17		0.40	0.38		
850699	13	Bo2	0.34	37	13	0.60			
850706	14	Bo2	0.12			0.35			
850713	15	Bto1	0.18	27		0.35	0.43		
850719	16	Bto1	0.36	34		0.45	0.48		
850721	16	Bo	0.40	40	13	0.30			
850730	17	Bo3	0.54	28	13	0.35		0.38	0.18
850738	18	Bo	0.10	34		0.30	0.48		
850740	18	Boc2	0.20	38	12	0.40			
850740	18	Bc2 (2)	0.50	17	3			0.33	
850746	19	Boc1	0.05	38		0.30	0.43		
850746	19	Boc1-(c)	0.80		8			0.28	0.18
850746	19	Boc1-(d)	0.00	15		0.10	0.08		
850753	20	Bo2	0.27	37	15	0.40			
850759	22	Bo2	0.56	37	16	0.40			

Note: (a) yellow mottles; (b) red mottles; (c) red petroplinthite nodules; (d) yellow spots in red petroplinthite nodules.

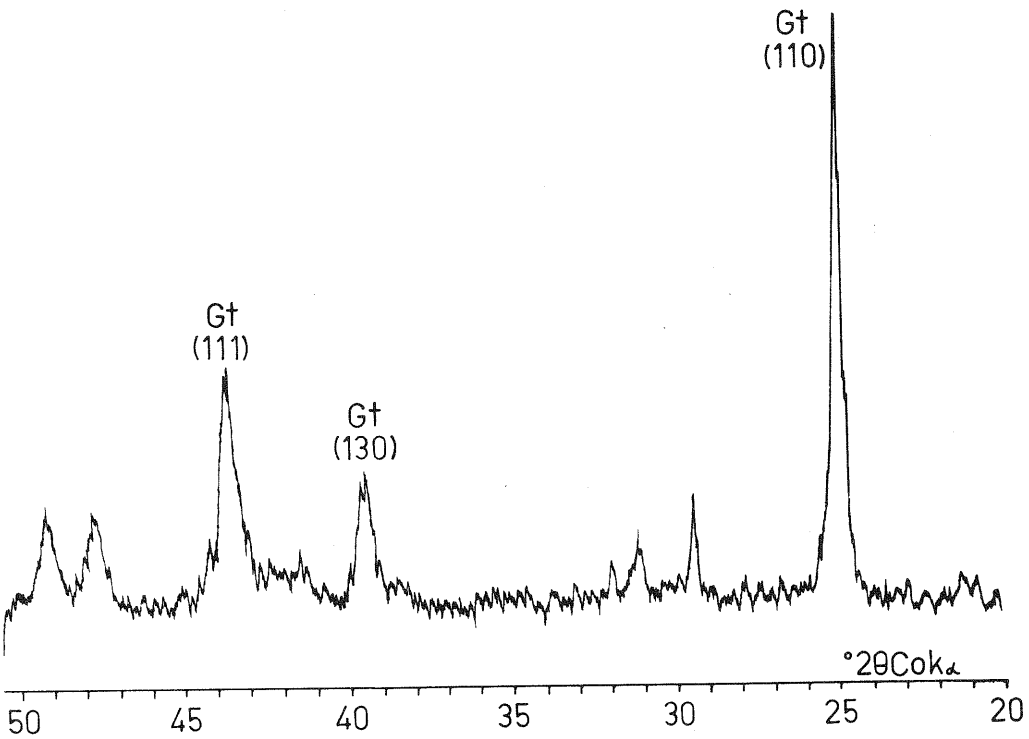


Fig. 1. X-ray diffractogram of 5M-NaOH treated clay fraction of Bo2 horizon of pedon 1 (sample 850610).

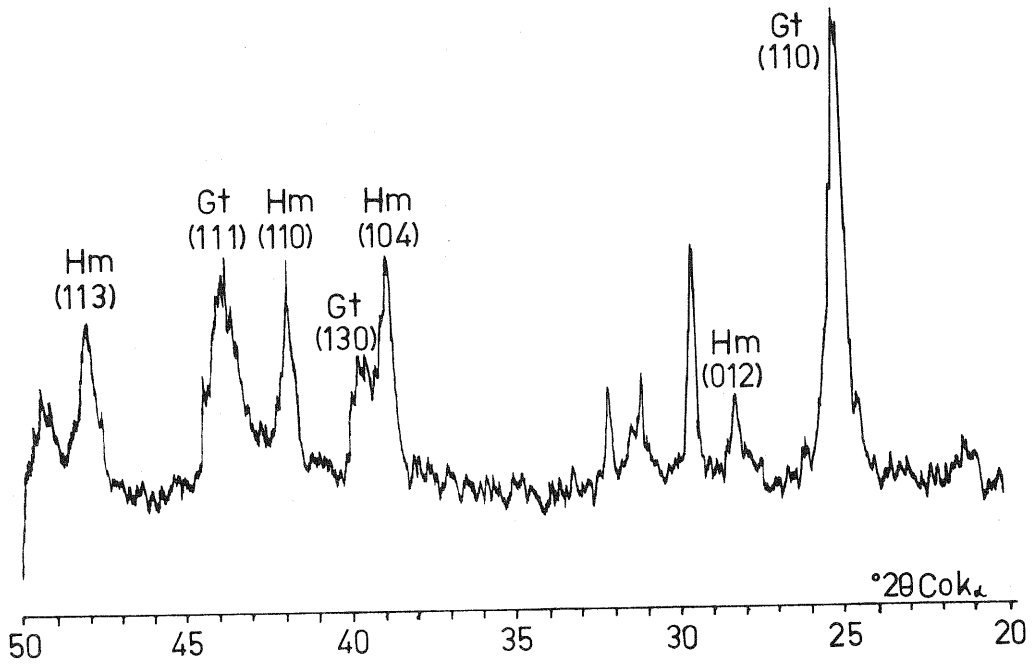


Fig. 2. X-ray diffractogram of 5M-NaOH treated clay fraction of Bo1 horizon of pedon 3 (sample 850625).

formation of clay minerals, so pedons with increasing weathering intensity have gibbsite increase and pedons with decreasing weathering intensity have HIV and mica content increase.

Conclusions

Kaolinite and gibbsite are present in all the horizons of the pedons examined. Hydroxy-interlayered vermiculite is present in 52 percent of the horizons and mica in 30 percent.

Pedons with increasing weathering intensity have gibbsite increase and lower Ki ratios (note the relative increase in aluminum).

Pedons with decreasing weathering intensity have mica and HIV content increase and higher Ki ratios.

Acknowledgments

Thanks to J. Lopes de Paula for the separation of the clay fraction; to Ruth A. L. Johas, Maria Elizabeth C. C. de M. Melo, and Rosa Lea Bensusan Dechliar for the pretreatment for mineralogical analysis; and to C. Chaffin for drafting the figures.

References

Antonello, L.L. et al. 1984. Mineralogia de argilas deferrificadas de Horizonte B de Latossolos do Sudeste e Sul do Brasil. *In* III Reunião de Classificação e Correlação de Solos e Interpretação de Aptidão Agrícola. Rio de Janeiro, Brazil. Pp. 32-68.

Barnhisel. R.I. 1977. Chlorites and hydroxy interlayered vermiculite and smectite. *In* J.B. Dixon and S.B. Weed (eds.). Minerals in soil environments. Soil Sci. Soc. of Amer. Madison, WI. Pp. 331-356.

Empresa Brasileira De Pesquisa Agropecuária. Serviço Nacional de Levantamento e Conservação de Solos. 1979. Manual de métodos de análise de solo. Rio de Janeiro, Brazil.

Jackson, M.L.. 1974. Soil chemical analysis, 2nd ed. Univ. of Wisconsin, Madison, WI. 835 p.

Soil Conservation Service, USDA. 1972. Soil survey laboratory methods and procedures for collecting soil samples. USDA. Washington, D.C. 63 p.

X-RAY DIFFRACTION OF IRON OXIDES OF SELECTED SAMPLES FROM THE VIIIth INTERNATIONAL SOIL CLASSIFICATION WORKSHOP PEDONS

N. Kämpf[1]

Abstract

Iron oxides from 22 pedons were examined by x-ray diffraction. Goethite (Gt) and hematite (Hm) are the most common oxides, with maghemite in soils derived from basic rocks and in red cemented nodules. The Hm/Hm+Gt ratio ranges from zero to 0.97 and is related to soil hue ($r^2 = 0.86$). The Al substitution ranges from 14 to 40 mole% Al in Gt, and from 3 to 16 mole% Al in Hm, with the lowest values in Plinthaquox and in petroplinthite nodules of Acrohumox and Acrustox pedons. The goethite WHH (110) and (111) show a broad range from 0.10 to 0.60°2θ and from 0.18 to 0.48°2θ.

Iron oxide minerals are important components of Oxisols. The proportion of goethite and hematite together with aluminum substitution, crystallinity, and the occurrence of maghemite are useful indicators of pedogenic environments. This paper reports the characteristics of iron oxides of selected samples from the VIIIth International Soil Classification Workshop (ISCW) pedons measured by x-ray diffraction.

Materials and Methods

Dry ground samples of fine earth from 22 pedons (sent by M.N. Camargo, SNLCS-EMBRAPA) were fractionated; the clay fraction was treated with boiling 5M-NaOH (Norrish and Taylor 1961; Kämpf and Schwertmann 1982a) to concentrate the iron oxides. Powder samples were examined by x-ray diffraction (XRD) (Philips instrument, Coka radiation, 35 Kv, 25 mA; graphite monochromator). The coarse fraction (> 2μ) of pedon 14, dry ground samples of a placic horizon (pedon 12), and petroplinthite nodules of pedons 18 and 19 were x-rayed without need of the NaOH iron concentration treatment.

The hematite/goethite ratio (Hm/Hm+Gt) was estimated from the integrated intensity of the hematite 012 or 104 XRD peaks, and the goethite 110 peak (Kämpf and Schwertmann 1982b).

Aluminum substitution of goethite was determined after Schulze (1984) from the *c* dimension of the goethite unit cell obtained from d(110) and d(111). Aluminum substitution of hematite was estimated from the *a* dimension of the hematite unit cell obtained from d(110) or d(300) after Schwertmann et al. (1979). The corrected width at half-height (WHH) of goethite (110) and (111) peaks and hematite (104) and (110) peaks was used to estimate crystallinity.

Results and Discussion

Iron Oxide Types

Goethite (α - FeOOH) and hematite (α - Fe_2O_3) are the common iron oxides; maghemite (γ - Fe_2O_3) occurs in soils derived from basic rocks and in petroplinthite nodules (Table 1). The proportion of hematite (Hm) and goethite (Gt) varies from goethitic (e.g., pedons 1 and 9) to dominantly hematitic (e.g., pedons 7 and 8) as indicated by the Hm/Hm+Gt ratio which ranges from zero to 0.97. Some x-ray diffractograms of samples with different proportions of goethite, hematite, and maghemite are given in Figures 1 to 5.

Goethite is present in all samples, while no hematite was detected in some of them (pedons 1 and 9; in the placic horizon [Bvm horizon] and yellow mottles of pedon 12, and in yellow spots in red petroplinthite nodules of pedon 19). The presence of maghemite (Mh) is evident in pedons 7 and 8, and the highest amounts occur in the coarse fraction of pedon 14 which also contains ilmenite ($FeTiO_3$), and in the red petroplinthite nodules of pedons 18 and 19.

The Hm/Hm+Gt ratio was not determined for samples 850690-4 due to the presence of mica which hinders the hematite (012) peak; but in both samples goethite dominates over hematite.

Aluminum Substitution

Goethite and hematite are both aluminum substituted (Table 1): in goethite the Al substitution ranges from 14 to 40 mole% Al, but most samples range from 31 to 38 mole% Al; hematite presents an Al-substitution range from 3 to 16 mole% Al. Similar high aluminum substitution in goethite and hematite of Oxisols and Ultisols has been reported before (Curi 1983;

[1] Departamento de Solos, Faculdade de Agronomia, UFRGS. Caixa Postal 776. CEP 90.001, Porto Alegre, RS, Brazil. CNPq Fellow.

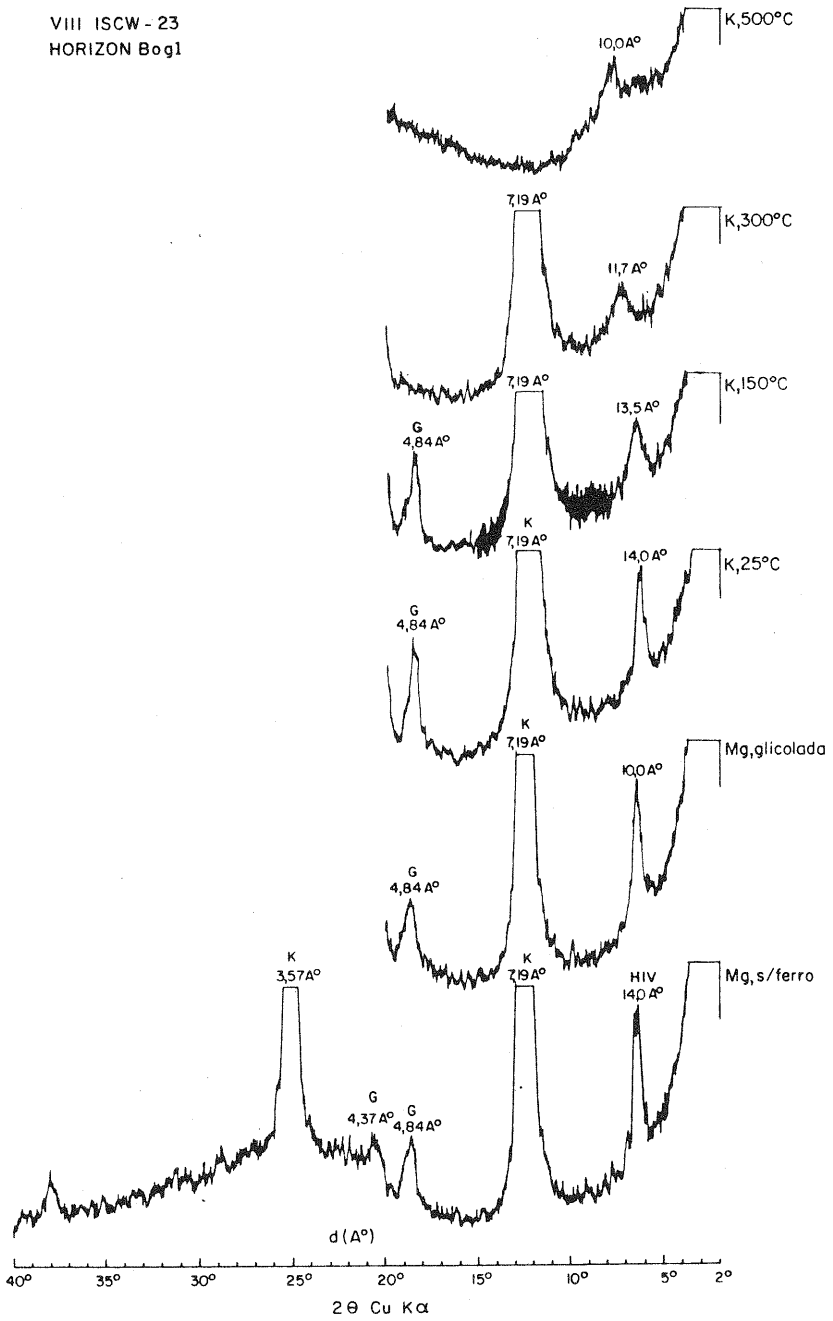


Fig. 26. X-ray diffraction patterns of the deferrified clay from Bog1 horizon of pedon 23 after Mg saturation and glycerol solvation, K saturation at room temperature (K 25°C), heating at 150°C, 300°C, and 500°C. Units of d spacing are in angstrom Å. Kaolinite (K); gibbsite (G); hydroxy-interlayered vermiculite (HIV).

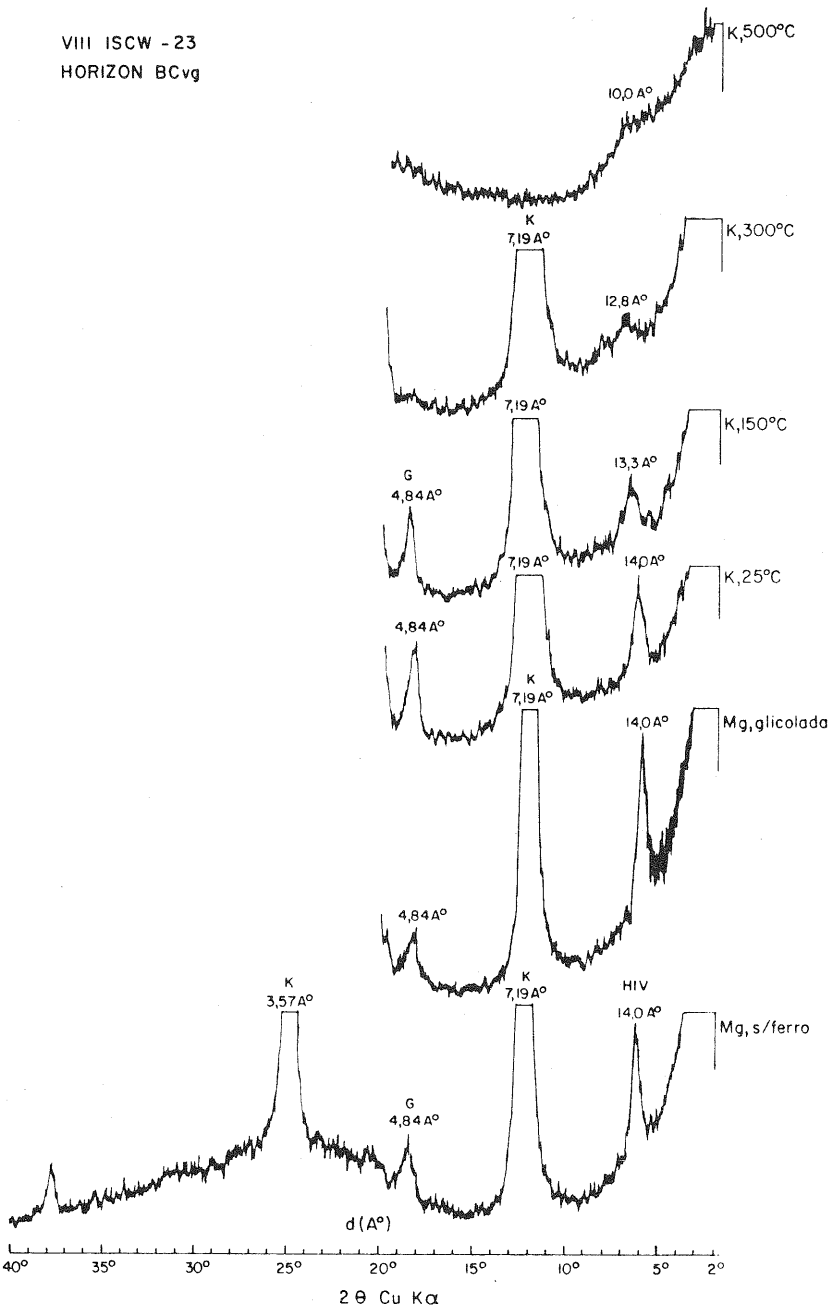


Fig. 27. X-ray diffraction patterns of the deferrified clay from BCvg horizon of pedon 23 after Mg saturation and glycerol solvation, K saturation at room temperature (K 25°C), heating at 150°C, 300°C, and 500°c. Units of d spacing are in angstrom Å. Kaolinite (K); gibbsite (G); hydroxy-interlayered vermiculite (HIV).

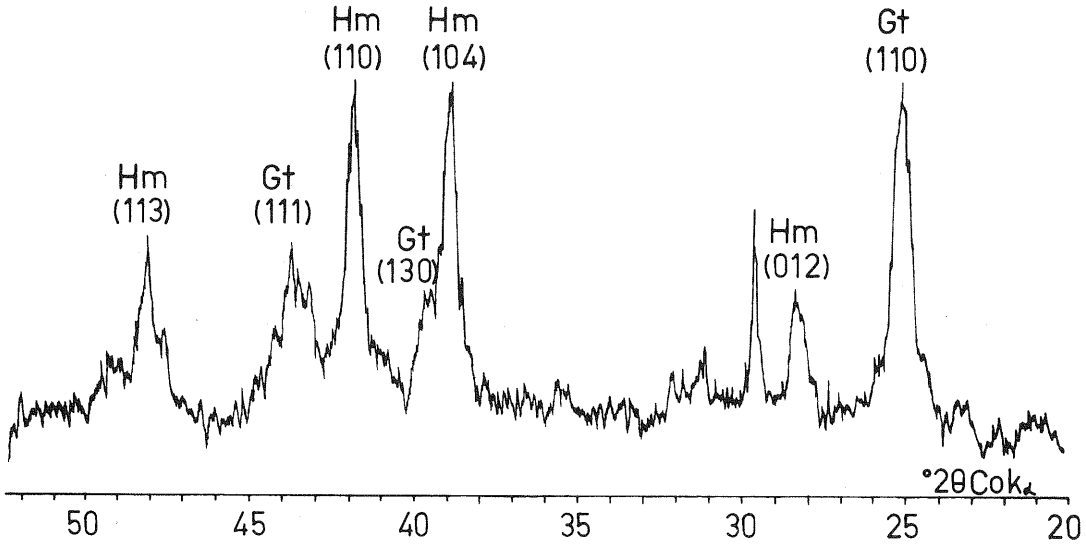


Fig. 3. X-ray diffractogram of 5M-NaOH treated clay fraction of Bo2 horizon of pedon 4 (sample 850632).

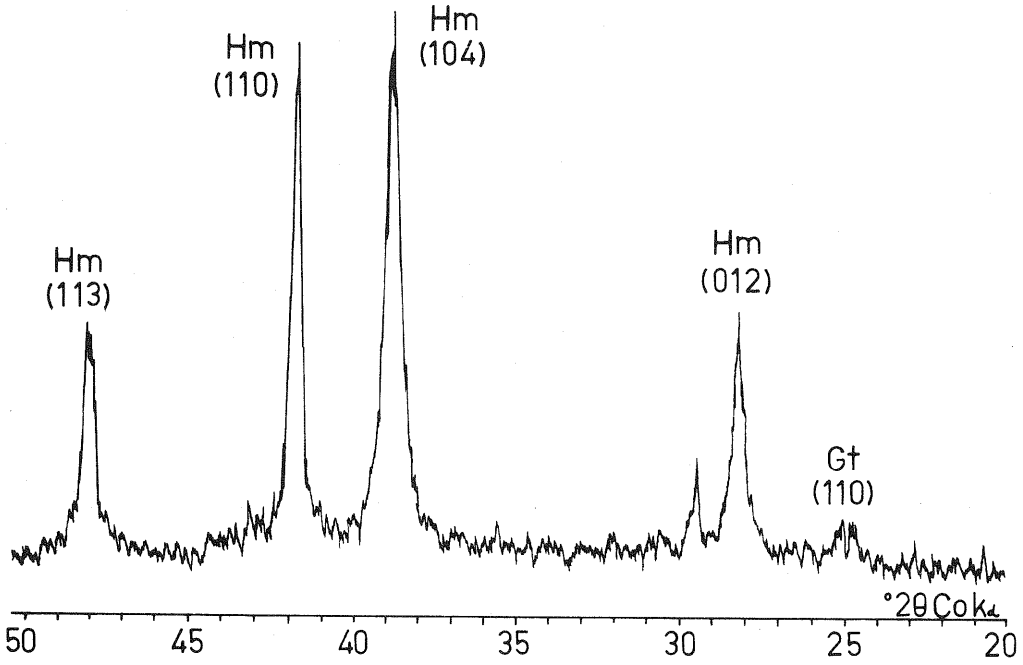


Fig. 4. X-ray diffractogram of 5M-NaOH treated clay fraction of Bo2 horizon of pedon 7 (sample 850655).

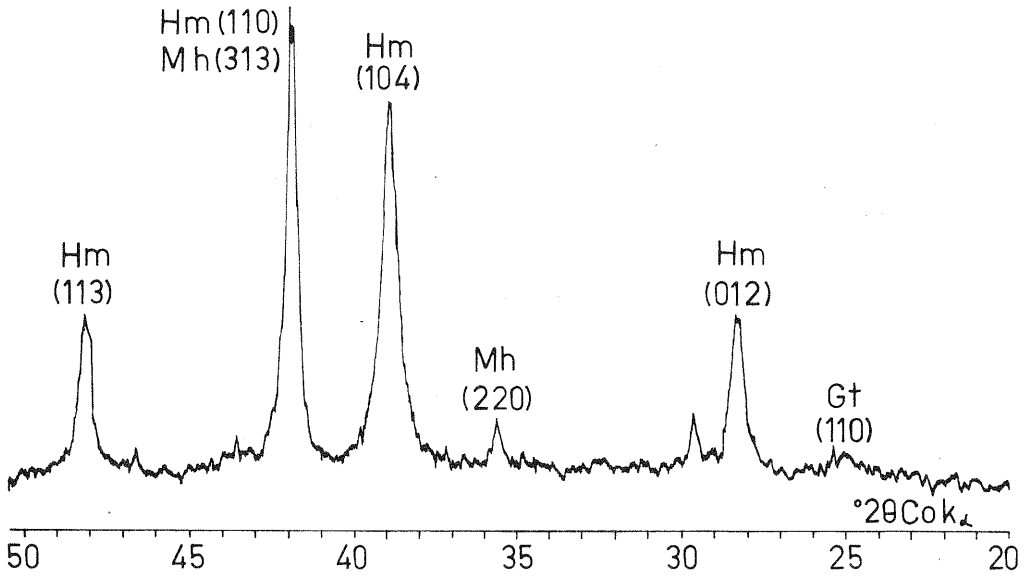


Fig. 5. X-ray diffractogram of 5M-NaOH treated clay fraction of Bo2 horizon of pedon 8 (sample 850661).

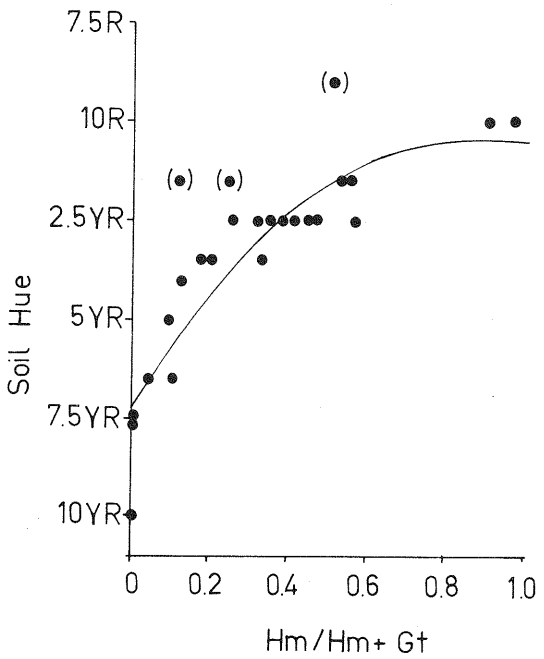


Fig. 6. Relationship of Hm/Hm+Gt ratio and moist hue (samples in brackets not included in the correlation; see text).

Table 1. Measured Volumetric Water Content (%) and Available Water in Bo1 or Bo2 or Bo3 Subhorizons of Oxisols

Pedon No. VIIIth ISCW	States[a]	Horizon	Volumetric water content 1/10	1/3	1	5	15	Available water 1/3 - 15
			bars					bars
			(%)					(mm/cm) (classes)
1	SP	Bo2	24.9	22.0	20.8	19.0	18.3	0.37 low
2	SP	Bo1	40.7	37.0	33.7	31.7	31.2	0.58 low
3	SP	Bo1	26.3	19.0	18.1	15.4	13.0	0.60 low
4	SP	Bo2	36.2	30.7	27.9	25.6	23.0	0.77 medium
7	SP	Bo2	37.4	35.1	33.6	29.4	28.0	0.71 medium
8	SP	Bo2	41.9	34.6	31.6	28.7	28.6	0.60 low
9	SP	Bo1	24.3	19.7	16.1	15.5	15.5	0.42 low
10	SP	Bo2	18.3	14.6	11.8	10.4	9.9	0.47 low
11	MG	Bo3	38.4	32.1	30.1	27.0	27.0	0.51 low
13	MG	Bo2	16.9	11.6	9.7	8.0	8.0	0.36 low
14	GO	Bo2	48.6	39.3	35.0	31.1	31.0	0.83 medium
17	GO	Bo3	27.7	23.4	20.8	20.1	19.9	0.35 low
18	GO	Bo	28.4	25.7	24.6	22.8	22.6	0.31 low
20	DF	Bo2	29.6	27.2	24.7	23.8	23.2	0.40 low
22	DF	Bo1	30.7	25.4	21.2	18.8	18.2	0.72 medium

[a] SP = São Paulo; DF = Distrito Federal; MG = Minas Gerais; GO = Goiás.
Source: SNLCS-EMBRAPA, Rio de Janeiro, Brazil.

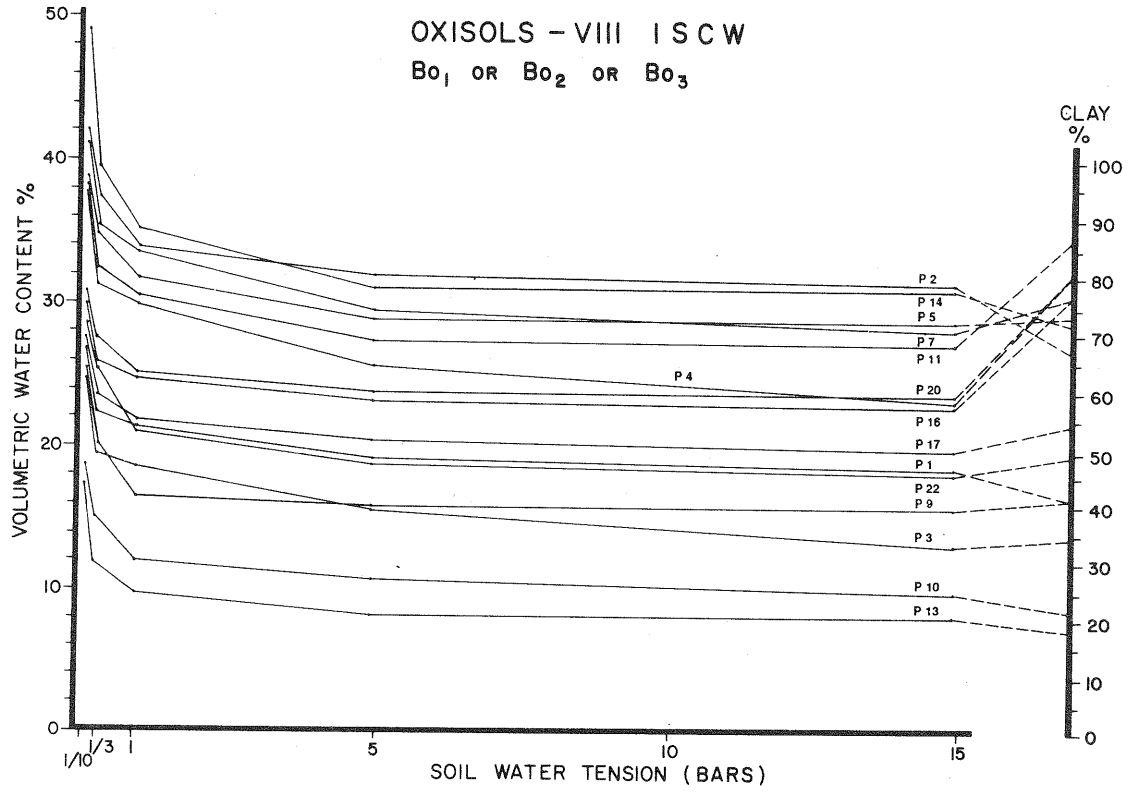


Fig. 1. **Volumetric water content % as a function of tension applied in the Bo1 or Bo2 or Bo3 subhorizons of medium and clayey textured Oxisols from Brazil.**

for the remaining 4 soil samples;

2. The shape of the volumetric water retention curves are similar, independent of the amount of total clay in the samples;
3. The tendency of volumetric water retention curves to become horizontal starts at 5 bars tension for almost all samples.

References

Empresa Brasileira de Pesquisa Agropecuária, Servico Nacional de Levantamento e Conservação de Solos. 1979. Manual de métodos de análise de solo. Rio de Janeiro, Brazil.

Richards, L.A. (ed.). 1954. Diagnosis and improvement of saline and alkali soils. Agric. Handb. no. 60. USDA. U.S. Govt. Printing Office, Washington, D.C.

U.S. Department of Interior. 1953. Irrigated land use: Land classification. *In* Bureau of Reclamaton Manual, v. 5, p.2. USDI. U.S. Govt. Printing Office, Washington. D.C.

Table 1. Data on Gravimetric Water for B Subhorizons of Oxisols Studied at the VIIIth ISCW

Pedon no. VIIIth ISCW	Horizon	Gravimetric Water Content							
		1/10 bar		1/3 bar		1 bar		15 bars	
		NSSL	SNLCS	NSSL	SNLCS	NSSL	SNLCS	NSSL	SNLCS
		(%)							
1	Bo2	20.1	19.9	17.6	17.6	15.6	16.6	14.5	14.6
2	Bo1	31.8	33.1	29.4	30.1	26.1	27.4	24.5	25.4
3	Bo1	18.8	20.4	15.2	14.7	13.2	14.0	11.3	10.1
4	Bo2	33.8	35.8	31.5	30.4	27.8	27.6	24.6	22.8
7	Bo2	34.1	32.0	32.1	30.0	25.8	28.7	23.6	23.9
8	Bo2	34.4	34.6	28.8	28.6	24.9	26.1	22.5	23.6
9	Bo1	21.2	19.6	16.4	15.9	13.3	13.0	12.2	12.5
10	Bo2	14.2	13.1	11.1	10.4	8.1	8.4	6.8	7.1
11	Bo3	35.7	37.6	33.4	31.5	27.9	29.5	26.0	26.5
13	Bo2	11.4	12.5	9.4	8.6	7.3	7.2	5.7	5.9
14	Bo2	34.0	39.2	31.4	31.7			24.6	25.0
17	Bo3	22.3	26.1	21.4	22.1	18.9	19.6	17.2	18.8
18	Bo	34.7	32.3	30.6	29.2	26.6	28.0	24.6	25.7
20	Bo2	34.0	33.3	31.8	30.6			24.8	26.1
22	Bo1	29.2	29.2	24.9	24.2	19.6	20.2	15.1	17.3

Source: NSSL, Lincoln, Nebraska, and SNLSC-EMBRAPA, Brazil.

Table 2. Correlation Coefficients for Pairs of Data at Four Tensions

X SNLCS	*Y* NSSL	Correlation Coefficient (*r*)
1/10 bar	1/10 bar	0.97
1/3 bar	1/3 bar	0.99
1 bar	1 bar	0.99
15 bars	15 bars	0.99

References

Empresa Brasileira De Pesquisa Agropecuária, Serviço Nacional de Levantamento e Conservação de Solos. 1979. Manual de Métodos de Análise de Solos. Rio de Janeiro, Brazil.

SMSS. EMBRAP. UPR. 1986. Tour guide. VIIIth International Soil Classification Workshop. Brazil.

Soil Conservation Service, USDA. 1967. Soil survey laboratory methods and procedures for collecting soil samples. USDA, SSIR 1. U.S. Govt.

WATER RETENTION IN B SUBHORIZONS OF SOME OXISOLS

L.B. Oliveira, J.C. Almeida, and J.L. Paula[1]

Abstract

Water retention at different tensions was determined in 15 B subhorizons (Bo1 or Bo2 or Bo3), previously selected from Brazilian Oxisols studied in the VIIIth International Soil Classification Workshop (ISCW). The volumetric water retention curves and the availability of water (calculated as the difference between the percent of water at 1/3 and 15 bars) are presented. It can be concluded that the volumetric water retention curves have similar shapes, independent of the amount of total clay in the samples; the curves become practically horizontal starting at the 5 bars tension in the majority of the samples. The amount of available water was low for 11 samples and medium for the remaining 4 samples.

The present study is a contribution to the VIIIth ISCW. Its main objective is to study the soil-water relationship in B subhorizons of Brazilian Oxisols selected for the VIIIth ISCW.

From the 24 soil profiles studied in the VIIIth ISCW, 15 classified as Oxisols were taken for the present study. From each soil profile the same subhorizon was studied by researchers of different areas of expertise. The data obtained in this study may be used along with that generated by other researchers to establish correlation with other physical, chemical, or mineralogical properties of the soil.

This study shows the data on soil-water relationships for only one subhorizon of each Oxisol sampled for the VIIIth ISCW. However, data on soil-water relationships for all soil horizons of the 15 Oxisols can be obtained from the authors if desired.

Materials and Methods

The soil analyses followed the methodology used by EMBRAPA (1979) as presented below in summarized form:

Bulk density: Determined by the core method or by the clod method.

Water retention at 1/10, 1/3, and 1 bar: The air-dried sieved samples (<2 mm) were put in a pressure cooker (Richards 1954) and desired pressure applied.

Water retention at 5 and 15 bar: Same as the previous procedure using a pressure apparatus and ceramic plate of 15 bars, applying the desired pressure.

Available water: The water retention difference between the volumetric water retained at 1/3 and 15 bars.

Classes of available water: For classification purposes the criteria suggested by the Bureau of Reclamation (U.S. Department of Interior 1953) were used:

Classes	*Available water*
low	< 0.60
medium	0.61 - 1.23
high	> 1.23

Results and Discussion

The data given in Table 1 show the measured volumetric water content percent at five different tensions (1/10, 1/3, 1, 5, and 15 bars) and the volumetric available water of 15 B subhorizons selected from profiles studied at the VIIIth ISCW.

The volumetric available water was low (0.37 to 0.60 mm/cm) for 11 (73 percent) of the 15 samples and medium (0.71 to 0.83 mm/cm) for the remaining 4 (27 percent) samples.

The moisture retention curves for the B subhorizons studied are shown in Figure 1.

The volumetric water retention curves shown in Figure 1 become horizontal starting at 5 bar tension. Only in pedon 9 and pedon 20 do the curves become horizontal starting at the 1 bar tension.

The most significant variations in volumetric water retention occur between 1/10 and 1/3 bar and between 1/3 and 1 bar tension for every sample studied.

Conclusions

Based upon the 15 soil subhorizons studied, the following conclusions can be made:

1. The available water was low for 11 samples and medium

[1] Authors are Soil Researchers at Servico Nacional de Levantamento e Conservação de Solos, Empresa Brasiliera de Pesquisa Agropecuária (SNLCS, EMBRAPA), Rua Jardim Botânico 1024. Rio de Janeiro, Brazil 22460.

Schwertmann and Kämpf 1985). The high Al substitution of goethite enhances the separation of the Gt (130) and Hm (104) peaks (Figs. 2, 3).

The lowest aluminum substitution of goethite occurs in the placic horizon and mottles of pedon 12 (Plinthaquox), and in the yellow spots of the petroplinthite nodules of pedon 19. The hematite with the lowest Al substitution occurs in the petroplinthite nodules of pedons 18 (Typic Acrohumox) and 19 (Typic Acrustox). The occurrence of high Al-substituted goethite (38 mole% Al) and hematite (12 mole% Al) in the clay fraction of pedons 18 and 19, and lower Al goethite (15 and 17 mole% Al) and hematite (3 and 8 mole% Al) in the petroplinthite nodules (Table 1) is an indication of the polygenetic nature of these soils.

Crystallinity

The width at half-height (WHH) 110 and 111 of goethite shows a broad range from 0.15 to 0.60°2θ and from 0.18 to 0.48°2θ respectively (Table 1). In most samples WHH 110 is smaller than WHH 111; this is common in natural goethites, and means no preferential crystal development in the three crystallographic directions (i.e., they have no acicular shape) (Schwertmann and Kämpf 1985). As aluminum substitution increases in goethite the particles become shorter and the acicular shape disappears (Schulze and Schwertmann 1984).

In samples from the Plinthaquox (pedon 12) the WHH 110 is broader than WHH 111 and may indicate some acicular shape for the goethite crystals; this could be related to a slower growing rate under hydromorphic conditions, and to the lower Al substitution.

In the few hematitic samples in which the WHH of hematite could be measured, the WHH 104 and 110 show a narrow range from 0.28 to 0.40°2θ and 0.13 to 0.18°2θ respectively. A WHH 104 broader than WHH 110 indicates that the hematite crystals are platy, which is commonly found in soil hematites (Schwertmann and Kämpf 1985).

Iron Oxides and Soil Color

Figure 6 shows that in most samples the Hm/Hm+Gt ratio of the clay fraction is related to the soil hue (data from the VIIIth ISCW tour guide) ($y = 7.42 - 16.4x^2$; $r^2 = 0.867$; $n = 22$). Exceptions are pedon 14 (sample 850706) in which the soil color is due to maghemite and hematite of the coarse fraction, whereas in the clay fraction goethite dominates over hematite; for samples 850863, 850684, 850753, and 850740 the reddish matrix and yellowish mottles (according to the profile descriptions) were not sampled separately, the Hm/Hm+Gt ratio represents the mixed sample. The saturation trend of the red color with increasing hematite proportions (Fig. 6) suggests the hue 2.5YR to separate goethitic (yellower than 2.5YR) from hematitic (2.5YR or redder) soils.

References

Curi, N. 1983. Lithosequence and toposequence of Oxisols from Goiás and Minas Geraís states, Brazil. Ph.D. thesis. Purdue Univ., Lafayette, Ind.

Kämpf, N., and U. Schwertmann. 1982a. The 5M-NaOH concentration treatment for iron oxides in soils. *Clays Clay Miner.* 30:401-408.

———. 1982b. Quantitative determination of goethite and hematite in kaolinitic soils by x-ray diffraction. *Clays Clay Miner.* 17:359-363.

Norrish, K., and R.M. Taylor. 1961. The isomorphous replacement of iron by aluminum in soil goethites. *J. Soil Sci.* 12:294-306.

Schulze, D.G. 1984. The influence of aluminum on iron oxides: VIII. Unit-cell dimensions of Al-substituted goethites and estimation of Al from them. *Clays Clay Miner.* 32:36-44.

Schulze, D.G., and U. Schwertmann. 1984. The influence of aluminium on iron oxides: X. Properties of Al-substituted goethites. *Clays Clay Miner.* 19:521-539.

Schwertmann, U., R.M. Fitzpatrick, R.M. Taylor, and D.G. Lewis. 1979. The influence of aluminium on iron oxides: 2. Preparation and properties of Al-substituted hematites. *Clays Clay Miner.* 27:105-112.

Schwertmann, U., and N. Kämpf. 1985. Properties of goethite and hematite in kaolinitic soils of southern and central Brazil. *Soil Sci.* 139:344-350.

COMPARISON OF GRAVIMETRIC WATER RETENTION AT DIFFERENT TENSIONS OBTAINED BY THE SNCLS-EMBRAPA AND NSSL-USDA LABORATORIES

L.B. Oliveira, J.C. Almeida, and J.L. Paula[1]

Abstract

Gravimetric water at different tensions was determined by the Soil Laboratory of the Serviço de Levantamento e Conservação de Solos, (SNLCS-EMBRAPA) and by the National Soil Survey Laboratory (NSSL-USA). Fifteen B subhorizons (Bo1 or Bo2 or Bo3) previously selected from Brazilian Oxisols studied during the VIIIth International Soil Classification Workshop (ISCW) were studied. The SNLCS soil laboratory used sieved samples and the NSSL used the clod method for determining the gravimetric water at 1/10 and 1/3 bar. The results for the soil studied are practically the same, as shown by the correlation coefficients ($r = 0.97$ and 0.99 respectively). For the gravimetric water retained at 1 and 15 bars, both soil laboratories used sieved samples, and the results once again were practically the same ($r = 0.99$ for both). In conclusion it can be said that for the B horizons of Oxisols similar results are obtained by the clod and by the sieved methods.

Data from 15 subhorizons (Bo1 or Bo2 or Bo3), one from each Brazilian Oxisol discussed and analyzed for the VIIIth ISCW, were taken for the present comparative study.

The analyses of the soil samples were simultaneously performed by both the soil laboratory of the SNLCS, EMBRAPA and the NSSL, Lincoln, Nebraska, United States.

The main objective of this paper is to compare the analytical results obtained by both laboratories which used different methodologies for 1/10 and 1/3 bar, and the same methodology for 1 and 15 bars.

Materials and Methods

Only B subhorizons of soil profiles classified as Oxisols, previously selected for the correlated studies beyond the routine analysis, were used.

The analytical procedure used by SNLCS is described in *Manual de Métodos de Análise de Solo* (EMBRAPA 1979), and the procedure used by NSSL is described in the Soil Conservation Service report (1976).

Water retention was determined by both laboratories at 1/10, 1/3, 1, and 15 bars. For the determination at 1/10 and 1/3 bar the NSSL used undisturbed samples (soil clods), while the SNLCS laboratory used sieved samples (fine-earth fraction). At 1 and 15 bars both laboratories used sieved samples.

Results and Discussion

The results obtained by both laboratories are presented in Table 1 and were taken from the paper "Water Retention in B Subhorizons of Some Oxisols" (Oliveira, Almeida, and Paula, this issue) and from the *Tour Guide* of the VIIIth ISCW.

The correlation coefficient for each tension is shown in Table 2. The results obtained permit the following comparison:

1. The water retained (percent weight) at 1/10 and 1/3 bar by the clod method (NSSL) and sieved sample method (SNLCS). For the Oxisols studied there is no significant difference between the two methodologies, and the correlation coefficients for the 1/10 and 1/3 bar are, respectively, $r = 0.97$ and $r = 0.99$.
2. The water retained (percent weight) at 1 and 15 bars by both laboratories using the same methodology (sieved samples). The analytical results and the respective correlation coefficient ($r = 0.99$ for both tensions) for 1 and 15 bars indicate that the results obtained by both laboratories are in perfect agreement.

Conclusions

For the Oxisols (B horizons) studied there is no significant difference, statistically speaking, between the clod method and the sieved method at 1/10 and 1/3 bar. For these soils, it seems advisable to use the sieved method at those tensions to save time and money. The results obtained by both laboratories for the water retained at 1 and 15 bars are in perfect agreement. There is no significant difference, statisticaly speaking, between them.

[1] Authors are Soil Researchers at EMBRAPA-SNLCS, Rua Jardim Botânico 1024. Rio de Janeiro, Brazil 22460.

THE RELATIONSHIPS OF SPECIFIC SURFACE AREA OF SOIL WITH SOME PHYSICAL PARAMETERS IN SUBHORIZONS OF BRAZILIAN OXISOLS AND OTHER ORDERS

J.L. Paula, L.B. Oliveira, and J.C. Almeida[1]

Specific surface area is an important soil property since most of the physical and chemical reactions occur at the surface of the soil.

The objectives of this work were to measure specific surfaces of several subhorizons of selected profiles for the VIIIth International Soil Classification Workshop (ISCW), with subsequent qualification and assessment of their relations with other physical properties of soils, and to extend the physical characterization of soils, aiming at their classification.

Materials and Methods

For the present paper 22 soil profiles, mostly of the order Oxisols from different regions, were studied. From each profile one subhorizon was taken and analyses performed.

The soil analyses followed the methodology used by EMBRAPA-SNLCS (1979) as presented below in summarized form.

1. Soil surface area: Measured by the EGME procedure of Heilmann, Carter, and Gonzalez (1965) simplified by Cihacek and Bremner (1979). The soil samples were crushed to pass a 0.25 mm screen and dried over P_2O_5 before exposure to EGME. All measurements were performed in triplicate.
2. Water retention at 1 bar: The air-dried, sieved samples (<2 mm) were put in retainer rings on the porous plate. Wet from below, excess water removed, put in a pressure cooker apparatus (Richards 1954), and submitted to 1 bar pressure.
3. Water retention at 15 bars: Same as previous procedure using a pressure plate apparatus (Richards 1954) and ceramic plate of 15 bars and submitted to 15 bars pressure.
4. Total clay: Determined by the modified hydrometer method (Vettori and Pierantoni 1968); no pretreatment to destroy organic matter.
5. Organic carbon: Determined by wet oxidation method with 0.4N $K_2Cr_2O_7$ (Tiurin method).

Results and Discussion

The data on specific surface area, percent of total clay and organic carbon, gravimetric water percent at 1 bar and 15 bars tension, and gravimetric water percent at 15 bars to specific surface ratio for the B subhorizons studied are given in Table 1.

Looking into the data it is seen that the specific surface varies from 25 to 125 m^2 per g. This large range of variation on specific surface is probably due to the combined effects of amount and activity of the organic and mineral colloids.

The linear relationship ($Y = a + bX$), where Y = soil properties and X = specific surface area of soil was observed. A highest correlation coefficient (0.9037 and 0.9090) significant at 1 percent probability was observed between surface area and moisture contents percent at 1 bar and 15 bars tension. Clay and organic matter contents in soil are the principal sources of its total specific surface area. Organic matter content being low in these soils (0.1 to 1.5 percent) was not found to be related with specific area. However, it was evident that clay content could be the only possible source of specific surface area in such soils as seen from a strong association ($r = 0.8796^{**}$) between these parameters.

Conclusions

Based upon 22 soil subhorizons studied, the following conclusions can be made:

1. There was great variability on specific surfaces due to clay content of soils;
2. There was close correlation of specific surface with 1 and 15 bars water content;
3. The relation 15 bars/St has shown great uniformity and, therefore, does not allow separation of soils in different groups.

[1] Authors are Soil Researchers at Serviço Nacional de Levantamento e Conservção de Solos, Empresa Brasilera de Pesquisa Agropecuária, (SNLCS-EMBRAPA). Rua Jardim Botânico 1024. Rio de Janeiro, Brazil 22460.

Table 1. Specific Surface, Organic Carbon, Total Clay, Gravimetric Water Percent at 1 Bar and 15 Bars, and Gravimetric Water Percent at 15 Bars to Specific Surface Ratio for the B Subhorizons Studied in the VIIIth ISCW, Brazil

Pedon number	States[a]	Soil horizons	Specific surface area (St)	Organic carbon	Total clay	Water retention		15 bars
						1 bar	15 bars	St
			(m^2/g)	(%)				
1	SP	Bo2	97	0.16	41	16.6	14.6	0.151
2	SP	Bo1	113	0.08	67	27.4	25.4	0.224
3	SP	Bo1	47	0.19	34	14.0	10.1	0.215
4	SP	Bo2	102	0.17	76	27.9	22.7	0.223
5	SP	Bto2	120	0.55	78	29.1	27.0	0.225
6	SP	Bo2	125	0.24	76	30.4	29.0	0.235
7	SP	Bo2	102	0.27	76	28.7	23.9	0.234
8	SP	Bo2	110	0.25	73	26.1	23.6	0.215
9	SP	Bo1	60	0.23	41	13.0	12.5	0.208
10	SP	Bo2	25	0.15	22	8.4	7.1	0.284
11	MG	Bo3	116	0.54	87	29.5	26.5	0.228
12	MG	Bov2	89	0.09	65	24.2	21.9	0.246
13	MG	Bo2	27	0.16	18	7.2	6.8	0.252
14	MG	Bo2	102	0.39	72	28.2	25.0	0.245
15	GO	Bto1	49	0.33	40	18.2	15.1	0.308
16	GO	Bto1	73	0.43	51	21.1	18.1	0.248
17	GO	Bo3	68	0.22	54	19.6	18.8	0.276
18	GO	Bo2	80	0.41	75	28.0	25.7	0.321
19	DF	BAc	103	0.82	83	28.8	26.4	0.256
20	DF	Bo2	95	0.87	80	27.8	26.1	0.275
22	DF	Bo1	72	0.69	48	20.2	17.3	0.240
23	DF	Bpg2?	106	0.41	60	25.1	22.7	0.214

[a] SP=São Paulo; MG=Minas Gerais; GO=Goiás; DF=Distrito Federal.

References

Bower, C.A. and F.B. Gscwend. 1952. Ethylene glycol retention by soils as a measure of surface and interlayer swelling. *Soil Sci. Soc. Amer. Proc.* 16(4):342-345.

Cihacek. L.J., and J.M. Bremner. 1979. A simplified ethylene glycol ether procedure for assessment of soil surface area. *Soil Sci. Soc. Amer. J.* 43(4):821-822.

Empresa Brasileira De Pesquisa Agropecuária. Serviço Nacional de Levantamento e Conservação de Solos. 1979. Manual de métodos de análise de solo. Rio de Janeiro, Brazil.

Heilman, M.D., D.L. Carter, and C.L. Gonzalez. 1965. The ethylene glycol monoethyl ether (EGME) technique for determining soil surface area. *Soil Sci.* 100(6):409-413.

Richards, L.A. (ed.). 1954. Diagnosis and improvement of saline and alkali soils. USDA Agric. Handb. no. 60. U.S. Govt. Printing Office, Washington, D.C.

Vettori, L., and H. Pierantoni. 1968. Análise granulométrica do solo; novo método para determinição da fração argila. Rio de Janeiro, Equipe de Pedologia e Fertilidade do Solo. Boletim Técnico 3. Ministério da Agricultura. EPE. EPFS. Brazil. 8 p.

OXISOLS OF DIFFERENT REGIONS

IMPACT OF THE ICOMOX PROPOSAL ON THE CLASSIFICATION OF SOILS OF THE UNITED STATES AND PUERTO RICO, THE TRUST TERRITORY, AND GUAM

J.E. Witty,[1] F.H. Beinroth,[2] and H. Ikawa[3]

Abstract

Thirty-nine soil series are classified as Oxisols, including 19 in Hawaii, 8 in Puerto Rico, 9 in the Trust Territory, and 3 in Guam. The soil moisture regimes of these soils are primarily udic and ustic; some are perudic, and one is torric. According to *Soil Taxonomy* (Soil Survey Staff 1975) they are included in the suborders of Humox, Orthox, Ustox, and Torrox.

Acceptance of the latest ICOMOX (International Committee on Oxisols) proposal (circular letter no. 16) would result in the reclassification of the Humox and Orthox as Udox where the moisture regime is udic, and as Perox where it is perudic. The Ustox and Torrox would remain the same in the suborder category but change at the lower levels.

Overall, the impact is positive, but it is largely confined to changes in nomenclature. The proposed changes will not precipitate the need for new series or the merging of existing series. A few series may require reclassification from Ultisols to Oxisols, because the proposed Oxisol key includes soils with 40 percent or more clay in the surface horizon which otherwise meet the criteria for Ultisols but have low activity clays and lack weatherable minerals.

The Soil Conservation Service, U.S. Department of Agriculture (SCS, USDA) is responsible for 39 soil series classified as Oxisols, including 19 in Hawaii, 8 in Puerto Rico, 9 in The Trust Territory, and 3 in Guam. The soil moisture regimes of these soils are primarily udic and ustic; some are perudic, and one is torric. According to *Soil Taxonomy* (Soil Survey Staff 1975) they are included in the suborders of Humox, Orthox, Ustox, and Torrox.

According to the latest ICOMOX proposal in circular letter no. 16, and as shown in Table 1, the Humox and Orthox would be reclassified as Udox where the moisture regime is udic, and as Perox where it is perudic. The Ustox and Torrox would remain the same in the suborder category but change at the lower levels. This means that all 39 series would have to be reclassified.

[1] National Leader for Soil Taxonomy, Washington, D.C.
[2] Professor, University of Puerto Rico, Mayaguez, Puerto Rico.
[3] Associate Soil Scientist, University of Hawaii, Honolulu, HI.

Discussion

Table 1 shows the distribution of the various taxa and the proposed changes. The proposed change from Orthox to Udox and Perox provides a consistent logic for differentiating suborders of Oxisols. The term *Orthox* implies that these are "the common ones," but Oxisols, having a ustic moisture regime, may be more common than those with a udic regime. The proposed suborders of Udox and Perox clearly differentiate between those soils with udic and those with perudic soil moisture regimes. The "loss" of the Humox suborder removes the taxa denoting appreciable amounts of organic matter, but with a "gain" in identification of the moisture regime.

At the great group level the greatest impact is the removal of the Gibbsi great groups and the addition of Kur great groups. This puts the mineralogical identity of Gibbsi into the family category where it is normally considered in *Soil Taxonomy*. Kur indicates a soil with 40 percent or more clay in the surface layer and a particle-size distribution that meets the clay increase requirement for a kandic horizon. Because the ICOMOX proposal includes these kinds of soils with Oxisols if they lack weatherable minerals, a few series currently classified as Ultisols may require reclassification to Oxisols.

The elimination of the tropepetic subgroups is welcomed since the term *tropeptic* has dual meaning, referring to either thickness of soil or strength of structure or both. The subjectiveness involved in determining the strength of soil aggregation has resulted in much uncertainty about placements. The tropeptic subgroups are split among typic, rhodic, humic, and lithic subgroups by the ICOMOX proposal for the soils considered in this paper. In the ICOMOX proposal the term *lithic* is used for soils that may be as deep as 125 cm to bedrock, which one might object to, especially since this subgroup usually identifies soils that are less than 50 cm thick. Besides the presence of dark red soil colors, rhodic subgroups indicate few accessory properties in a consistent manner and thus have limited interpretative value.

The introduction of the fine and very fine subclasses for the clayey particle-size class in Oxisols is meant to facilitate soil interpretations. Two thirds of the soil series have very fine

Table 1. Classification of the Oxisols of Guam, Hawaii, Puerto Rico, and The Trust Territory

Soil Series	Soil Taxonomy (1975)	ICOMOX (1986)
Atate (GU)	c, kaol, isohyp Tropeptic Eutrustox	f, kaol, isohyp Typic Eutrustox
Babelthuap (TT)	c, oxid, isohyp Haplic Acrorthox	f-lo, ferrit, isohyp Typic Kuriperox
Bayamon (PR)	c, oxid, isohyp Typic Haplorthox	v-f, kaol (or allic), isohyp Typic Hapludox (or Rhodic Eutrudox)
Catalina (PR)	c, oxid, isohyp Tropeptic Haplorthox	v-f, ferrit, isohyp Rhodic Hapludox
Cotito (PR)	c, kaol, isohyp, shallow Tropeptic Eutrorthox	v-f, ferrit, isohyp Lithic Eutrudox
Coto (PR)	c, kaol, isohyp Tropeptic Haplorthox	v-f, ferrit (or kaol), isohyp Typic Hapludox (or Typic Eutrudox)
Delicias (PR)	c, oxid, isohyp Typic Haplorthox	f, ferrit, isohyp Rhodic Hapludox
Gagil (TT)	c, oxid, isohyp Tropeptic Haplorthox	v-f, ferrit, isohyp Typic Haploperox
Halii (HI)	c, ferr, isother Typic Gibbsihumox	v-f, ferrit-gibb, isother Humic Akrudox
Hanamaulu (HI)	c, oxid, isohyp Tropeptic Umbriorthox	v-f, ferrit, isohyp Humic Akrudox (or Humic Kurudox)
Halemano (HI)	c, kaol, isohyp Tropeptic Haplustox	v-f, ferrit, isohyp Typic Eutrustox (or Rhodic Eutrustox)
Kahana (HI)	c, kaol, isohyp Tropeptic Haplustox	v-f, ferrit, isohyp Typic Eutrustox (or Rhodic Eutrustox)
Kahanui (HI)	c, ferr, isother Petroferric Acrohumox	v-f, ferrit, isother Petroferric Akrudox
Kapaa (HI)	c, oxid, isohyp Typic Gibbsiorthox	v-f, ferrit-gibb, isohyp Typic Akrudox
Koloa (HI)	c, kaol, isohyp, shallow Tropeptic Eutrustox	v-f, ferrit, isohyp Rhodic Euthrustox
Kunuweia (HI)	c, ferr, isother Plinthic Acrorthox	c-skel, ferrit, isother Plinthic Akrudox
Lahaina (HI)	c, kaol, isohyp Tropeptic Haplustox	v-f, ferrit, isohyp Typic Eutrustox (or Rhodic Eutrustox)
Lawai (HI)	c, oxid, isohyp Tropeptic Umbriorthox	v-f, ferrit, isohyp Humic Kurudox
Lihue (HI)	c, kaol, isohyp Tropeptic Euthrustox	v-f, ferrit, isohyp Rhodic Eutrustox
Mahana (HI)	c, oxid, isother Typic Acrohumox	v-f, ferrit, isother Rhodic Akrudox
Makapili (HI)	c, oxid, isohyp Tropeptic Umbriorthox	v-f, ferrit, isohyp Humic Akrudox
Matanzas (PR)	c, oxid, isohyp Tropeptic Eutrorthox	v-f, ferrit, isohyp Lithic Rhodic Eutrudox
Molokai (HI)	c, kaol, isohyp Typic Torrox	f, ferrit, isohyp Typic Eutrotorrox
Ngardok (TT)	c, oxid, isohyp Tropeptic Haplorthox	v-f, ferrit, isohyp Typic Haploperox
Ngatpang (TT)	c, halloy, isohyp Tropeptic Haplorthox	v-f, ferrit, isohyp Typic Haplorperox
Nipe (PR)	c, oxid, isohyp Typic Acrorthox	f (v-f), ferrit, isohyp Rhodic Akrudox
Niu (HI)	c, kaol, isohyp Tropeptic Haplustox	v-f, ferrit, isohyp Typic Eutrustox (or Rhodic Eutrustox)
Palau (TT)	c, halloy, isohyp Tropeptic Haplorthox	v-f, halloy, isohyp Typic Haploperox
Pooku (HI)	c, oxid, isohyp Typic Gibbsiorthox	v-f, ferrit-gibb, isohyp Typic Akrudo
Puhi (HI)	c, oxid, isohyp Tropeptic Eutrorthox	v-f, ferrit, isohyp Humic Alfic Eutrudox
Rakied (TT)	c-skel, oxid, isohyp Plinthic Acrorthox	c-skel, kaol, isohyp Plinthic Akroperox
Rosario (PR)	c, oxid, isohyp Tropeptic Haplorthox	f, ferrit, isohyp Lithic Rhodic Hapludox
Saipan (GU)	c, kaol, isohyp Tropeptic Eutrustox	f, ferrit, isohyp Typic Eutrustox
Umpump (TT)	c, oxid, isohyp, shallow Typic Gibbsihumox	f, gibb, isohyp, shallow Typic Akroperox
Wahiawa (HI)	c, kaol, isohyp Tropeptic Eutrustox	v-f, ferrit, isohyp Rhodic Eutrustox
Wahrekdam (TT)	c-skel, oxid, isohyp Plinthic Acrorthox	c-skel, kaol, isohyp Plinthic Akroperox
Wailuku (HI)	c, kaol, isohyp Tropeptic Haplustox	v-f, ferrit, isohyp Typic Eutrustox (or Rhodic Eutrustox)
Yap (TT)	c, mix, isohyp Tropeptic Eutrorthox	f, kaol, Typic Eutrudox
Yigo (GU)	c, gibb, isohyp Tropeptic Eutrustox	f-lo, gibb, isohyp Rhodic Eutrustox

Note: GU = Guam; HI = Hawaii; PR = Puerto Rico; TT = Trust Territory.
Abreviations: c = clayey, f = fine, ferrit = ferritic, gibb = gibbsitic, halloy = halloysitic, isohyp = isohyperthermic, isother = isothermic, kaol = kaolinitic, lo = loamy, mix = mixed, oxid = oxidic, skel = skeletal, v = very.

particle-size control sections. The remaining one-third is divided among the fine, clayey-skeletal and fine-loamy classes. No soils have been added as the result of expanding the course-loamy class. The three series for which Table 1 shows a change from clayey particle-size class to fine-loamy or clayey-skeletal have been reclassified on the basis of additional data and not as the result of the ICOMOX proposal.

Perhaps the mineralogy classes can also be improved through modifying the key by accommodating the kaolinitic class right after the halloysitic class and by introducing ferritic-halloysitic, ferritic-kaolinitic, and mixed classes. As it now stands, it may be possible to have a kaolinitic class with a low percentage of kaolinite. On the other hand, it is questionable whether mineralogy classes should be developed and approved in isolation from other orders. It might result in considerable disruption if these mineralogy classes were approved and applied in other orders without revising all mineralogy classes.

Dual ICOMOX classifications are presented for several series. These placements are supported by analytical and morphological evidence (Soil Survey Staff 1967, 1976, and unpubl. SCS data). It may also be noted that the soils mapped as Bayamon sandy clay loam include a soil that has been classified as a fine-loamy, mixed, isohyperthermic Ultic Haplorthox (Beinroth 1982). This soil would no longer qualify as an Oxisol and would become a Kandiudult according to the ICOMLAC (International Committee on Low Activity Clays) proposal.

Summary

The impact of the ICOMOX proposal on the Oxisols of the United States, Puerto Rico, The Trust Territory, and Guam is as follows:

1. Properties associated with the Humox will not be recognized in the taxonomic names unless there is an umbric epipedon and the humic subgroup is so identified. General soil interpretation based on the presence of organic C and related accessory properties will have to be made from the laboratory data rather than from the taxonomic names.
2. Properties expressed by the Gibbsi great groups may not be recognized at levels above the family. Soil interpretation based on taxonomic names, as far as it is influenced by significant amounts of gibbsite, will have to be made at the family rather than the great group level.
3. Kaolinitic properties are less emphasized than the ferritic properties, so there is a need to introduce ferritic-kaolinitic, ferritic-halloysitic, and mixed classes and to rearrange the position of the kaolinitic class in the family key. The presence of a ferritic-kaolinitic class will, for example, aid in making interpretation of the degree of P retention in the different kinds of Oxisols.
4. Deleting the tropeptic subgroups will mean an improvement because the criteria used in their definition cannot be applied consistently.
5. Overall the impact is largely confined to changes in nomenclature. The proposed changes will not precipitate the need for new series or for the merging of existing series. A few series, however, may require reclassification from Ultisols to Oxisols if they have 40 percent or more clay in the surface horizon, contain low activity clays, and lack weatherable minerals.

References

Beinroth, F. H. 1982. Some highly weathered soils of Puerto Rico. 1. Morphology, formation and classification. *Geoderma* 27:1-73

Soil Survey Staff, SCS, USDA. 1967. Soil survey laboratory data and descriptions for some soils of Puerto Rico and the Virgin Islands. USDA, SCS, in coop. with Puerto Rico Agric. Exp. Sta., SSIR no. 12. 191 pp.

———. 1975. Soil taxonomy. USDA Agric. Handb. no. 436. U.S. Govt. Printing Office, Washington, D.C.

———. 1976. Soil survey laboratory data and descriptions for some soils of Hawaii. USDA, SCS. in coop. with Hawaii Agric. Exp. Sta. and Hawaiian Sugar Planters Assoc., SSIR no. 29. 208 pp.

EVALUATION OF THE ICOMOX PROPOSAL IN THE VENEZUELAN CONTEXT

R. Schargel[1] and J. A. Comerma[2]

Abstract

Oxisols together with Ultisols, Alfisols, and Inceptisols with low activity clays cover approximately 25 percent of the surface area of Venezuela. Their classification will be deeply affected by the changes proposed by ICOMOX (International Committee on Oxisols). Positive changes are the following:

1. Reduction of the minimum clay content of the oxic horizon to 8 percent.
2. Establishment of the Perox suborder based upon the perudic moisture regime.
3. Color criteria to define rhodic, xanthic, and typic subgroups.
4. Definition of the humic subgroups.
5. Substitution of the oxidic family criteria by ferritic, gibbsitic, and ferritic-gibbsitic.
6. Greater consistency in the separation of Oxisols from Ultisols and Alfisols with low activity clays, by relying on a sharp clay increase with depth, instead of the presence of clay skins.

An important negative change is related to a pronounced decrease of the area occupied by Oxisols, as a result of using sharp clay increase with depth as a dominant criterion. This is considered particularly unfavorable for soils with the extremely low cation exchange capacity of the Acr great groups, where clay increase with depth does not seem to be as important for soil management as the very low cation exchange capacity and other related properties.

Venezuela covers an area of about 912,000 km^2 between latitudes 0°43'N and 12°12'N and longitudes 59°48'W and 73°25'W. It is a country characterized by a great diversity of landscapes and soils. To the north and northwest, mountain ranges (Coast, Perijá, Andes) with elevations up to 5000 m, have an abrupt relief and deep valleys, while hills and mountains which seldom exceed 1200 m characterize the Falcon Region. These elevated areas surround structural depressions, the largest being the Maracaibo Lake Basin (Fig. 1).

Southward, the Guayana Highlands occupy 45 percent of the country. It is an ancient shield, characterized by undulating to rolling peneplains to the north, west, and southwest. Toward the south and southeast, relief is more rugged, showing massive tablelands or mesas with maximum elevations close to 3000 m. Between the mountain ranges and the Guayana shield, the plains or *llanos* and the Orinoco Delta occupy about one-third of the country. Mostly at less than 200 m above sea level, they are to a large extent covered by Pleistocene and Holocene alluvium and some wind-blown sediments.

The climate of the country is influenced both by latitude and physiography. Mean annual rainfall varies between 300 mm along the coast and 4000 mm in southern Venezuela. In the *llanos* and the northern Guayana shield, mean annual rainfall is mostly between 1000 and 2000 mm, with distinct wet and dry seasons. The mountain ranges and associated depressions show great climatic variability with mean annual rainfall between 400 and 3000 mm.

With increasing precipitation, vegetation varies from semidesert, thornbush to deciduous, semievergreen and evergreen forests. Large areas of the *llanos* and the northern Guayana Highlands are covered by savanna vegetation of edaphic, paleoclimatic, and man-made origin.

Comerma (1971) indicated the soils belonging to the 10 orders of *Soil Taxonomy* are found in the country. Within the Oxisols, Ustox and Orthox are the most important suborders followed by Aquox.

Oxisols, together with Ultisols, Alfisols, and Inceptisols with low activity clays, probably cover about 25 percent of the surface area of the country, with most of them located in the Guayana Highlands. Marked changes in the classification of these soils will originate from the modifications proposed by ICOMOX, as presented by Buol (1986). Evaluation of the ICOMOX proposal will be considered in this paper from the viewpoints of soil survey, interpretations, and soil genesis.

Classification of Oxisols in Venezuela

The 7th Approximation of the new soil classification, developed by the Soil Survey Staff (SCS, USDA) and published

[1] Professor of Soils, Universidad Nacional Experimental de los Llanos Occidentales Ezequiel Zamoro (UNELLEZ), Venezuela.
[2] Senior Research Scientist, CENIAP-MAC (Centro Nacional de Investigaciones Agropecuarias), Maracay, Venezuela.

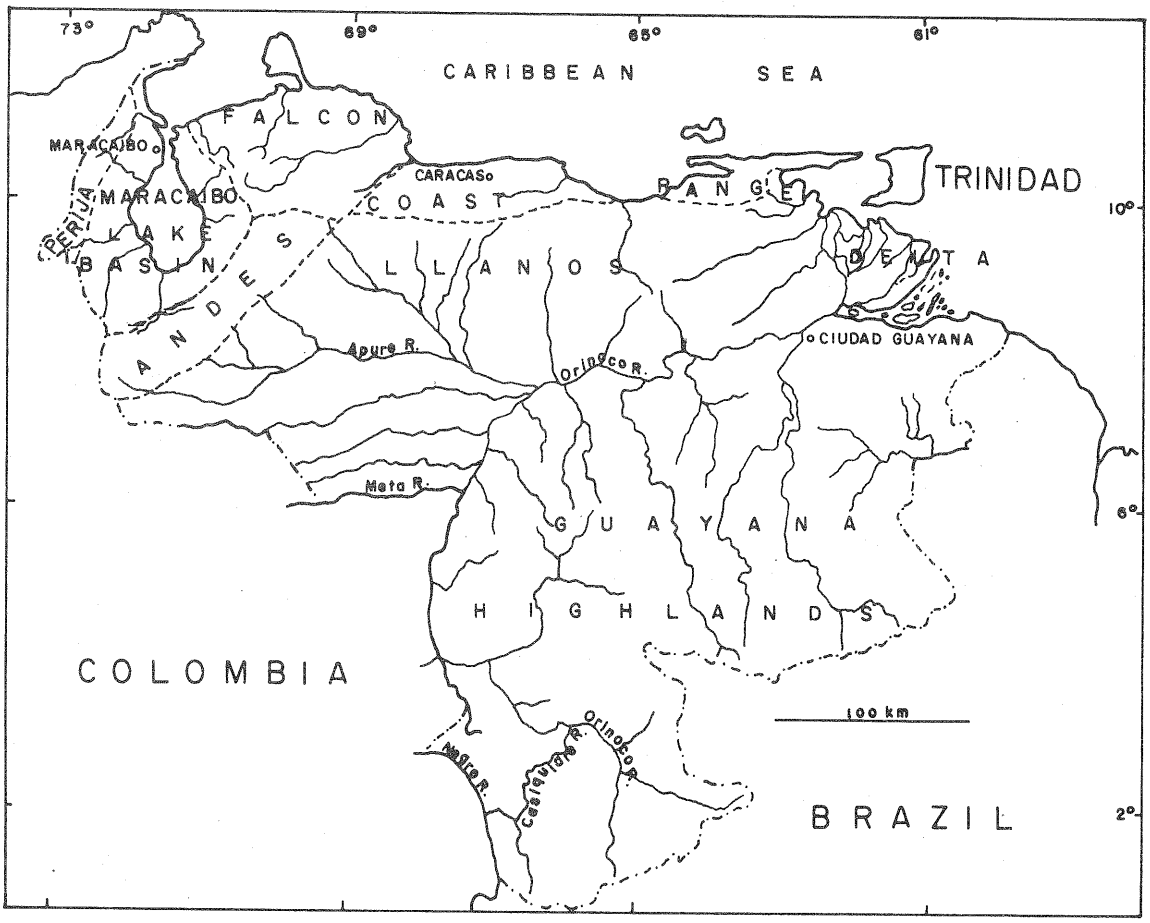


Fig. 1. Physiographic provinces of Venezuela.

in 1960, was immediately applied in Venezuela. The application of this system coincided with a period of rapid expansion of soil survey. Better profile descriptions, more precisely defined soil series, the utilization of phases of subgroups and great groups to define mapping units in small scale surveys, and improved soil correlation were the main inputs of the new soil classification to the Venezuelan soil survey.

The following statements in the 7th Approximation favored the placement within the Oxisol order of all soils with a clay fraction dominated by a mixture of free sesquioxides and 1:1 lattice clays:

1. "It should be pointed out that an oxic horizon may occur in the same profile with an argillic horizon, and that the oxic horizon may contain an argillic horizon."
2. "The oxic horizon can conceivably include an argillic horizon consisting of 1:1 lattic clay and free oxides."
3. "The Oxisols....They may have argillic horizon."

Furthermore, Oxisols keyed out above Ultisols and Alfisols.

This approach to the classification of soils with low activity clays is favored by most Venezuelan soil scientists because it is well adapted to the soils of the country. In fact, considering genesis and geographic distribution, these soils predominate in the Guayana Highlands on deeply weathered parent materials, or on alluvium and colluvium derived thereof. In the northern half of Venezuela, they occupy mostly middle to early Pleistocene alluvial terraces, fans, and tablelands. Old age or strongly weathered parent materials are the factors of their formation.

From the point of view of their use, these soils were mostly under extensive grazing or the extraction of forestry products. Only recently have they been used for crop production, with the application of fertilizers and lime. The low activity of the clay fraction and associated characteristics are considered of prime importance for soil management, because low activity usually implies low base saturation as well.

Furthermore, the grouping of all soils with low activity clays and few weatherable minerals at the order level is advantageous for soil survey, because the identification of the argillic horizon becomes less crucial. Work in Venezuela has shown difficulties in the consistent identification of the argillic horizon in strongly weathered soils (Schargel 1977).

The 1967 Supplement to the 7th Aproximation excluded from the oxic horizon clay skins associated to clay increases with depth (Soil Survey Staff 1967). This created considerable trouble in the classification of Oxisols, and of Ultisols and

Alfisols with low activity clays, due to difficulties in the consistent identification of clay skins in the field, and the lack of facilities for thin section production in Venezuela. However, in case of doubt, the Oxisol classification was usually preferred.

Soil Taxonomy of 1975 does not show great changes in the classification of Oxisols when compared to the 1967 Supplement (Soil Survey Staff 1975). Some great groups and subgroups were added. Among the latter the ultic subgroups recognize that some Oxisols might have relatively sharp clay increases with depth. However, the key states that to classify a soil as an Oxisol, the oxic horizon should not be overlain by an argillic or natric horizon. This has been interpreted in the sense that in Oxisols the clay increase should not be associated with evidences of illuviation. Or if an argillic horizon is present, it should be underneath the oxic horizon. In the latter case the oxic horizon would occupy the position of an eluvial horizon, a situation which can be found in soils on the tablelands of the eastern *llanos*.

In conclusion, changes in *Soil Taxonomy* since the 7th Approximation have reduced the area occupied by soils classified as Oxisols in Venezuela and also have complicated consistent placement of soils into this order.

Evaluation of the ICOMOX Proposal

Definition of the Oxic Horizon

The ICOMOX proposal includes the following changes in the definition of the oxic horizon:

1. The minimum clay content of the oxic horizon decreases from more than 15 to 8 percent. This modification allows to be classified as Oxisols deep, strongly weathered sandy loams, with less than 15 percent clay. Presently, these soils have to be classified as Ustorthents in spite of the fact that genesis and response to management are similar to associated Haplustox, with slightly higher clay contents. Soils with these characteristics are important on the early Pleistocene tablelands of the eastern *llanos*, where they occur together with Paleustults and Quartzipsamments (Comerma and Chirinos 1976; Luque 1975).
2. The oxic horizon must have a diffuse upper textural boundary, with a relative increase in clay content of less than 20 percent, within a vertical distance of 15 cm. At the present time sharp clay increases are allowed in oxic horizons as long as clay skins are not present. This change is the result of work done by the International Committee on the Classification of Alfisols and Ultisols Dominated by Low Activity Clays (ICOMLAC), under the leadership of Frank Moormann. This committee proposed the definition of the kandic horizon, based upon low cation exchange capacities and sharp clay increases with depth. Many of the oxic horizons in Venezuela have these characteristics. Consequently, soils will be excluded from the Oxisol order.
3. The maximum content of weatherable minerals in the 50-250 micron fraction has to be less than 10 percent. The present definition requires less than 3 percent weatherable minerals in the 20-200 micron fraction, but allows as much as 6 percent of muscovite. This change will have little influence on the classification of Venezuelan soils, because low activity of the clay usually is accompanied by very low levels of weatherable minerals in the sand fraction.
4. The maximum apparent ECEC (NH_4 OAc exchangeable bases plus N KCl extractable Al per 100 g clay) increases from 10 me to less than 12 me, while the maximum apparent CEC7 (CEC per 100 g clay by ammonium acetate pH 7) remains equal or less than 16 me. Also the oxic horizon has to meet the requirements of only one of these measurements, instead of both of them. These changes, in addition to augmenting the possibilities of recognizing soils with this diagnostic horizon, reduce the need to determine the NH_4OAc CEC. An apparent CEC7 to 16 me per 100 g clay usually corresponds to less than 10 me per 100 g clay of apparent ECEC in oxic horizons of Venezuelan soils.

Rock fragments are limited to less than 85 percent by volume. This additional criteria does not seem to affect a large area of soils.

Key to the Oxisol Order

The following changes are included in the ICOMOX proposal:

1. Oxisols are no longer defined on the basis of an aquic moisture and plinthite that forms a continuous phase within 30 cm of the soil surface. This change will not affect many soils in Venezuela. It appears that continuous plinthite is not very common anyhow and less so at shallow depth (Daugherty 1975).
2. Soils with less than 40 percent clay in the upper 18 cm after mixing, that have an oxic horizon with an upper boundary within 1 m of the soil surface, are not classified as Oxisols if they have the sharp clay increases of a kandic horizon, or an argillic horizon within a depth of 2 m. This change will increase the area occupied by Ultisols at the expense of Oxisols.

In the northern half of Venezuela Oxisols as presently defined occupy less than 10,000 km^2. Most of these soils do not have the sharp clay increase with depth of the kandic horizon, and would remain within the Oxisol order (Comerma 1968; Comerma and Chirinos 1976; Ochoa 1983; Westin 1962). Clay increases with depth, sufficiently large for an argillic horizon, are common in these soils in which case clay skins are absent or very scarce. On the other hand, clay skins are readily observed in associated Ultisols in which sharp clay increases with depth are common (Comerma and Chirinos 1976; Schargel 1977).

Oxisols are extensive in the Guyana Highlands, many showing the sharp clay increase with depth of the kandic horizon and few or no clay skins in the field. Of 63 profiles of Oxisols described during surveys in the Venezuelan Amazon Territory, 51 showed sharp clay increases, most of them with the very low CEC of the Acr great groups. Micromorphological studies have shown the absence of clay skins in many but not all of these soils (Schargel 1977). Similar soils have been classified as Oxisols and Ultisols in different soil surveys, due to oxic

properties combined with clay increases with depth, and difficulties in identifying clay skins consistently in the field (Schargel and Buol 1978).

The ICOMOX proposal would reduce this confusion by relying upon clay increase to separate Oxisols from Ultisols and Alfisols with low activity clay. From the point of view of soil genesis, the ICOMOX proposal based upon differing rates of change of clay content with depth would separate soils in which similar processes have operated, mainly leaching and desilication. The textural changes with depth in these soils are often related to local phenomena, like the deposition of a colluvial mantle, or erosion. Consequently, small and medium scale soil maps will show association of great groups or subgroups of both Oxisols and Ultisols, where originally only Oxisols were mapped.

Considering soil management, the sharp clay increase with depth will group in many cases soils with similar management requirements that were previously separated based upon the presence or absence of clay skins. However, many soils of the Guayana Highlands have the extremely low cation exchange capacity characteristic of the Acr great groups of the Oxisols, with or without sharp clay increases with depth and with medium to fine textured surface horizons (Blancaneaux, Hernández, and Araujo 1977; Blancaneaux, Araujo, and Pouyllau 1981; Blancaneaux and Dubroeucq 1983; Dubroeucq and Sanchez 1981; Hermoso and Dubroeucq 1978; Padilla 1984; Schargel 1977). These soils usually have high contents of gibbsite or iron oxides, although some are dominated by kaolinite with relatively low levels of oxides (Alegría and Comerma 1982; Padilla and Elizalde, in press; Schargel 1977). In the latter case it appears that a high degree of crystallinity of the kaolinite could account for the very low cation exchange capacity (Alegría and Comerma 1982).

These soils have very high infiltration rates, low water holding capacities, and show considerable resistance to erosion (Padilla and Elizalde, in press; Páez 1985). Cation exchange capacity is very much dependent on the organic matter, with little influence of the clay content. Clay increase with depth is less meaningful in these soils. It seems reasonable to classify these soils as Oxisols, even when the texture of the surface horizon is not fine, by allowing the very low cation exchange capacity to override the sharp clay increase with depth.

Oxisol Suborders and Great Groups

Aquox. Changes in the definition of this suborder include the utilization of a hue of 2.5Y or yellower, together with mottles and saturation with water at shallow depth. On the other hand, plinthite at shallow depth is not part of the new definition. Soils belonging to this suborder have been described in Venezuela (Padilla 1984; Schargel 1976; Westin 1962). However, due to their poor drainage, only descriptions of borings with few analyses are often available. Consequently, it is not possible at the time to test the proposal in the country. It appears that they will be most extensive in the southern half of the Guayana Highlands, mostly with little or no plinthite. The most common great groups will be the Umbraquox and Ochraquox.

Torrox. No changes have been proposed in the definition of this suborder. A few Torrox probably exist on Pleistocene terraces in the arid valleys of the Falcon Region.

Humox. This suborder has been eliminated by the proposal, with few consequences for Venezuela. Humox could only be found above 1000 m over sea level.

Ustox. These are the dominant Oxisols in the northern half of Venezuela, especially on the pleistocene tablelands of the eastern *llanos* (COPLANARH 1974) and the northern part of the Guayana Highlands (Schargel, Gonzalez, and Strebin 1980). The ICOMOX proposal removes the Sombriustox great group, which had not been described in Venezuela, and adds the Kurustoxs, based upon a sharp clay increase with depth and more than 40 percent clay in the surface horizon. Haplustox is the most extensive great group. Acrustoxs are important in the Guayana Highlands, where also some Kurustoxs will be found. Eutrustox are rare.

Perox. This new suborder has a perudic moisture regime. Soils with these characteristics are important in the southern part of the Guayana Highlands. Most of them will belong to the Akroperox and Haploperox great groups. The introduction of the Perox suborder is significant for land use, and also has genetic implications. Gibbsite tends to increase from the ustic to the perudic soil moisture regime.

Udox. Similar to the previously defined Orthox, minus Oxisols with a perudic soil moisture regime. The ICOMOX proposal does not provide equivalents for the Sombriorthox and Gibbiorthox. Only the latter has been mapped in Venezuela, within the Guayana Highlands. However, the gibbsite content of the concretions usually has not been reported (Padilla 1984). The great group of the Umbriorthox has also been dropped. Its place will be taken by the humic subgroups. Hapludox and Acrudox are the most common great groups and are mostly found in the Guayana Highlands. Small areas of Hapludox have been mapped on remnants of Pleistocene alluvial fans in the eastern piedmont of the Andes (Ochoa 1983). The newly defined Kurudox will be common and Eutrudox very rare.

Subgroup and Family Criteria

New subgroup criteria that will be common in Venezuelan Oxisols are xanthic for yellow color and rhodic for dark red. The use of color for the classification of Oxisols seems advantageous from the points of view of soil survey, genesis, and interpretations. Color is easy to map and is related to differences in parent material, topographic position, or moisture regime. Although little data is available on the management of Venezuelan Oxisols, the rhodic criteria often seems to relate to the Oxisols better for crop production, even when they have the characteristics of the Acr great group.

The humic subgroups are based upon the presence of a mollic or umbric epipedon. However, many Oxisols which do not meet the color reqirements of these epipedons have high levels of organic carbon in the upper part of the profile. It seems advisable to broaden the humic criteria using the definition of the Umbriorthox by adding: "or an ochric epipedon that has

more than 1 percent organic carbon in all subhorizons to a depth of 75 cm or more below the mineral soil surface."

The objective of this modification is to include in the humic subgroups all the better drained Oxisols with a relatively high level of organic matter, significant to soil management, in the upper part of the profile.

Improvements are evident in the mineralogy classes of the ICOMOX proposal, with different levels of iron oxide content, gibbsite, and combinations thereof. The oxidic family will be separated into ferritic, gibbsitic, and ferritic-gibbsitic. These are common mineralogy classes of Oxisols of the Guayana Highlands. Ferruginous with more than 40 percent iron oxide is rare. Kaolinitic Oxisols are the most extensive. The allic mineralogy class has important management implications due to high levels of exchangeable aluminum. It is rather uncommon. No data are available on a halloysitic mineralogy class.

Conclusions

The evaluation of the ICOMOX proposal in the Venezuelan context shows positive and negative aspects. Among the positive are the following:

1. Reduction of the minimum clay content of the oxic horizon to 8 percent.
2. Establishment of the Perox suborder based upon the perudic moisture regime. A similar approach seems convenient for the ICOMLAC proposal, with the definition of the Kandiperults and Kanhaploperults.
3. Color criteria to establish the rhodic, xanthic, and typic subgroups.
4. Definitions of the humic subgroups, which can be used in all the great groups of the Ustox, Udox, and Perox. This definition should be broadened to include Oxisols with an ochric epipedon that has more than 1 percent organic carbon, to a depth of 75 cm or more below the mineral soil surface.
5. Substitution of the oxidic family criteria by ferritic, gibbsitic, and ferritic-gibbsitic, based upon moderately high levels of gibbsite and iron oxides.
6. Greater consistency during soil survey in the separation of Oxisols from Ultisols and Alfisols with low activity clays, by relying on a sharp clay increase with depth, instead of the presence of some clay skins.

The negative aspect is related to a pronounced decrease of the area occupied by Oxisols, especially in the Guayana Highlands, as a result of utilizing the sharp clay increase with depth as a dominant criterion. This is considered particularly unfavorable for soils with the extremely low cation exchange capacity of the Acr great groups. In these soils, clay increase with depth does not seem to be as important for soil management as the very low cation exchange capacity and other related properties. If this characteristic is not used to override the sharp clay increase with depth, and to classify these soils as Oxisols, then acric subgroups should be established in the ICOMLAC proposal for Alfisols and Ultisols.

References

Alegría, M., and J.A. Comerma. 1982a. Características mineralógicas de oxisoles venezolanos. VII Congreso Venezolano de la Ciencia del Suelo. San Cristóbal. 40 p.

———. 1982b. Relación entre la capacidad de intercambio catiónico y la mineralogía en oxisoles. VII Congreso Venezolano do la Ciencia del Suelo. San Cristobal. 26 p.

Blancaneaux, P., J. Araujo, and M. Pouyllau. 1981. Estudio geomorfo-pedológico preliminar del secto Asita-Cacuri-Paru, Alto Ventuari, Territorio Federal Amazonas. Serie Informes Técnicos OGSIIA/IT/72. MARNR, Caracas, Venezuela. 104 p.

Blancaneaux, P., and D. Dubroeucq. 1983. Características edáficas y ambientales del área muestra Maroa-Yavita. Serie Informes Técnicos OGSIIA/IT/128. MARNR, Caracas, Venezuela. 45 p.

Blancaneaux, P., S. Hernández, and J. Araujo. 1977. Estudio edafológico preliminar-Sector Puerto Ayacucho, Territorio Federal Amazonas. Serie Informes Científicos OGIIA/IC/01. MARNR, Caracas, Venezuela. 120 p.

Buol, S.W. 1968. ICOMOX Circular Letter no. 16. January 1986.

Comerma, J.A. 1968. Pedogénesis de dos asociaciones de suelos en el nor-centro de Venezuela. *Agronomía Tropical*, 18:3-56.

———. 1971. La 7a Aproximación y los suelos venezolanos. *Agronomía Tropical* 21:365-377.

Comerma, J.A., and A.V. Chirinos. 1976. Características de algunos suelos con y sin horizonte argílico en las mesas orientales de Venezuela. Centro Nacional de Investigaciones Agropecuarias. Maracay, Venezuela. 29 p.

COPLANARH. 1974. Regiones Centro Oriental y Oriental. Inventario Nacional de Tierras. Publicación No. 35. Comisión del Plan Nacional de Aprovechamiento de los Recursos Hidráulicos. Caracas, Venezuela. 415. p.

Daugherty, L.A. 1975. Characterization of some plinthitic soils on alluvial landforms in Venezuela. Ph. D. thesis. Cornell Univ., Ithaca, NY. 350 p.

Dubroeucq, D., and V. Sanchez. 1981. Características ambientales y edáficas del área muestra San Carlos de Río Negro-Solano. Serie Informes Científicos OGSIIA/IC/12. MARNR, Caracas, Venezuela. 38 p.

Hermoso, F., and D. Dubroeucq. 1978. Características de una toposecuencia de suelos ferralíticos (oxisoles) en el Territorio Federal Amazonas. V. Congreso Venezolano de la Ciencia del Suelo. Barquisimeto, Venezuela. 29 p.

Luque, O. 1975. Génesis de tres órdenes de suelos en los llanos orientales de Venezuela. Centro Nacional de Investigaciones Agropecuarias. Maracay, Venezuela. 19 p.

Ochoa, G. 1983. Caracterización mineralógica y génesis de una secuencia de suelos desarrollada en depósitos aluviales del río Socopó, Ticoporo, Estado Barinas. Facultad de Ciencias Forestales, Universidad de los Andes, Talleres Gráficos Univesitarios. Mérida, Venezuela. 178 p.

Padilla, C. 1984. Estudio de suelos semidetallado del valle del río Cataniapo, Sector Culebra-Gavilan, Territorio Federal Amazonas. Serie Informes Técnicos Zona 2/IT/247. MARNR, Caracas, Venezuela. 145 p.

Padilla, C., and G. Elizalde. In press. Relaciones entre la mineralogía y las propiedades quimicas y físicas de oxisoles del valle del rio Cataniapo, Territorio Federal Amazonas, Venezuela.

Paez, M. 1985. Evaluación de la erodabilidad relative y de la eficiencia de índices de erodabilidad en suelos agrícolas de Venezuela. Trabajo de grado par optar al Doctorado en Ciencias. Facultad de Agronomía, Universidad Central de Venezuela, Maracay, Venezuela. 146 p.

Schargel, R. 1976. Estudio de suelos gran visión de las márgenes del río Orinoco desde Tamatama hasta la confluencia del Cunucunuma. División de Edafología, Ministerio de Obras Públicas, Caracas, Venezuela. 50 p.

———. 1977. Soils of Venezuela with low activity clays. Characteristics and classification of selected soil profiles. Ph.D. thesis. Dept. of Soil Science, North Carolina State Univ., Raleigh, NC. 412 p.

Schargel R., and S.W. Buol. 1978. Characteristics of some well drained Oxisols and Ultisols of the savannas and rainforests of Venezuela. *In* Agronomic-economic research on soils of the tropics. Ann. Rep. for 1976-1977. Soil Sciences Dept., North Carolina State Univ., Raleigh, NC. Pp. 210-226.

Schargel, R., R.A. González, and S. Strebin. 1980. Estudio agrológico gran visión sector Caicara del Orinoco, Estado Bolivar. Serie de Informes Científicos OGIIA/IC/05. MARNR, Caracas, Venezuela. 148 p.

Soil Survey Staff, SCS, USDA. 1960. Soil classification, a comprehensive system, 7th approximation. SCS, USDA, U.S. Govt. Printing Office, Washington, D.C. 265 p.

———. 1967. Supplement to soil classification system. SCS, USDA, Govt. Printing Office, Washington, D.C. 207 p.

———. 1975. Soil taxonomy. Agric. Handb. no. 436. SCS, USDA, U.S. Govt. Printing Office, Washington, D.C. 754 p.

Westin, F.C. 1962. The major soils of Venezuela. Report to the Government of Venezuela. F.A.O., Rome, Italy. 515 p.

EVALUATION OF THE ICOMOX PROPOSAL IN THE SOUTHEAST ASIAN CONTEXT

S. Paramananthan,[1] L. Moncharoen,[2] and M. Recel[3]

Abstract

This paper examines briefly the extent of Oxisols in Southeast Asia, and their placement in the proposed ICOMOX (International Committee on Oxisols) key is discussed. Due to lack of information, only the probable placement of soils in the proposed key is discussed. The proposed key is considered an improvement over the existing key.

Most of the Oxisols mapped in Southeast Asia key out as Akrudox, Kurudox, Hapludox, Akrustox, Kurustox, and Haplustox, although a few may be in the Haploperox great group. Common subgroups are typic, pertroferric, xanthic, rhodic, plinthic, and aquic. In some cases the criteria selected will split the current criteria used to define soil series in some countries. In spite of these problems the new proposals are an improvement but need further testing. Additional data needs to be collected to do this.

By definition Oxisols are highly weathered soils and hence can be expected to be extensive in areas where intensive weathering occurs. The tropics, where high ambient temperatures and rainfall are common, are therefore expected to be the "ideal home" for Oxisols. However, Oxisols, as defined in *Soil Taxonomy* (Soil Survey Staff 1975), were based primarily on data from Hawaii and Puerto Rico. Thus, these definitions, particularly at the lower levels, applied to soils in other parts of the world soon created problems. The desire to make *Soil Taxonomy* a universal tool in soil survey classification demanded a review of these definitions. Thus, ICOMOX was established. After many years of discussions through circulars, meetings, and field tours, this committee has come up with a draft—the ICOMOX-Oxisol Key 1986 (circular letter16). While it is certain that this proposed key will not meet the approval of all concerned, it should satisfy most. The objective of this paper is to discuss the ICOMOX-Oxisol Key 1986 in the context of Asia.

[1] Soil Science Department, Agriculture University Malaysia, 43400 UPM Serdang, Selangor, Malaysia.
[2] Soil Survey Division, Department of Land Development, Bangkhen, Bangkok 10900, Thailand.
[3] Research Division, Bureau of Soils, Ministry of Agriculture and Food, Manila, Philippines.

Extent of Oxisols in Asia

The lack of reliable published information for many countries in Asia makes it almost impossible to give reliable estimates of the extent of Oxisols in this continent. Many countries in Asia have their own systems of soil classification. These systems often use criteria that differ considerably from the limits used in *Soil Taxonomy*. Over the last few years, particularly through the *Soil Taxonomy* forums, soil classification workshops, and the strong support given by USDA/SMSS, an increasing number of countries are using *Soil Taxonomy*. This is particularly true in Southeast Asia where Indonesia, the Philippines, Malaysia, Thailand, and Singapore have incorporated the criteria in *Soil Taxonomy* into their national classification systems. In the other countries often a national system is retained but the local soil map units are also equated to *Soil Taxonomy*. The lack of reliable information on the extent and properties of Oxisols in areas outside Southeast Asia means that the discussions in this paper are based mainly

Table 1. Extent of Oxisols

Country	Approximate extent	
Indonesia	18,382,000 ha[a]	Sudjadi (1954)
Philippines		
Malaysia	50,000 sq km	Paramananthan & Lim (1979)
Thailand	1,180 sq km	Rojanasoothon & Panichapong (1979)
Singapore		Ives (1977)

[a] Includes some Ultisols.

on soils found in Southeast Asia. An estimate of the extent of Oxisols in some countries in Southeast Asia is given in Table 1.

In most of Southeast Asia no large stable landscapes such as those found in Africa and South America (Brazil) occur. Thus, most Oxisols are developed over highly weatherable parent materials such as basalts, serpentinites, amphiboles, and so on (Paramananthan 1977; Paramananthan and Lim 1979; Sudjadi 1984; Rojanasoonthon and Panichapong 1979).

In Indonesia volcanic and basic parent materials are relatively extensive. On the very young volcanic ash deposits, as those found in Sumatra, Andepts occur. However, in many areas, as in Kalimantan, Oxisols have been mapped (Clyde Surveys Ltd. 1981). Oxisols are again relatively rare in the Philippines where recent volcanic deposits occur (Raymundo, Dayot, and Alcalde 1985). In Malaysia fairly large areas of Oxisols have been mapped on a variety of parent materials such as serpentinites, basalts, andesites, gabbros, and schists (Paramananthan 1977). Only two soils, the Tha Mai and Chok Chai series on basalt, have been identified as being Oxisols in Thailand. Similarly, in Singapore, Oxisols have been mapped only over gabbros and granodiorites, but these are very localized (Ives 1977).

Evaluation of the ICOMOX Proposal

The limitations of the classificaiton with particular reference to Oxisols is clearly recognized in *Soil Taxonomy* by the statement: "The classification of Oxisols that follows seems to produce satisfactory groups of the Oxisols in Hawaii and Puerto Rico. It needs to be tested more widely, for it is far from completion and is certain to have many shortcomings" (p.323). The definition of the oxic horizon is inadequate (Recel 1983). It is with this in mind that the ICOMOX proposal has been made for testing.

Definition of the Oxic Horizon

The current definition of the oxic horizon has been defined in circular letter 14 and modified in letters 15 and16 and now reads as follows:

The oxic horizon is a subsurface horizon that:

1. is at least 30 cm thick;
2. has a fine-earth fraction (<2 mm) that has an apparent ECEC (NH_4OAL bases plus IN-KCL extractable Al/% clay) less than 12 meq per 100 g clay or has an apparent CEC_7 (NH_4OAL/% clay) of less than 16 meq/100 g clay;
3. has less than 10% weatherable minerals in the 50-250 micron fraction or less than 40 meq of bases (Ca + Mg + K + Na)/100 g soil total elemental analysis of fine earth (< 2 mm);
4. has a sandy loam or finer texture in the fine-earth fraction and has more than 8% clay;
5. has a diffuse upper textural boundary (i.e., 1.2 x clay increase within a vertical distance of 15 cm);
6. has less than 5% by volume that shows rock structure unless the lithorelicts containing weatherable minerals are coated with sesquioxides;
7. has less than 85% gravel, by volume.

Our experience with Oxisols in Southeast Asia indicates that this new definition is far superior to that in *Soil Taxonomy*. Most of the Oxisols found in this region have an oxic horizon that is more than 30 cm in thickness. Some soils with a transitional E horizon which would meet the requirements of the oxic horizon would now be placed in the Kandi great groups. No problems regarding the CEC values are expected as most of our soils have a very low CEC. The weatherable mineral content of most Oxisols is also low but in areas where new ash showers have rejuvenated soils with oxic features, as in Sabah, this would be a problem. However, the limited analysis available of these soils indicates that the CEC values are too high to qualified them for Oxisols. As mentioned earlier, Item 5 of the clay increase can be expected to be a problem with some soils. Thus, for example, the Senai series (Paramananthan 1977) would no longer have an oxic horizon. If, however, the profile was a truncated one then it would have an oxic horizon, as the clay increase would not be present. This criteria in our opinion may present us with some minor problems. Items 6 and 7, in our opinion, are welcome additions, as many of our Oxisols have iron-coated schist fragments.

Proposed Suborders

The ICOMOX proposed key definition of Oxisols reads:

Other soils that either have:

1. an oxic horizon with its upper boundary within 1 m of the soil surface and do not have a clay content increase necessary to define the upper boundary of an argillic or kandic horizon within a depth of 2 m, or
2. 40 percent or more clay in the surface 18 cm, after mixing, and either an oxic horizon or a kandic horizon with an apparent CEC of the clay fraction of less than 16 meq/100 g clay (NH_4OAL) or an apparent ECEC of the clay (bases plus KC1 Al) , 12 meq/100 g clay with upper boundary within 1 m of the soil surface and meeting the weatherable mineral and rock fragment criteria of an oxic horizon.

As mentioned earlier most of the Oxisols would meet Item 1 of this definition. However, the Senai series, as mentioned above, would still no longer be an Oxisol as it would also not meet Item 2. Some of the current Ultisols that have sandy clay to clay surface horizons may now become Oxisols, as many Ultisols in this region would have a kandic horizon and an apparent CEC of less than 16 meq/100 g clay. In Thailand, the differences in surface soil texture of any soil family do not take into consideration series differentiation, since it was considered as phases of series. Therefore, the introduction of 40 % or more clay into the order key statement of Oxisols would affect some soil series' definitions. For example, the clay loam phase of the Pak Chong series will be classified into the Ultisols order, while the clay phase would be in Oxisols. It is our opinion that this new definition would almost double the amount of Oxisols in this region.

The proposal uses soil moisture regimes to key the different suborders. In this region to date only three soil moisture regimes—the ustic, udic, and perudic—have been identified. Hence, the Oxisols in this region would fall in to Perox, Udox,

and Ustox. The areas with a perudic moisture regime are localized, while those with udic and ustic moisture regimes are extensive. We are of the opinion that this split is satisfactory, although it means that some of our existing mapping units may have to be split.

Proposed Great Groups and Subgroups

Soils of the suborder Perox will probably all fall into the Haploperox great group. The lack of reliable data will not allow further comments on these soils.

Soils of the Udox and Ustox suborders will fall into Akrudox, Kurudox, Hapludox, Akrustox, Kurustox, and Haplustox. A factor that is not clear in the key to the great groups is whether the criteria of less than 1.5 meq is for any subhorizon or is throughout the oxic horizon. This will need to be clearly stated. Some Oxisols in this region only have a subhorizon with an apparent ECEC of less than 1.5 meq. The main subgroups which occur in Southeast Asia are typic petroferric, xanthic, rhodic, aquic, and plinthic. It is our opinion that the proposed changes are acceptable. However, as with any change in the classification, it cannot satisfy everyone. Hence, the criteria for rhodic and xanthic subgroups will split the current soil series used in Malaysia where a color split at 5YR rather than at 2.5YR is used. The few analyses we have suggest that soils with hues of 5YR or redder often key out as Kurudox, while those with yellower hues are often Hapludox.

Family Criteria

Most of the Oxisols in Southeast Asia are expected to fall into the following families:

Particle Size Class:	fine-loamy fine very fine clayey-skeletal
Mineralogy Classes:	Ferritic Allic Gibbsitic Ferritic-Allic Kaolinitic
Soil Temperature Classes:	Isohyperthermic Isothermic

Conclusion

In spite of the expected difficulties we will face with existing soil series, we are of the general opinion that the new ICOMOX proposal is a definite improvement on the existing key and should be adopted. Further testing and, more important, soil sampling and analysis is required, however, before a final decision can be made.

References

Clyde Surveys, Ltd. 1981. Phase II screening. HANJALIPAN WPP VI SKP C and D East (transmigration studies). Min. of Public Works, Rep. of Indonesia.

Ives, D.W. 1977. The soils of Singapore. New Zealand Soil Survey Report no. 36.

Paramananthan, S. 1977. Soil genesis on igneous and metamorphic rocks of Malaysia. D.Sc. thesis. State Univ. of Ghent, Belgium.

Paramananthan, S., and C.P. Lim. 1979. Oxisols of Malaysia. Proc. IInd Intl. Soil Classif. Workshop. Part 2 Malaysia. Soil Survey Div., Land.Dev. Dept., Thailand. Pp. 95-111.

Raymundo, M.E., A.A. Dayot, and C.B. Alcalde. 1985. The soils of the Philippines: Their association with geology and landforms. *In* Soil taxonomy: Tool for agrotechnology transfer. PCARRD Book Series no. 34/1985. Manila. Pp. 79-87.

Recel, M.R. 1983. Revision of Soil Taxonomy in the classification of low activity clay soils. Ph.D. thesis. Univ. of Hawaii, Honolulu, Hawaii.

Rojanasoonthon, S. and S. Panichapong. 1979si. Oxisols of Thailand. Proc. IInd. Intl. Soil Classif. Workshop. Part 1 Malaysia. Soil Survey Div., Land Dev. Dept., Thailand. Pp. 113-122.

Soil Survey Staff, SCS, USDA. 1975. Soil Taxonomy: A basic system of soil classification for making and interpreting soil surveys, U.S. Dept. of Agric. Handb. 436. U.S. Govt. Printing Office, Washington, D.C. 754 p.

Sudjadi, M. 1985. Problem soils in Indonesia and their management. In Ecology and management of problem soils of Asia. FFTC Book Series no. 27, Taipei, Taiwan, Republic of China. Pp. 58-73.

OXISOLS IN ZAMBIA

C. Kalima[1] and O. Spaargaren[2]

Abstract

The classification and chemical, physical, mineralogical, and micromorphological characteristics of the three main Oxisol great groups in Zambia (Haplustox, Acrustox, and Haplohumox) are discussed. In addition, the occurrence of a few other Oxisols (Eutrustox, Plinthaquox, Ochraquox, and Orthox) whose extent is very limited and usually bound to specific places, is briefly reported.

Oxisols occur mainly in the northern and northeastern part of Zambia. The most southern occurrence is reported from the Kapini area, just north of Lusaka.

Problems with management of Zambian Oxisols are the sometimes disastrous effects of modern land clearing practices, the rapid decrease in organic matter content upon cultivation, the often high Al levels, and the fragile nutrient balance.

The ICOMOX (International Committee on Oxisols 1986) and ICOMLAC (Intenational Committee on Low Activity Clays 1984) proposals allow for a better and more rational grouping of Oxisols (and Ultisols) in Zambia. However, there still exists a discrepancy between the two proposals, leaving soils that obviously belong, managementwise, with the Oxisols and Ultisols out of these groups.

Since its publication *Soil Taxonomy* (Soil Survey Staff 1975) has been used in Zambia mainly for soil profile classification and international correlation. The complexity of the definitions and the difficulty of matching field characteristics into these definitions has often led to misinterpretation and misclassification, in particular with respect to Oxisols and Ultisols. Many soils with low activity clays that have an increase in clay content with depth, but in which no clay skins were observed, were usually classified as Oxisols. Recent research and better understanding of the principles and logic of *Soil Taxonomy*, as promoted by the XIth International Forum on Soil Taxonomy and Agrotechnology Transfer held in Zambia in 1985, however, has shown that many of these soils are in fact Ultisols. Consequently, the area occupied by Oxisols in Zambia will probably be less than estimated previously (Magai and Veldkamp 1984).

This paper intends to discuss the classification and characteristics of Oxisols in Zambia, their distribution and management, and the implications of the proposals for modification of *Soil Taxonomy* made by ICOMOX and ICOMLAC.

Classification and Characteristics of Oxisols in Zambia

The Haplustox Great Group

General Characteristics. In Zambia most of the areas where Oxisols occur experience a ustic soil moisture regime and an isohyperthermic soil temperature regime. Therefore, the most common Oxisol in Zambia is the Haplustox, because base saturation is generally less than 20 to 25 percent. Almost all Haplustox show an increase in clay content with depth, ranging from 5 percent to more than 80 percent, relatively, if control section and topsoil (0 - 25 cm) are compared. Consequently, both Typic and Ultic Haplustox are dominant. To a lesser extent Tropeptic Haplustox occur, in particular where Oxisols are derived from basic rocks.

Chemistry. The cation exchange capacity of the control section varies, in general, between 8 and 16 cmol (NH_4^+)/kg clay. However, sometimes the CEC in the top part of the control section is up to 20 cmol (NH_4^+)/kg clay, due to the presence of an appreciable amount of organic matter in that part of the solum. As stated above, base saturation is usually less than 20 to 25 percent with Ca and Mg as dominant absorbed bases. Aluminium saturation is almost always more than 40 percent and in most cases even more than 60 percent, while some soils also have very high soluble Mn levels (soluble in 0.02 M $CaCl_2$). This suggests high manganese saturation as well, in particular where these high soluble Mn levels coincide with low soluble Al levels.

Most pH($CaCl_2$) values are between 4.0 and 4.5. Rarely does the pH go up to 4.8 to 5.0. The pH(KCl) is usually the same or

[1] Acting Senior Soil Suveyor, Soil Survey Unit, Research Branch, Department of Agriculture, P/Bag 7, Chilanga, Zambia.

[2] Soil Correlator, Soil Survey Unit, Research Branch, Department of Agriculture, P/Bag 7, Chilanga, Zambia.

only 0.1 or 0.2 units lower, while pH($H_2$0) is 1.0 to 1.5 units higher. "Free iron" content (citrate - dithionite extractable iron) is very variable. It ranges from about 0.5 percent in the yellow (xanthic) members to more than 9 percent in the red (rhodic) members. Preliminary research suggests that the percentage of "free iron" is highly correlated ($r = 0.95$) with the percentage phosphate retention (Fig. 1).

The organic matter is usually confined to the upper 10 cm of the soils. When cultivated the organic matter content rapidly decreases to levels of less than 1 percent.

Physics. Most Haplustox have, macroscopically, a porous massive appearance, or show only a weakly developed blocky structure. However, usually strong microaggregation, resulting in an extremely fine granular structure, can be observed using a hand lens. In general the oxic horizons of the Haplustox are plastic and slightly sticky.

The intergranular porosity is high, leading to bulk densities between 1.1 and 1.3 Mg/m³. Water retention is low to moderate, ranging from 30 to 80 mm/m. Studies in the North Western Province have shown that between 70 and 90 percent of the available water is released between 10 and 200 kPa pressure (Wen, Magai, and Kalyango 1984), while the flattest part of the soil moisture retention curves lies close to 100 kPa. It indicates that in these Oxisols most available water is held at low suction in the intergranular (interstitial) pores. This property contributes significantly to the moisture stress often experienced in the region where Oxisols occur.

Mineralogy and Micromorphology. The mineralogical data and the related chemical and physical data available indicate that the Haplustox have a kaolinitic or mixed clay mineralogy and a siliceous silt and sand mineralogy. Accessory minerals recorded are goethite, hematite, gibbsite, vermiculite, and mica. Generally, the plasma in thin sections of these soils is described as insepic (Bal, pers. comm.; Brewer 1976). The s-matrix usually shows a porphyroskelic related distribution pattern, while pedotubles and sesquioxide segregations are common special features. The microscopic granular structure is one of the most conspicuous elements in the thin sections.

The Acrustox Great Group

General Characteristics. The second most important group of Oxisols are the Acrustox. These soils are usually clayey, and the low effective cation exchange capacity required occurs in general in the lower part of the oxic horizon. Invariably, the Acrustox in Zambia have a net negative charge, pH(KCl) usually 1.0 unit lower than pH($H_2$0). Consequently, they are classified as Haplic Acrustox, as implied by the subgroups definitions.

Chemistry. Exchangeable bases, the most important chemical characteristic of these soils are present in very small quantities (less than 0.2 cmol (p+)/kg clay), or as traces, while exchangeable aluminium is usually less than 1 cmol (p+)/kg clay. However, there are indications that, besides Ca, Mg, K, Na, and Al, other cations, in particular Mn, may play a role in the exchange characteristics. For the study in North Western Province (Wen, Magai, and Kalyango 1984), a number of soils were analyzed for "soluble Al and Mn." In some cases a sharp drop in soluble Al (e.g., from about 20 ppm to less than 1 ppm) coincided with a significant increase in soluble Mn (e.g., from about 0.2 ppm up to about 11 ppm). If further research reveals that exchangeable Mn plays an important role, it should be taken into account in the effective cation exchange capacity, and a number of soils now classified as Acrustox would likely become Haplustox.

Organic matter content is similar to the organic matter content in the Haplustox, except where these soils are transitional to the Humox (see the Haplohumox Great Group). No data are available on the phosphate retention capacity, but it is thought to be similar or slightly higher than the phosphate retention capacity of the Haplusox.

Physics. Compared to the Haplustox, the Acrustox have slightly lower bulk densities, ranging from 1.1 to 1.2 Mg/m³. Available water (difference between 33.3 and 1500 kPa) is 50 to 80 mm/m. Structurally, these soils appear to be porous massive. Weakly developed blocky structures are only seldom recorded. They are slightly sticky and plastic when wet., although the very clayey members can become very sticky.

Mineralogy and Micromorphology, The few mineralogical data available indicate that the Acrustox are more strongly weathered than the Haplustox. Invariably, the clay mineralogy is kaolinitic, with sometimes oxidic tendencies. Accessory minerals are goethite, hematite, and gibbsite. The amount of the latter mineral is usually higher in the Acrustox than in the Haplustox and is indicative for the stronger weathered stage. In the lower part of the solum mica may occur. The silt and sand fraction almost entirely consists of quartz and other minerals resistant to weathering.

The thin sections usually show an asepic plasma. Where the amount of iron is high, undulic plasma patterns are recorded. Again, the extremely fine granular structure is the most conspicuous feature.

The Haplohumox Great Group

General Characteristics. This third important Oxisol group in Zambia has only a limited extent. It occurs in areas where the soil temperature regime is isothermic (i.e., along the borders with Zaire, Tanzania, and Malawi), and where the organic carbon content is high (more than 16 kg/m³ soil). Characteristically these soils have low color values and are usually described as dark red, dark reddish brown, or dusky red. The are dominantly derived from dolomite of dolomitic limestone.

The Haplohumox known all classify as Typic Haplohumox. However, only a few data are available on KCl extractable aluminium, which is required to be less than 4 cmol (p+)/kg clay. It may therefore be possible that an allic subgroup of the Haplohumox also exists in Zambia.

Chemistry. The main characteristic of this soil is its high organic carbon content. Amounts recorded in Zambia are up to 23 kg/m³ soil. Consequently, CEC values in the upper part of

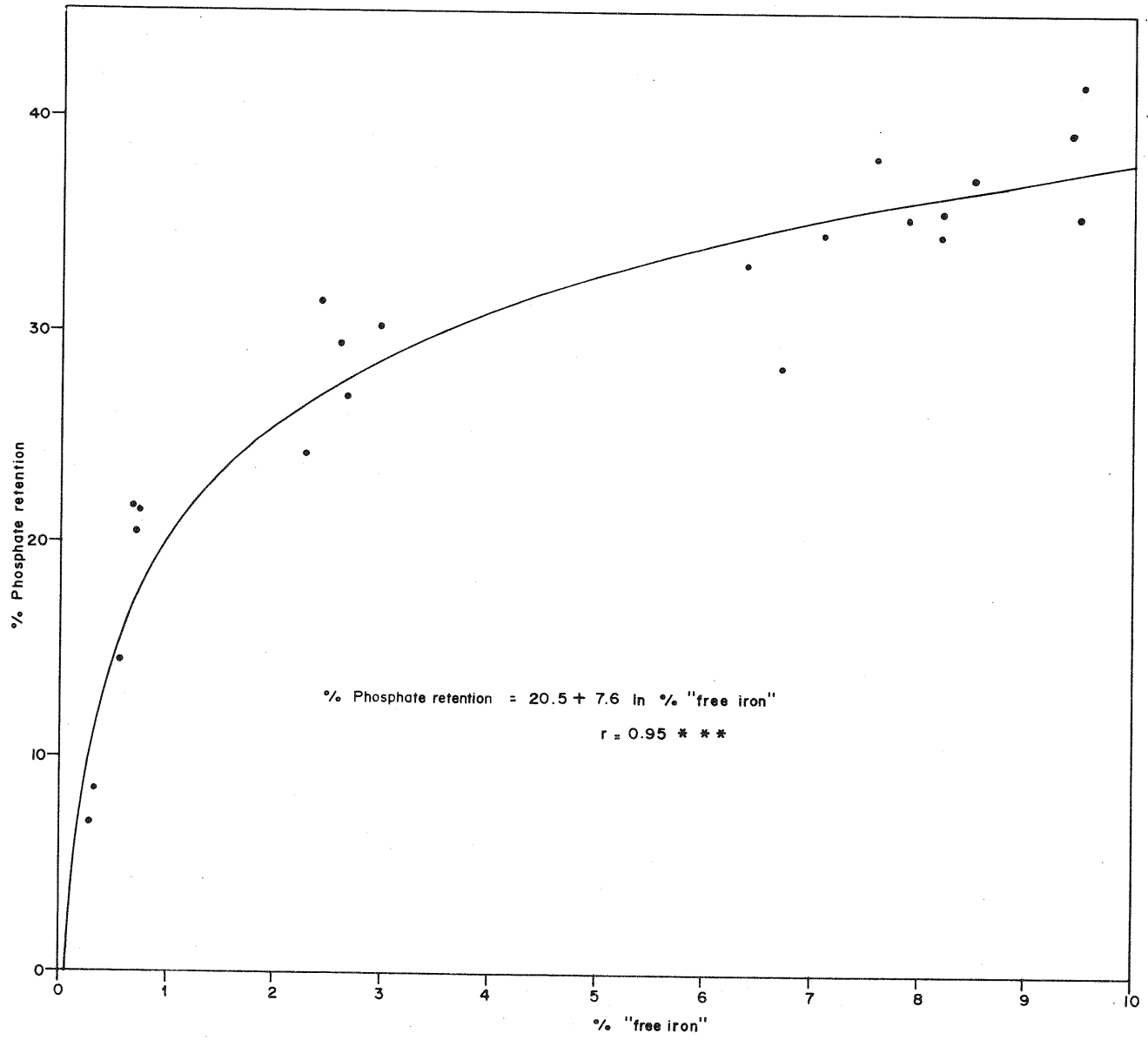


Fig. 1. Correlation between % phosphate retention and % "free iron" of 22 samples of Oxisols from North Western Province, Zambia.

the control section are high compared to the other Oxisols. Commonly, they drop below 16 cmol (NH_4^+)/kg clay at a depth between 75 and 100 cm. Base saturation by NH_4OAc (pH 7) of the control section is between 5 and 20 percent, while bases saturation of the topsoil is only slightly higher, between 15 and 40 percent.

The effective cation exchange capacity is 2–4 cmol (p+)/kg clay, increasing up to 8 cmol (p+)/kg clay in the topsoil. The pH (KCl) is between 4.0 and 5.0. Aluminium saturation varies considerably, from less than 10 percent up to 80 percent.

Physics. The Haplohumox tend to have weak to moderate blocky structures. This better developed structure as compared with the Haplustox and Acrustox is likely to be attributed to the greater amount of organic matter. Derived from dolomite or dolomitic limestone, the soils are heavy textured, with clay percentages between 40 and 80 percent.

No data are available on bulk density and available water holding capacity. It is believed that bulk density is somewhat higher than that of the Haplustox, about 1.3 to 1.4 Mg/m^3, because of the clayey texture and the medium porosity recorded in the field (Dalal-Clayton 1982a, b).

Using the correlation equations for available water, developed by Maclean (1970), these soils hold between 100 and 150 mm/m.

Mineralogy and Micromorphology. Because mineralogical data of the Haplohumox are lacking, the mineralogy has to be inferred from chemical and physical properties. Where the organic carbon content becomes low (i.e., less than 0.3 percent), the cation exchange capacity of the clay fraction indicates that the dominant clay mineral is, most likely, kaolinite. Usually the CEC of the clay fraction increases toward the surface, even when corrected for organic matter. This points to admixture with other clay minerals, probably interlayered Al chlorites or vermiculites. The sand fraction, macroscopically examined, consists almost entirly of quartz.

Micromorphological data of Haplohumox in Zambia are not available.

Other Oxisols

Some other Oxisols occur in Zambia, however, their extent and significance is very limited. Therefore they will be discussed only briefly.

The Eutrustox Great Group. Incidentally, Oxisols are encountered that have a high base saturation. In most cases they occur on lower slopes. Enrichment with laterally leached bases from upland soils is thought to be the main reason for development of these soils. They also occur in areas in Zambia with only moderate rainfall, and are therefore less severely leached compared to the Oxisols of the high rainfall zone.

These soils classify as Typic, Ultic, or Tropeptic Eutrustox, depending on a coarser textured layer in the upper part of the solum, or the development of moderate blocky structures influenced by the enrichment of bases.

The Ochraquox Great Group. Scattered Ochraquox occur in wet places at the foot of slopes or in *dambos* or valleys associated with other Oxisols. In many cases they are underlain by ironstone and/or contain much ironstone gravel. They are classified as Typic or, tentatively, as Petroferric Ochraquox.

The Plinthaquox Great Group. As this is one of the most difficult soils to recognize due to the laborious process of identifying plinthite, only very few data exist that positively indicate its occurrence in Zambia. Invariably, they are found in valleys or at valley fringes. They classify as Typic Plinthaquox.

The Orthox Subgroup. Orthox occur in seepage zones and in places where groundwater does not fluctuate much. The soil moisture control section of these soils is kept moist for a significant part of the year through capillary rise. The ones encountered so far classify as Haplorthox (Aquic, Quartzipsammentic, or Typic), but it is likely that Acrorthox (associated with Acrustox) also occur.

Distribution of Oxisols in Zambia

Oxisols are found mainly in the northern and northwestern part of Zambia, and their occurrence is closely related to the so-called "high rainfall zone" (the zone that receives more than 1000 mm of rain per year). Incidentally, Oxisols are reported outside this area.

The Haplustox are the dominant soils in the northern part of North Western Province. In the Copperbelt, Northern and Luapula Provinces, it is in places codominantly, mainly associated with Oxic Paleustult and Oxic Haplustult.

The Acrustox occur in scattered places in North Western Province, mainly south of Solwezi and east and southeast of Mwinilunga. In Northern Province they are found southwest of Mbala. They are often associated with Haplustox.

The Haplohumox are confined to an area around Solwezi in North Western Province, where an isothermic soil temperature regime prevails. They have not been reported yet from the other isothermic areas near the Tanzanian and Malawian borders.

The distribution of the main Oxisols in Zambia is shown in Figure 2. Outside the high rainfall zone Oxisols have been reported from the Kahare area in Western Province (Henneman, in press) and the Kapini area in Lusaka Province (Kalima 1983). The latter one represents the most southern occurrence of Oxisols in Zambia.

Management of Oxisols in Zambia

The specific exchange characteristics and the often severe acidity of the Oxisols in Zambia require careful management. In addition, the fragile balance in organic matter poses management problems, in particular in relation to land-clearing practices.

Of old, the subsistence farmers practice the so-called "Chitemene" system, a slash-and-burn technique set in shifting cultivation. Branches of trees are cut off and carefully placed over a field of about 0.25 ha (in Zambia called a *lima*). Just before the rains start the then dried branches are set on fire to release the nutrients. After the fields have been (chemically) exhausted and the weed problem has worsened, the people shift to another field to allow the old field to regenerate for about

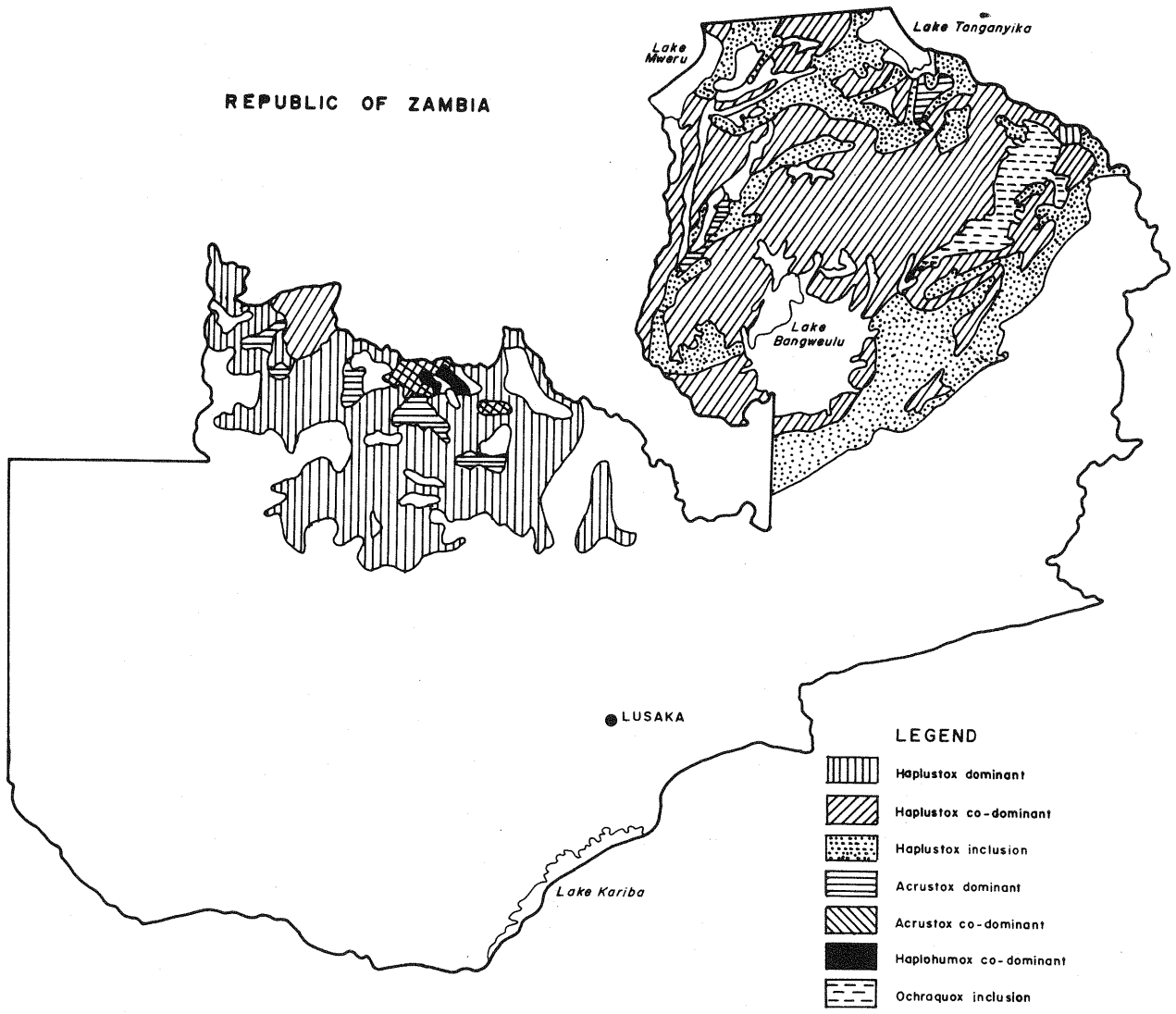


Fig. 2. Distribution of Oxisols in Zambia.

25–30 years.

Newly introduced mechanical land-clearing practices have dramatic effects on these soils where organic matter and most nutrients are concentrated in the first 10 cm. Careful management through hand-clearing and crop rotation is required to retain the organic matter status at acceptable levels to provide the necessary nutrient retention capacity, and to prevent structural degradation of the topsoil.

The deficiencies in nutrients have to be counteracted by heavy fertilization. Except for the Haplohumox, these soils have a low nutrient retention capacity in the rooting zone. Consequently, split application of fertilizer is necessary in order to get an optimum effect and to prevent loss of fertilizer. The Haplohumox have, relative to the other Oxisols, high nutrient retention capacity, in particular in the upper part of the solum. Split application of fertilizer is not necessary on these soils.

Liming of most Oxisols is a must. Aluminium levels found are toxic to most crops, and a raise of the pH is necessary to keep these soils productive. This is especially the case where nitrogen fertilizers are used to neutralize its acidifying effect. Liming is also important to supply Ca (and Mg) to the soil. The absolute levels in Haplustox and Acrustox can be so low that Ca deficiency and various imbalances between Ca, Mg, and K occur. The Oxisols in Zambia tend to be liable to erosion and physical degradation, although not as sever as with Ultisols. They need protection from sun and rain by mulching, cover crops, and so on. The traditional crops grown are sorghum, cassava, beans, and, to a lesser extent, finger millet. Because of the tsetse fly no cattle are kept. Coffee is likely to become the most important cash crop on these soils.

Implications of the ICOMOX and ICOMLAC Proposals

The purpose of soil classification is to group soils together that have a similar response to a given management. It is with this in mind that the proposals of ICOMOX and ICOMLAC have to be tested. The main implication in Zambia of the proposals is the enormous shift from Oxisol to Ultisol. Magai and Veldkamp (1984) estimate that from the 20 percent Oxisol in Zambia about 6 percent will be left. Presumably, this will be even less because a number of Ultisols have been misclassified as Oxisols.

Management of Oxisols with an appreciable increase in clay content and Ultisols with low activity clays does not differ significantly. For both soils fertilization and controlling acidity are essential, as is the upkeep of the organic matter status. Both are liable to physical degradation when cultivated. Capping and structural decline have often been recorded from cultivated Ultisols and Ultic Oxisols. These latter properties differentiate these soils from Oxisols without an appreciable increase in clay content. To this extent the "kandic horizon" concept is an improvement because now similar soils are classified in the same order.

On the other hand, soils with low activity clays without a kandic horizon but with an increase in clay content diagnostic for an argillic horizon ought to be grouped together with the soils having a kandic horizon, as their response to the same management is similar. Under the present proposals soils having sufficient increase in clay content for an argillic horizon, but insufficient for a kandic horizon, will be classified as Inceptisols. This results from the proposed key to the Oxisols, which states: "Other soils that either have: (1) an oxic horizon with its upper boundary within 1 m of the soil surface and do not have a *clay content increase necessary to define the upper boundary of an argillic of kandic horizon* within a depth of 2 meters, or (2)..." (ICOMOX Circular Letter no. 16, Appendix I, 1986). The soils with a clay content increase sufficient to warrant an argillic horizon (but no kandic horizon) will pass the Oxisols because of this, but will also pass the Ultisols/Alfisols because they do not fulfill all requirements for an argillic horizon (no clay skins). Consequently, they will key out in the Inceptisols. It may therefore be better to bring the argillic and kandic horizon requirements in line with each other or drop the clay skin requirement for the argillic horizon.

Another matter of concern is the impact of the kandic concept in field-mapping of Oxisols. To establish the difference between a Kurustox and a Haplustox the surveyor must be able, in clayey materials, to judge an increase in clay content of more than 8 percent (e.g., from 50 to 60 percent). It is doubtful if surveyors will be able to depict this difference in the field, particularly because this increase often occurs in the top part of the soil where the presence of organic matter hampers an accurate field estimated of clay content. Consequently, many suspected kandic horizons have to be tested in the laboratory. This will increase the work load and expenditure enormously. Besides, it remains in dispute whether the occurrence of a kandic horizon in clayey materials does alter the management of these soils with respect to clayey Oxisols without a kandic horizon.

Table 1 shows, as an example, the break-up of the Typic Haplustox subgroup as defined in *Soil Taxonomy* (1975) and as they are found in Zambia, according to the new proposals of ICOMOX and ICOMLAC. Most other Oxisols show a similar differentiation, with incidentally some other subgroups (e.g., petrofierric, lithic).

It is concluded that although the proposals of ICOMOX and ICOMLAC allow for better and more rational separation of Oxisols, Ultisols, and Alfisols, some doubtful groups still exist and that the main issue of ICOMLAC, namely to solve the problem of soils with an argillic horizon dominated by low activity clays versus soils with an oxic horizon, has not been entirely solved.

Acknowledgements

The authors are indebted to W.J. Veldkamp, Land Evaluator SSU, for his careful reading and constructive suggestions. The permission of the Director of Agriculture, Ministry of Agriculture and Water Development, to present this paper during the VIIIth International Soil Classification Workshop, is gratefully acknowledged.

Table 1. Correlation between *Soil Taxonomy* (1975) and ICOMOX (1986)/ICOMLAC (1984) Proposals for a Typic Haplustox

Characteristics applicable in Zambia	ICOMOX/ICOMLAC
No diagnostic clay content increase	Typic Haplustox
• but with mollic or umbric epipedon	Humic Haplustox
• but color hue 2.5YR or redder, value moist less than 4	Rhodic Haplustox
• but color hue 7.5YR or yellower, value moist 6 or more	Xanthic Haplustox
With 40 % or more clay in topsoil and more than 8 % increase in clay content within 15 cm	Typic Kurustox
• but with mollic or umbric epipedon	Humic Kurustox
• but color hue 2.5YR or redder, value moist less than 4	Rhodic Kurustox
• but color hue 7.5YR or yellower, value moist 6 or more	Xanthic Kurustox
With 40 % or more clay in topsoil and more than 8 % increase in clay content betwen 15 and 30 cm	Ustoxic Dystropept
• but with 12 kg/m^3 or more organic carbon	Ustoxic Humitropept
With less than 40 % clay in topsoil and kandic horizon without significant decrease in clay content	Kandiustult
• but with 12 kg/m^3 or more organic carbon	Ustic Kandihumult
With less than 40 % clay in topsoil and kandic horizon with significant decrease in clay content	Kanhaplustult
• but with 12 kg/m^3 or more organic carbon	Ustic Kanhaplohumult
With less than 40 % clay in topsoil, no kandic horizon, but with sufficient increase in clay content to meet argillic horizon requirement	Ustoxic Dystropept
• but with 12 kg/m^3 or more organic carbon	Ustoxic Humitropept

References

Brewer R. 1976. Fabric and mineral analysis of soils. Krieger Publ. Co., NY. 482 pp.

Dalal-Clayton, D.B. 1982a. Semi-detailed soil survey of the Chafukuma area, North Western Province. Soil Survey Report no. 89. Dept. of Agric., Lusaka, Zambia. 71 pp.

———. 1982b. Semi-detailed soil survey of the Solwezi State Farm, North Western Province. Soil Survey Report no. 90. Dept. of Agric., Lusaka, Zambia. Pp 76

Henneman G.R. (in preparation). Semi-detailed soil survey of the Kahare area, Kaoma District, Western Province. Soil Survey Report no. 81. Dept. of Agric., Lusaka, Zambia.

ICOMLAC. 1984. A proposal for reclassification of Ultisols and Alfisols with low activity clays. 32p.

ICOMOX. 1986. Circular Letter no. 16. 25p.

Kalima, C. 1983. Soil classification, pedogenesis and land evaluation in Kapini area, Lusaka, Zambia. M.Sc. thesis. Univ. of Dar-es-Salaam, Tanzania. Pp 269.

Maclean, A.H. 1970. Moisture characteristics of some Zambian soil. Soil Survey Report no. 5. Dept. of Agriculture, Lusaka, Zambia. 54p.

Magai R.N. and W.J. Velkamp. 1984. Soil survey in Zambia. *Soil Taxonomy News* 8:11-12.

Soil Survey Staff, SCS, USDA. 1975. Soil Taxonomy. A basic system of soil classification for making and interpreting soil surveys. USDA Agric. Handb. no. 436. U.S. Govt. Printing Office, Washington, D.C. Pp 754.

Wen T.T., R.N. Magai, and S.N. Kalyango. 1984. Exploratory soil survey of Solwezi, Mwinilunga, and Kasempa districts, North Western Province. Soil Survey Report no. 120. Dept. of Agric. Lusaka, Zambia. Pp 204

OXISOL-LANDSCAPE RELATIONSHIPS IN BRAZIL

I.F. Lepsch[1] and S.W. Buol[2]

Abstract

General principles regarding planation surfaces formation and their preservation are considered. Data are presented and discussed about general Oxisol-landscape relationships as well as for specific soil-landscape studies on or nearby the pedons sampled for the VIIIth International Soil Classification Workshop (ISCW) field trip. Pointed out is the necessity of detailed and accurate studies on geomorphic surface mapping, stratigraphy of superficial deposits, and soil variability within toposequences in order to better understand Oxisol genesis and thus access development of *Soil Taxonomy*.

In Brazil, the country within the world's largest concentration of Oxisol areas, several soil-landscape studies including this soil order have been performed. Although these studies may not yet be sufficient, both in number and detail, to establish firm geomorphic association for Oxisols, they sum up a considerable amount of information useful for pedogenic understanding. As a general rule they have pointed out the occurrence of Oxisols on the older and/or more stable part of the landscape in reworked free-drained superficial deposits and have pointed also to less-weathered soils, mostly with argillic horizons on the steeper younger nearby slopes. However, in some instances young erosional and depositional (soil) surfaces, grading to recent streams, may also have Oxisols when over recently truncated, or deposited, highly weathered superficial deposits with high permeability and free vertical drainage.

The oldest, relatively well-preserved surface is the Tertiary Sul Americana planation, standing as smooth highlands. In the lower areas succeeding the Tertiary planation remnants, a series of Pleistocene sedimentation cycles related to former semiarid stages have played a definite role on landscape sculpturing and formation of superficial deposits now bearing Oxisols. Smooth relief Tertiary planation remnants are dominated by the mostly weathered Acr great groups (Acrustox and Acrorthox) that can eventually be found also on Pleistocene areas bearing deposits that had undergone several weathering cycles before being deposited. The Acr great groups can eventually be found also on Pleistocene areas bearing deposits that had undergone several weathering cycles before being deposited. Hapl and Eutr great groups are found mostly on Pleistocene surfaces, the latter almost exclusively where basic rock has contributed to parent material.

[1] Soil Scientist with Instituto Agronômico, Campinas, Brazil.
[2] Professor of Soil Science, North Carolina State University, Raleigh, NC.

The importance of geomorphic factors on the formation of Oxisols has long been recognized by many pedologists. Buol (1979) has reviewed the concepts regarding the geomorphic factors in Oxisol formation over the development of *Soil Taxonomy* (Soil Survey Staff 1975). Oxisols on "old land surfaces" or "very stable surfaces" and/or "strong weathered parent material" have remained the dominant themes over the approximations of this comprehensive morphogenetic taxonomic system.

In the following discussion general concepts necessary for the correct interpretation of geomorphic work will be discussed. General Oxisol-landscape relations in Brazil and examples of specific soil-landscape studies from areas on or nearby the pedons visited in the VIIIth ISCW will be presented and discussed.

Old Surfaces: Their Formation and Preservation

"Surface" as used in *Soil Taxonomy* (Soil Survey Staff 1975) is a general term that may refer either to a *planation surface*[3] or to a *geomorphic surface*. Planation surface is a more comprehensive term used by geomorphologists to represent "the combination of various denudation-type and accumulation-type plains, having the same age and connected with the same base level of erosion" (Mescherikov 1968), or to describe "the geographically plain surface which is the end product of planation by erosion; it is an omnibus term and, among other features, includes the Davisian peneplane, the panplane, the pediment and the pediplain" (Brown 1968). Geomorphic surface is a less comprehensive term, mostly used by pedologists on detailed soil-landscape studies, meaning "a portion of the landscape specifically defined in space and time" (Ruhe 1969).

[3] The term *erosion surface* is frequently employed as synonymous with planation surfaces, the use of which may lead to confusion either because many surfaces that may be correctly called surfaces are by no means plane in character (Brown 1968) and also because the planation surfaces are frequently of a polygenetic (denudation-accumulation) type.

Old planation surfaces standing as gently undulating highlands are important landscape elements in the tropics. Lester C. King (1956) has described several of these surfaces attributed to a series of erosion cycles. One of the more important of these surfaces, from which most of the world's present scenery was carved, is a Tertiary planation surface that is often evident upon high country, mountains as well as plateaus (Fig. 1).

In the Southern Hemisphere these old landscape remnants when in Africa have been called African Surface (King 1976), in Australia Tennent Creek Surface and its equivalents Bradshaw and Aurukun (Beckmann 1983), and in Brazil Sul Americana (King 1956) or its equivalent Paleogenic or Cristas Médias (De Martonne 1940). Vestiges of still more ancient surfaces, dating back from the Mezosoic, the Gondwana and post-Gondwana surfaces (King 1956) or Campos surface (de Martonne 1940) (Fig. 1), have also been identified but only as small protruding, highly striped, vestiges on rejuvenated erosional areas. In the lower areas adjoining these Tertiary surfaces, there might be remnants of a series of younger planation surfaces that were formed from old deeply weathered soil profiles and/or slightly weathered rock.

Late Tertiary surfaces have been referred to as Rolling and Widespread in Africa (King 1976), Wavehill, Strathgordon, and Campaspa in Australia (Beckmann 1983), and as Velhas (King 1956) or Neogenic (De Martonne 1940) or Pd1 (Bigarella and de Andrade 1965) in Brazil.

Bigarella and de Andrade (1965) have also described for the South American continent a series of Pleistocene surfaces and related them with the glacial stages of the Northern Hemisphere: there were humid phases during interglacial and semiarid phases during the glacials. Under the latter stages active erosion forces over deeply weathered mantles widened the valleys forming several minor planation surfaces (Table 1 and Fig. 2). According to Garner (1974), from the idea that aridity had alternated with humidity, now supported by many authors, emerged the concept of large-scale secular changes of climate; these concepts comprise the "polygenetic theory of landform genesis" that may also here be understood as a "polygenetic soil parent material formation."

The study of planation surfaces on a continental scale can provide a basic generalized chronological framework useful for pedology. However, studies relating soils to these surfaces should take into account a series of circumstances in order to avoid some mistakes in their interpretation. One of these circumstances is linked to some belief in the absolute stability of the planation surface and the inherent possibility of the existence of sedentary soils of contemporary age. The planation surfaces are formed during successive periods of relative crustal stability and mostly grow, at the expense of others, successively inland by parallel retreat of their marginal scarps. However, most geomorphologists believe that drainage basins, internal to the smooth upland planation, have been providing new base levels causing continuous rejuvenation of river systems, with excision of valleys and continuous destruction of earlier landscapes. Although one may argue that such processes operate mainly in the lower and middle reaches, and near the headwaters very little erosion takes place, authors (e.g., Bennema 1983) call attention to the fact that 1 mm loss each 10 years would be about 100 m lowering during the Pleistocene.

Most probably the Tertiary and early Pleistocene planation surfaces, and their correlative superficial deposits, are no longer on their original position. They could have been lowered and their superficial deposits reworked due to the continuous active erosive processes throughout many millions of years. On the other hand, conditions may exist for the preservation of the general shape of the original low relief, by some aerially restricted redistribution of superficial deposits and only their partial removal. Also, formation of a thick saprolite on the oldest planation surfaces could be explained by a smaller rate of reduction as compared to the inward extension rate of the weathering front (Lepsch et al., in prep.). Under these circumstances the saprolite thickness and the soil weathering degree should be directly related to the time the superficial deposits remained under rainwater action, even when the original soil horizons were eroded.

Another important point that has to be taken into account when relating soils to surfaces is that the criteria adopted on most large-scale geomorphological studies are not sufficiently critical to detect relatively small relief dissections and/or minor local planations. These can be recognized only by detailed local studies, such as the ones using the groundsurface concept (Butler 1959) or the geomorphic surface concept (Ruhe 1969). Also, the real "soil surface" is not generally used by geomorphologists as a mapping criterion, and in many instances the referred surfaces are actually only vestiges of former planation levels. Many of the land segments generically referred to as old surfaces are in fact recent erosion surfaces that may not now bear a regolith, have only shallow, poorly

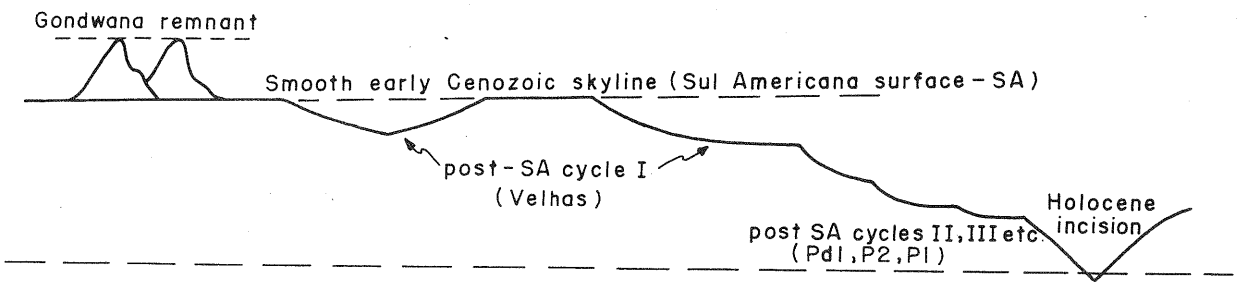


Fig. 1. Diagrammatic profile of the pattern of planation surfaces in South America (adapted from King 1968).

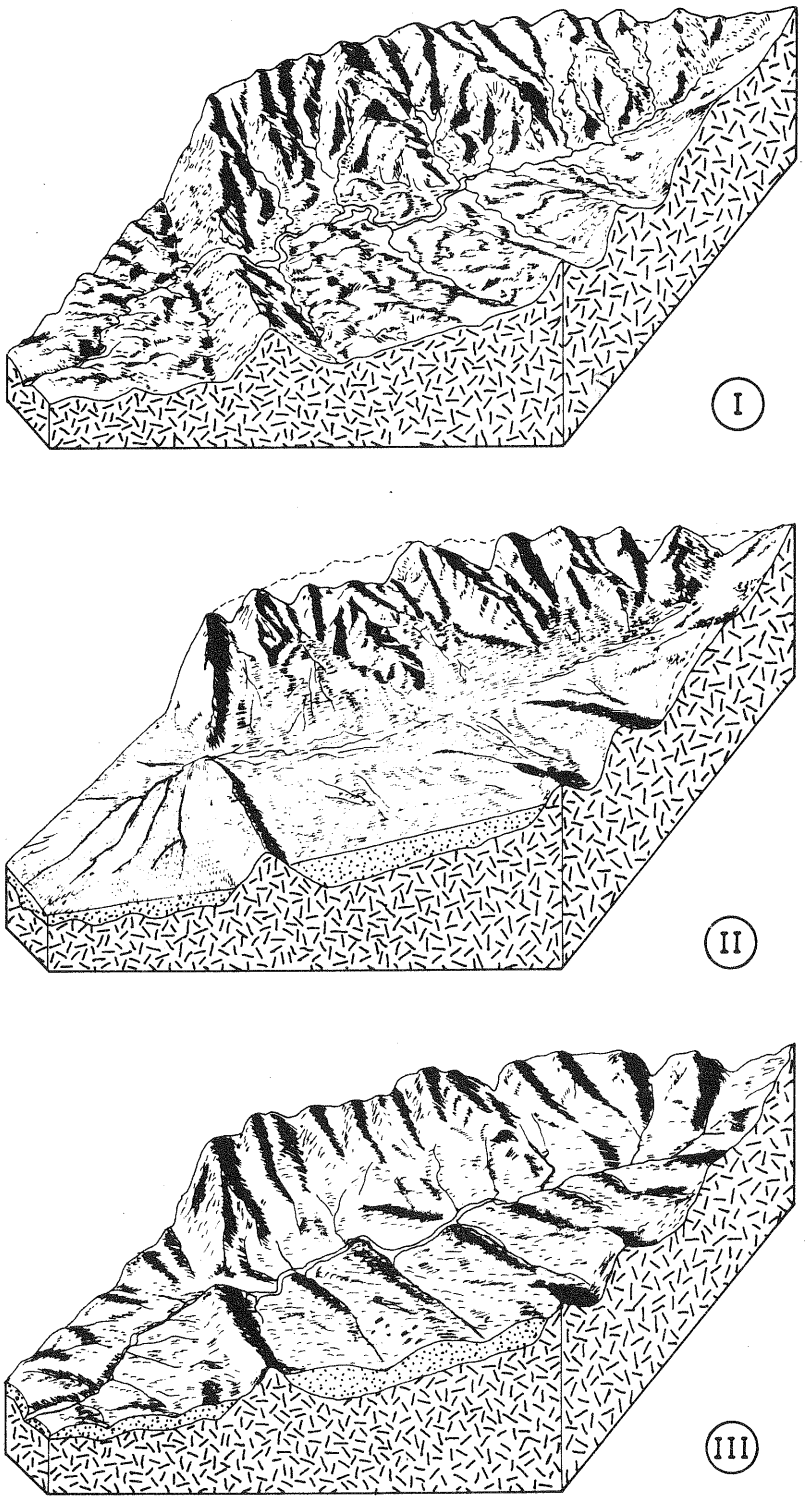


Fig. 2. Schematic representation of a crystalline basin in Southern Brazil before and after climatic changes evolving tropical humid (I and III) to semiarid (II) conditions (adapted from Suguio and Bigarella 1979).

Table 1. Quaternary Events in Southeast Brazil

Time period	Glacial/ interglacial	Climate	Process	Geomorphic features
Holocene		Humid with dry phases	Dissection and sedimentation	Low terraces
Pleistocene	Wisconsin (Würm)	Semiarid	Mechanical morphogenesis	Paleopavement
	Sangamom	Humid	Dissection	
	Illinoian (Riss)	Semiarid	Mechanical morphogenesis	Pediment P1
	Yarmouth	Humid	Dissection	
	Kansan (Mindel)	Semiarid	Mechanical morphogenesis	Pediment P2
	Aftonian	Humid	Dissection	
	Nebraskan (Gunz)	Semiarid	Mechanical morphogenesis	Pediplain Pd1

Source: Bigarella and de Andrade (1965).

developed soils, or correspond to truncated, deep, highly weathered superficial deposits.

Butler (1959), for instance, stated that: "[for geomorphologists] the surfaces are defined in terms of relative erosion, form and shape, or agency of formation or in terms not involving soil criteria. Hence, it cannot be assumed that the definition of surfaces by either geologist or geomorphologist will bear any constant relationship to those defined by the pedologist." However, Daniels, Gamble, and Cady (1971) disagreed with Butler's statements stating that "if the geomorphic work is detailed and accurate then the surface of interest of soil scientists and geomorphologists are the same."

When one does not have detailed and accurate geomorphic surface studies, the general relief features and large-scale defined surfaces can be examined and some interpretation about the age and/or stability of their soils may be inferred, but only after taking into account the above mentioned restrictions on scale of mapping and definition. On the following soil-landscape examples, a terminology was attempted in order to distinguish the degree of preservation of planation surfaces from the presumably best preserved to the more eroded. These terms include: "slightly dissected," "partial remnants with incised valleys," deeply dissected surface," and "(eroded) vestige."

General Oxisol-Planation Surface Relations in Brazil

Continental platforms comprising old planation surface remnants and their correlative superficial deposits form the major Oxisol regions within the humid tropics. Most of these landscapes stand over a very ancient crystalline/metamorphic platform, have modest altitude elevations, and do not present mountain chains related to Tertiary folding, such as the Andes.

Moormann and Van Wambeke (1978), comparing soil weathering on Precambrian crystalline formations in West Africa with those of central Brazil, have stated that: "In these two cases, on different continents, but with comparable present day climate and natural vegetation, neither the average soil depth nor the degree of weathering in the solum is comparable—both are much greater in the Brazilian case." According to them the explanation for these differences was based on the repeated migration of the Sahara southward during the Pleistocene, promoting strong dessication and denudation of West Africa, where topographies are more dominated by partially or totally stripped etchplains.

A comparison of generalized maps of geomorphic cycles (Braun 1982) and soils (EMBRAPA 1981), Figures 3 and 4, shows some correspondence between well-drained (non-Aquox) Oxisol areas and old planation surface remnants of the Sul Americana and Velhas cycles. The relationship is more evident when one considers also, together with Oxisols, the Quartzipsamments that are similar to the Oxisols, except for the low clay contents.

However, comparison of Oxisol and Quartzipsamment areal distribution (Fig. 4) with their equivalent Sul Americana and Velhas areas (Fig. 3) shows a less continuous and less extensive Oxisol pattern. This may be due to differences in the original scale of maps. The EMBRAPA (1981) soil map is on a much larger scale. Also, Braun's (1982) old geomorphic cycle areas encompass several small discontinuous, dissected remnants as well as eroded vestiges (Lepsch et al., in prep.).

The area related to the Sul Americana cycle is dominated by the Red Yellow and Dark Red Oxisols, sometimes associated with the Quartzipsamments. Many of them are Acrusthox and Acrorthox. Other areas, within the marginal Tertiary deposits (Barreiras Form.), have kaolinitic yellow (or xanthic) Oxisols. Noteworthy Oxisols are rare in the western Amazon area referred to as the Solimões depression (Fig. 3), notwithstanding this being one of the highest rainfall areas of the country. The Solimões area has mostly soils with argillic horizons (Plinthaquults and various plinthic subgroups) including also

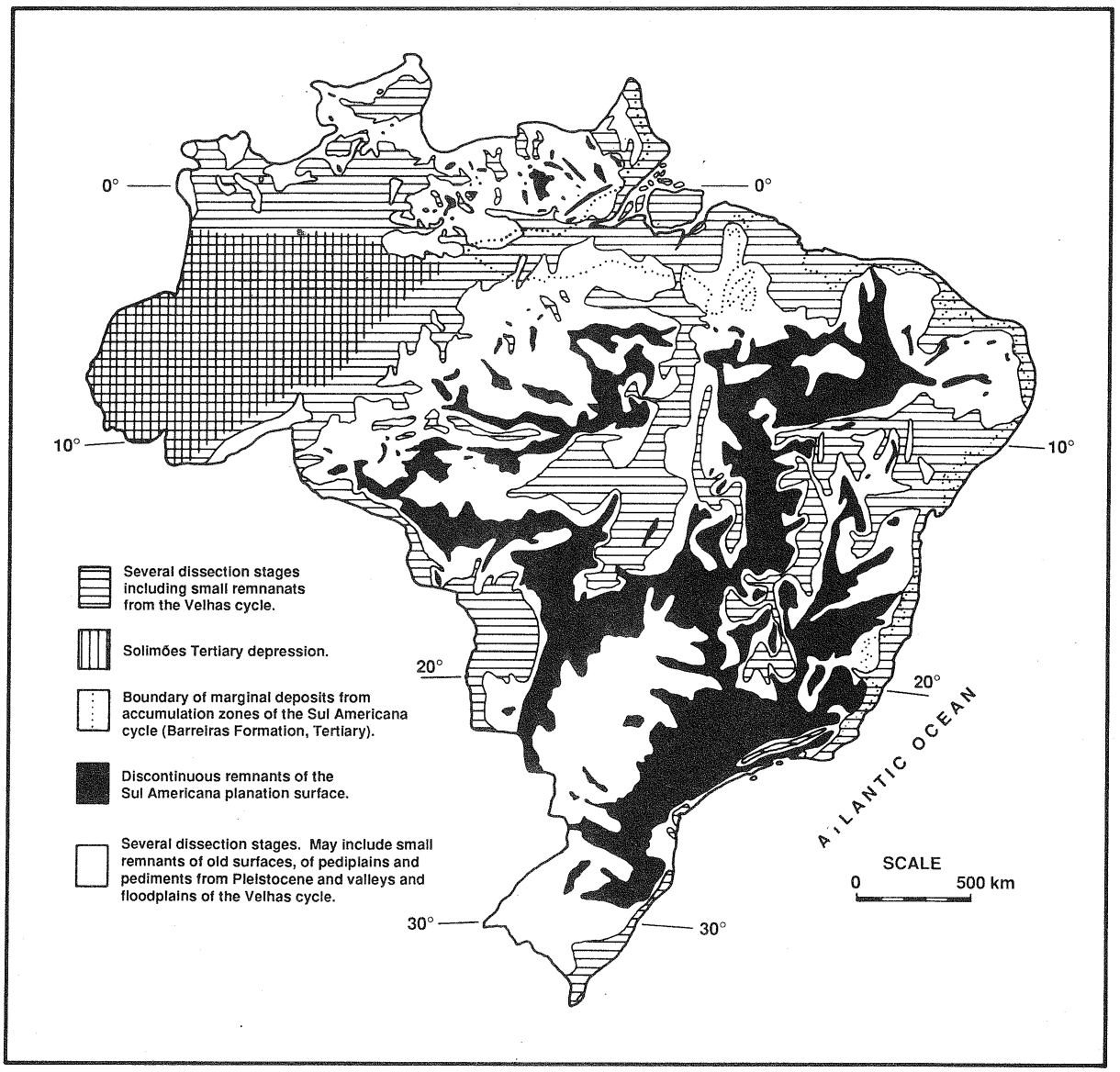


Fig. 3. Generalized aereal distribution of remnants of the main geomorphic cycles in Brazil (according to Braun 1982).

some soils with high CEC clays (Sombröek and Camargo 1983; EMBRAPA 1981).

On the other hand in some instances soils do not conform with present semiarid climatic conditions as in a few Oxisol areas within the Brazilian northeast. These are considered to be relict features of former humid climates.

The most common parent material of the Oxisols has been frequently referred to as pseudo-autochthonous or reworked material that may have been subject to many previous cycles of pedogenesis and transportation. However, this generalization has been contested, at least, in two situations. Areas with parent rocks of mafic (basic) composition were mentioned by Buol (1978) as one possibility for in situ Oxisols. Bennema (1983) has also contested the generalized idea that all Oxisols would be always formed on these reworked superficial deposits arguing that, on the older and higher planation surface sites, the slow wearing down would remove most of these deposits.

In the lower adjacent areas succeeding the Sul Americana planation, the reworked superficial deposits, related to the alternation of semiarid and humid tropical climate of the Pleistocene, seem to have played a more definitive role in the formation of Oxisols. When still covered by their original superficial deposits, originated from the reworking of the thick regolith developed under humid conditions (Fig. 2), these Pleistocene remnants have various kinds of Oxisols and also some Quartzipsamments. However, in the semiarid Brazilian northeast, two of the main pediplaned, low relief areas (locally named Sertaneja and Soledade surfaces, both related to the

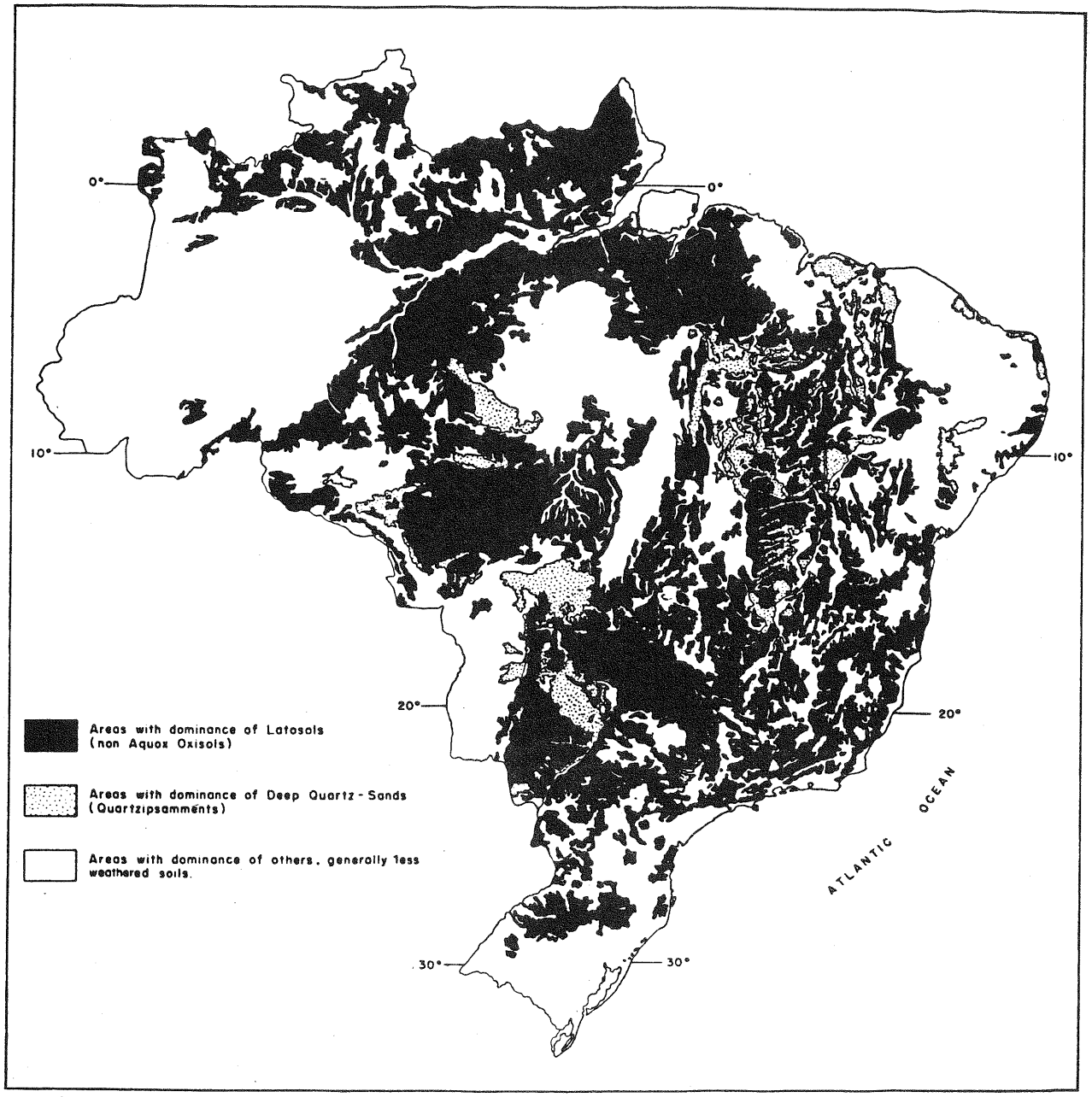


Fig. 4. Main Oxisol (non-Aquox) and Quartzipsamment areas of Brazil (generalized from EMBRAPA/SNLCS Soil Map of Brazil, 1:5,000,000, 1981).

Velhas cycle) differ considerably from humid areas. They neither have thick superficial deposits nor Oxisols. These sites were possibly subject to etchplanation processes that removed any depositional mantle that might have been eventually present.

Specific Oxisol-Landscape Studies

The generalized comparisons, as the ones discussed from Figures 3 and 4, are useful for an understanding of large-scale Oxisol distribution patterns as well as to position local soil studies within the broad continental geomorphic framework. However, in order to better understand how Oxisols are formed, detailed studies on stratigraphy of superficial deposits and spatial distribution of geomorphic surfaces and soils are necessary.

General soil landscape studies involving Oxisols were reported in the Central Brazilian Plateau (Feuer 1956) in the Eastern Brazilian Highlands (Bennema, Camargo, and Wright 1962), in Southern Brazil (Queiroz Neto 1975; Klamt and Beatty 1972), and for various parts of eastern South America (Lepsch et al., in prep). More detailed and localized Oxisol landscape studies were carried out, among others, in the central highlands of Brazil (Cavalcante 1977; Rodrigues and Klamt 1978; Carmo, Curi, and Resende 1984), in eastern Brazil, (Demattê and Holawaychuc 1974; Lepsch and Buol 1974; Carvalho 1976; Lepsch, Buol, and Daniels 1977; Perez Filho, Donzelli, and Lepsch 1980; Moniz and Buol 1982; Tie-Bi-Youan et al. 1983; Carvalho, Chauvel, and Gonçalves 1983). All these studies reported Oxisols preferentially on the older and/or more stable part of the landscape and of less-weathered soils, mostly with argillic horizons, on the nearby younger and or less stable slopes. Although they sum up considerable information on Brazilian Oxisol-landscape relationships, very few of them have all the desirable detail either on stratigraphy of superficial deposits, geomorphic surface mapping, or quantification of spatial variability within the reported toposequences.

A few of these studies that are more related to sites visited during the VIIIth ISCW field trip will be reviewed below in some detail.

The São José dos Compos Area

The São José dos Campos area is within a rift valley located between crystalline-metamorphic Precambrian horsts and filled in with Tertiary-Quaternary sediments (Fig. 5). The valley is drained by the medium course of the Paraiba do Sul and Parateí rivers, flowing between the Mar and Mantiqueira mountain chains, approximately parallel to the Atlantic coastline. The local general landscape features are linked to a long history involving sequential local tectonics, old planations, and dissection cycles.

After the breakdown of the Gondwanaland protocontinent, while the African and South American plates were being disjoined, the coastline was almost continuously uplifted due to stresses released from the active Atlantic shelf trench. These forces promoted an asymmetric coast uplifting, a general westward tilting, and a marginal crustal arching. This arching promoted northwestward-tilted blocking from extensive fault line scarps, originating the Mantiqueira and Mar mountain chains. All these orogenic movements have changed the proto-Paraiba streams, compelling then to run either from parallels to the coast or toward the west, even though their headwaters are close to the western Atlantic border.

During the Paleogene, there was a period of relative crustal stability, and conditions were suitable for a landscape planation cycle recognized as the Paleogenic or "Cristas Medias" by De Martonne (1940) or as the Sul Americana by King (1956). While in the Central Plateau of Brazil the crustal stability period remained relatively unaffected, along the Paraiba Valley there was some important block faulting originating the Taubaté graben. This graben was accentuated in the Middle Tertiary, thus promoting the subsidence of the old Paleogenic planation surface that now is probably under the Tertiary-Quaternary basin sediments (Titarelli 1975; Coltrinari and Coutard 1978).

During the Neogene Period, after a session of the Tertiary intracratonic sedimentation, there was a general planation shaping an extensive pediment (Pd1) whose remnants are now about 650 to 670 m of altitude (Fig. 5). This surface was subsequently subject to minor planation episodes (P2? in Fig. 5) and to stream dissections. Superficial deposits correlative to these Pleistocene planations are present on most of the near level summits and gentle low hill slopes.

The ISCW pedon no. 1 site probably corresponds to a remnant of a Pleistocene local planation episode (Fig. 5.) that may be related to the semiarid phase contemporaneous to the Kansan glaciation (Table 1). The pedon is a kaolinitic Oxisol commonly associated with Tertiary pellitic sediments that have their largest representative area within the Barreiras formation (Fig. 3).

Northwest of the main graben faultline scarpment toward the Mantiqueira Sierra (area between ISCW pedons 1 and 2) there is a dissected plateau whose aligned rounded summits were interpreted as vestiges of the Paleogenic (Pd2) surface (Coltrinari, Coutard, and Nakashima 1978) corresponding to King's (1956) Sul Americana. Most of the slopes of this rolling high landscape grade to the depositional surfaces of the nearby creeks. According to Ruhe's (1969) criteria, their geomorphic surface may be interpreted as being of the same age as these young depositional sites. However, one has also to take into account that the rate of denudation has been relatively slow as compared with the longer and steeper slopes of the nearby escarpments and mountains; these rolling hills stand as marks of very old surfaces, and thus the rate of erosion should not have been much different from the rate of inward extension of their weathering front, preserving some of the position shape of the old surface, now identified by the aligned summits.

In Figure 5 this rolling plateau is depicted as "Sul Americana dissected remnants." One can expect neither in situ remains of original Sul Americana superficial deposits nor even their "polygenetic" remains. Nevertheless, this assumed slow rate of denudation seems to be confirmed in this area, since it has a very thick saprolite overlayed either by Oxisols or by oxic subgroups of some Inceptisols mostly on convex 10 to 20 percent hillslopes.

These dissected-plateau Oxisols commonly have a relatively thin oxic horizon (50 to 150 cm) and/or small

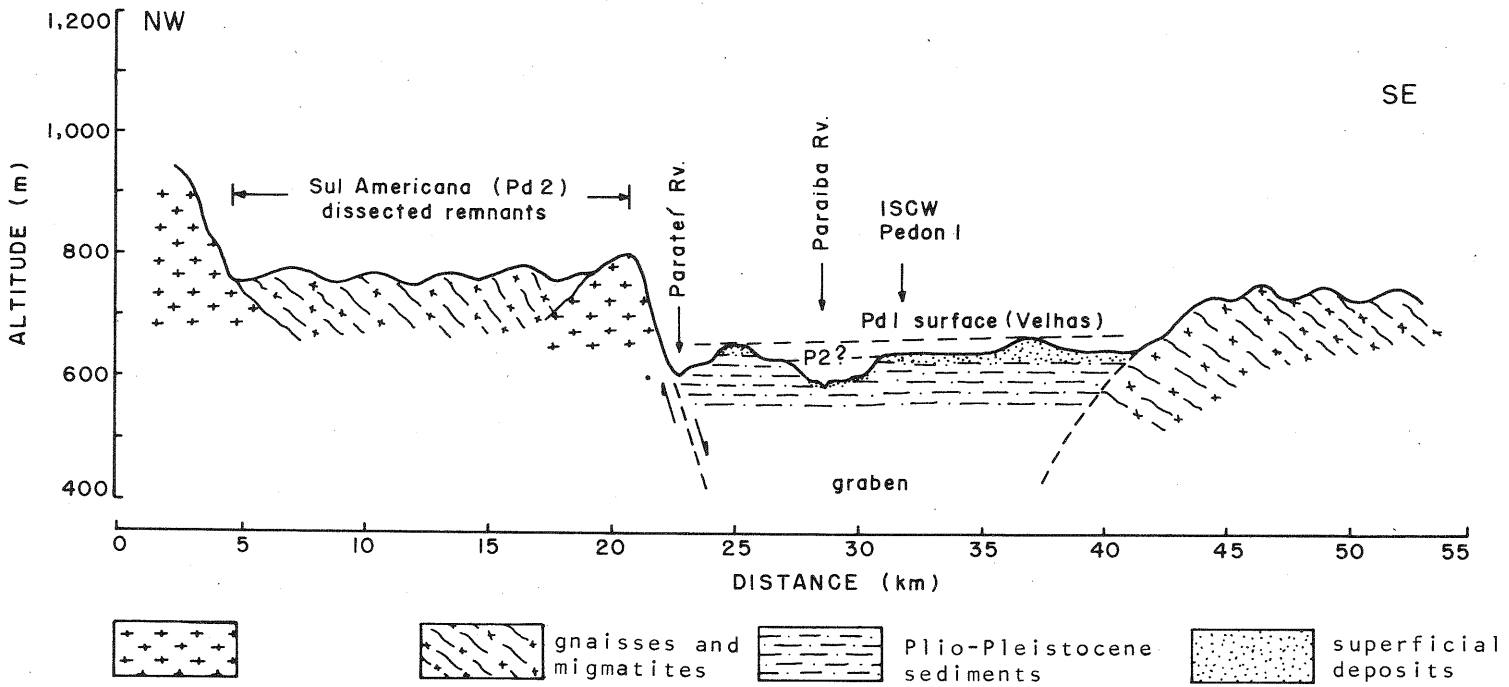


Fig. 5. Semischematic cross-section showing the location of ISCW pedon no. 1, in the Sao José dos Campos valley in relation to surrounding major landscape and substrata features (adapted from Coltrinari, Coutard, and Nakashima 1978).

amounts (3 to 10 percent in fine sand) of weatherable minerals (especially muscovite). Stone lines between the B and C horizons are also very common. Over the stone line the colluvium probably is a mixture of reworked old soil materials with materials derived from the stone line underlying saprolite that still retains some of the original rock structure. These soils may be interpreted as examples of Oxisol-Inceptisol intergrades. In the slight concave minor adjacent valleys, buried dark layers resembling sombric horizons are commonly found, suggesting that they were aggraded by colluvium originated from the nearby slopes (Coltrinari, Coutard, and Nakashima 1978).

The Bragança Paulista Humox

The Bragança Paulista area is located within the Mantiqueira mountain chain borders. The landscape is characterized by some residual crystalline massifs, whose summits are at about 1000 m altitude, along with their connected somewhat elongated lower hills at about 799-800 m height (Fig. 6).

Over the slopes of the higher massifs there are relatively shallow and less-weathered Ultisols, Lithic Inceptisols, and rock outcrop. The elongated piedmont hills can be separated into two topographic levels that were interpreted by Queiroz Neto and Castro (1974) as related to the Pd1 and P1 Pleistocene pedimentation phases. Superficial deposits about 3 to 4 m thick, bearing Oxisols, are present on both of these levels. Generally, pedons with very thick (about 1 m) dark-colored epipedon occupy the Pd1 surface tops. On the lower levels dark epipedons are rare and found over layered colluvium, possibly originating from nearby higher Humox areas (Queiroz Neto 1975).

The overall landscape evolution model of this area seems to fit well the sequence portrayed in Figure 2, corresponding to two succeeding additional dry humid cycles below block diagram III.

The ISCW pedon no. 2 is an example of a Humox commonly found in this region and elsewhere in similar landscapes of the Mantiqueira and Mar *cordilleras*. Their genesis is not yet completely understood but it seems that the thick dark epipedon is a relic feature derived from former "unique" environmental conditions favorable to organic matter accumulation to great depths and, until now, maintained due to surface stability and favorable clay-humus adsorption. These special environmental conditions apparently were not repeated after the Pd1 cycles since their nearby, younger but also very stable, P1 levels (Fig. 6) do not normally present these thick umbric epipedons.

The Rio Claro Toposequence

ISCW pedons 3 to 6 are in the Peripherical Depression of São Paulo within their characteristically smooth relief areas of dissected pediplains.

Pedon nos. 4, 5, and 6 and "extra I" are located on the same toposequence studied by Lepsch and Buol (1974). Three geomorphic surfaces were identified; the gentle undulating top (pedon 4) is the oldest site, related to the Rio Claro surface of Middle Pleistocene age. The adjacent 3 to 8 percent slopes (pedons 5 and 6) correspond to a younger erosion surface cut into the Rio Claro superficial deposits and underneath shale (Fig. 7). The ISCW extra I pedon, located close to a nickpoint on the third youngest surface on the toposequence, does not have an oxic horizon.

There is a toposequence gradation from soils with only an oxic subsurface horizon (pedon 4) to soil with argillic horizons on top of the oxic horizon (pedons 5 and 6) to soils with only an argillic subsurface diagnostic horizon (extra I pedon). The oxic horizon has its greatest expression where the surface is older and where there is a thicker soil mantle derived from Rio Claro superficial deposits. The argillic horizon appears where the surface is younger and the soil mantle is both shallower, less weathered, and derived from a mixture of preweathered superficial deposits and entrapped saprolite. It is also expressed more with increasing downslope contribution of the illitic shale to the parent material. Differences from oxic to argillic were explained by Lepsch and Buol (1974) as due to lessivage being at present the dominant process in the material containing the lesser weathered superficial deposit while absence of lessivage and prolonged pedoturbation exerts dominance in the Oxisol. Rates of lessivage were hypothesized to be proportional to the amounts of "contamination" with unweathered noniron-cemented clay from the shale material.

The development of argillic horizons within erosional slopes cutting deep superficial deposits of "oxic" materials exemplified on this sequence is a common feature and also has been studied on similar topographic situations elsewhere. Formation of the argillic has been attributed to "activation" of clays, thus freeing them for lessivage upon removal of iron oxide coating either by shear stresses action (Beinroth, Uehara, and Ikawa 1974), by laterally moving water promoting short-term reduction of iron oxide (Lepsch, Buol, and Daniels 1977), or silica and base enrichment of the soil solution media (Carvalho, Chauvel, and Gonçalves 1983). Laterally moving groundwater, promoting formation of blocky structure initiated by saturation-dissection-induced compression has also been hypothesized to explain the formation of these argillic horizons from very fine granular structured oxic materials (Moniz and Buol 1982).

The Ribeirão Preto Basaltic Province

The Ribeirão Preto comprises one of the largest continuous red basaltic soils areas of Brazil. The basalts are from the lower Cretaceous great Parana Trap that flowed over and between eolian sandstone strata. During the middle and lower Cretaceous this trap was completely covered by fluvial and lacustrine sandstones and siltstones of the Bauru group. These Bauru sediments in this area were thereafter almost completely removed during Pliocene-Pleistocene dissection planation phases, exposing the basalts and some of their contemporary eolic sandstones.

Soil moisture regimes are udic transition to ustic (*Cwa* climate according to Köppen). The topography is dominated by gentle, undulating low hills, small and scattered protruding mesas or *cuestas* remnants, and some continuous table-shaped interfluves. These landscape features are probably derived from the polycyclic Pleistocene events due to the alternating

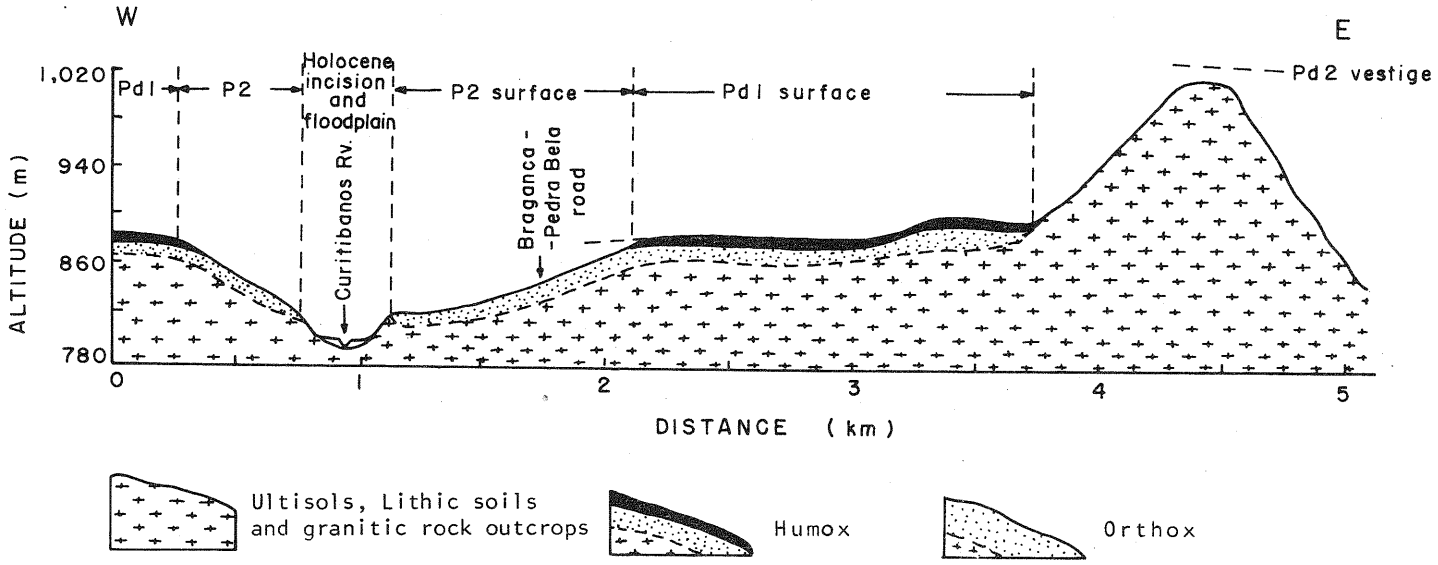


Fig. 6. Cross-section along the Curitibanos River valley, north of Bragança Paulista, SP, showing relationships between landscape elements substrata and the Humox and Orthox (adapted from Queiroz Neto and Castro 1974, and from Queiroz Neto 1975).

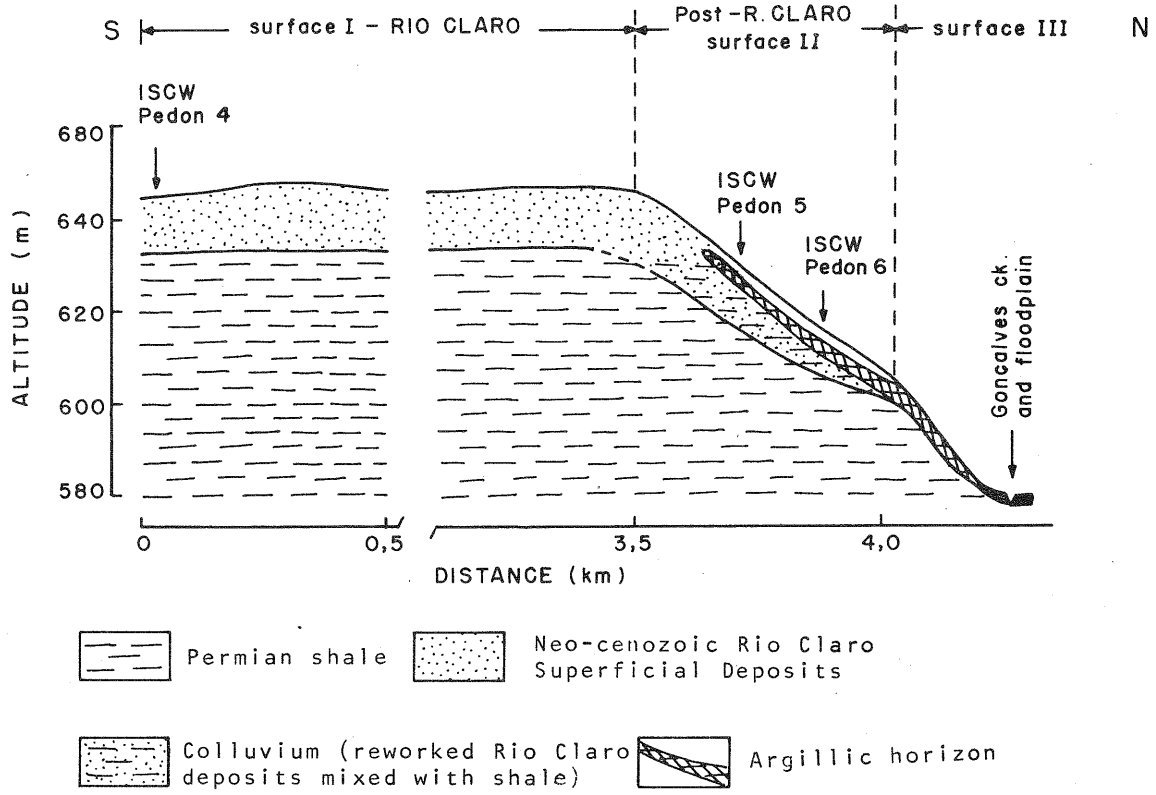


Fig. 7. Semischematic cross-section of the Rio Claro toposequence showing position of ISCW pedons nos. 4, 5, and 6 in relation to the geomorphic surfaces and substrata (adapted from Lepsch and Buol 1974).

humid and semiarid cycles (Pd1, P2, and P1, Table 1). Small remnants related to the Sul Americana surface can be found only on surrounding higher areas that are still mantled by the Bauru sandstone, such as the Franca Plateau, where ISCW pedons 8 and 10 are located.

On the Ribeirão Preto gentle undulating low hills and high almost flat interfluves, the dominant soils are the dusky red (hematitic) Oxisols, locally known as *Latossolo Roxo*. According to Oliveira and Prado (1983), these may be either Typic Acrorthox, Haplorthox, or Eutrorthox. There are also a few Acrorthox with considerable amounts of petroplinthite in some of the summit areas. Their parent material is described as thick (more than 2 m) reworked superficial sediments, mainly derived from the local thoelitic basalts, but also with some contribution from coarse materials derived from previously overlying sediments. Quartz, found in considerable amounts in the soils, is an indication of the contribution of the sandstones to the parent material. These deposits may have been subject to various weathering cycles and eventually may have been dissected and mixed with some less-weathered products pertaining to the more recent erosion of fresh regolith underlying the superficial deposits.

Acrorthox, like ISCW pedons 7 and Extra II, are found mostly on the almost flat slopes (2-3 percent), whereas the Haplorthox and the Eutrorthox (ISCW pedon 8) are found mostly on slightly steeper slopes (3-8 percent) where surface drainage streams are more frequent. The Eutrorthox are formed exclusively in superficial deposits derived from basic rock. On the moderated hills (8-20 percent), or steep scarp slopes, there are usually Oxisols, except for a few pedons with relatively thin oxic horizons over basalt (shallow *Latossolo Roxo*, according to Oliveira and Prado 1983). On these younger rejuvenated areas there are soils with argillic horizons either with low CEC clays (Paleudalf or Paleudult, both rhodic or with high CEC clays and Typic Argiudoll). They generally are associated with shallower soils of the escarpment free faces (Hapludoll and Udorthent, both lithic).

Carvalho, Chauvel, and Gonçalves (1983) have studied soil variation along a toposequence from the base of a small basaltic mesa hill remnant toward its footslope pediment (Fig. 8). On the backslope, very near the hill base, they have described a relatively shallow brown soil (probably a Typic Argiudoll) associated with a thicker dusky red and blocky structured kaolinitic *Terra Roxa Estruturada* soil (probably Rhodic Paleudalf) changing progressively downslope into the essentially gibbsitic *Latossolo Roxo* (Fig. 8). The latter is an Acrorthox with typical very fine, granular "coffee powder" structure and sharp contact with the underlying basalt, which is a few centimeters below a stoneline.

The less-weathered brown soil (Argiudoll) and the *Terra Roxa* (Paleudalf), according to Carvalho, Chauvel, and Gonçalves (1983), correspond to a rather particular situation

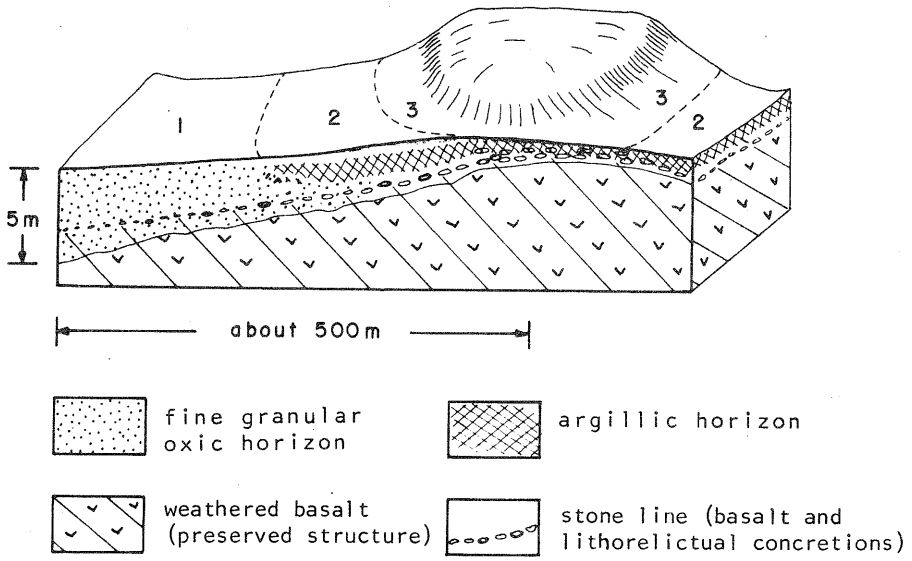


Fig. 8. Schematic block diagram of the Ribeirão Preto toposequence with associated soils. 1. *Latossolo Roxo* (Acrorthox), 2. *Terra Roxa Estruturada* (Rhodic Paleudalf), and 3. Brunizem (Hapludoll) (adapted from Carvalho, Chauvel, and Gonçalves 1983).

due to the proximity of weathering basalt: water moving down from the fresh basalt to induce a silica and base-saturated medium inhibiting gibbsite formation. Silans, found in the base of the less-weathered soils and disappearing gradually toward the gibbsitic soil, seem to confirm this evolution.

The general soil-landscape relationships that can be inferred from studies in the Ribeirão Preto area point out that Oxisols are present almost exclusively on the more gentle slopes in a geomorphic position where reworked superficial deposits, probably of polycyclic origin, have been deposited and preserved. Oxisol formation also occurs where these deposits are not receiving enriched water that has moved laterally, either passing through an extensive soil volume or through a fresh weathering rock zone.

In this region, Oxisols are not normally found on erosional surfaces cutting basalt, contrasting with other tropical areas where Oxisols have been reported on residual material from mafic rocks, as for instance in the perudic area of Northeast Australia (Sleeman and Lepsch, in press). This might be because, for the development of Oxisols in these residual in situ materials, a higher rate of soil leaching would be necessary. In Ribeirão Preto rainfall is about 1400 mm yearly while in Northeast Australia it is around 3000 mm. Also noteworthy is the fact that the in situ developed basaltic Oxisols, reported by Sleeman and Lepsch (in press), have an oxic horizon with strong angular blocky structure, especially in their lower part, contrasting with the more typical very fine granular structure with "massive appearance" or "pseudostructureless" soil structure of the Ribeirão Preto *Latossolo Roxo*.

The São Gotardo Plateau

Soil-landscape relationships in the São Gotardo plateau were studied by Carmo, Curi, and Resende (1984). The extensive gentle level plateau top is related to the Sul Americana surface and is mantled by fine-sized superficial deposits that probably received contributions of Cretaceous basic tuffs. These tuffs are exposed on lower dissected areas adjacent to the plateau tops (Fig. 9) and originated from the nearby Patos de Minas volcanic region.

Soils from the almost leveled plateau surface, where ISCW pedon 11 was examined, are highly weathered Typic Acrorthox with reddish yellow colors. These soils are apparently "too yellow" for the relatively high iron contents (about 16 percent of "free" Fe_2O_3). The high iron content is explained as an inheritance from ferromagnesian minerals from the tuffs, whereas the yellower colors are due to the formation of goethite only because, presumably during the first stages of soil formation before dissection of the nearby rivers, the planation surface had somewhat poor drainage conditions (Carmo, Curi, and Resende 1984). More details on soil color–iron oxide relationships were also studied by Curi and Franzmeier (1984) in a basaltic toposequence in Itumbiara, a few kilometers north of ISCW pedon 14.

Soils which have developed over the exposed, basic tuffs valley sides are either dark red Haplic Acrorthox (like ISCW pedon extra III), when over the pediment shoulders, remnants, or Alfisols and Mollisols on the more recently dissected steep valley sides (Fig. 9). All these soils from rejuvenated areas had the semideciduous forest as their primeval vegetation contrasting with the edaphic savanna or *cerrado* of the near level upland plateau.

The *Latossolo Roxo* (Haplic Acrorthox) can be found on 10-20 percent slopes normally too steep for basaltic Oxisols. (In the Ribeirão Preto area they are not common on slopes greater than 10 percent.) This apparent exception for Oxisols on such steep slopes was pointed out by Carmo, Curi, and Resende (1984), who explained it as due to the higher permeability of the tuff parent material, when compared to the basalts. This would

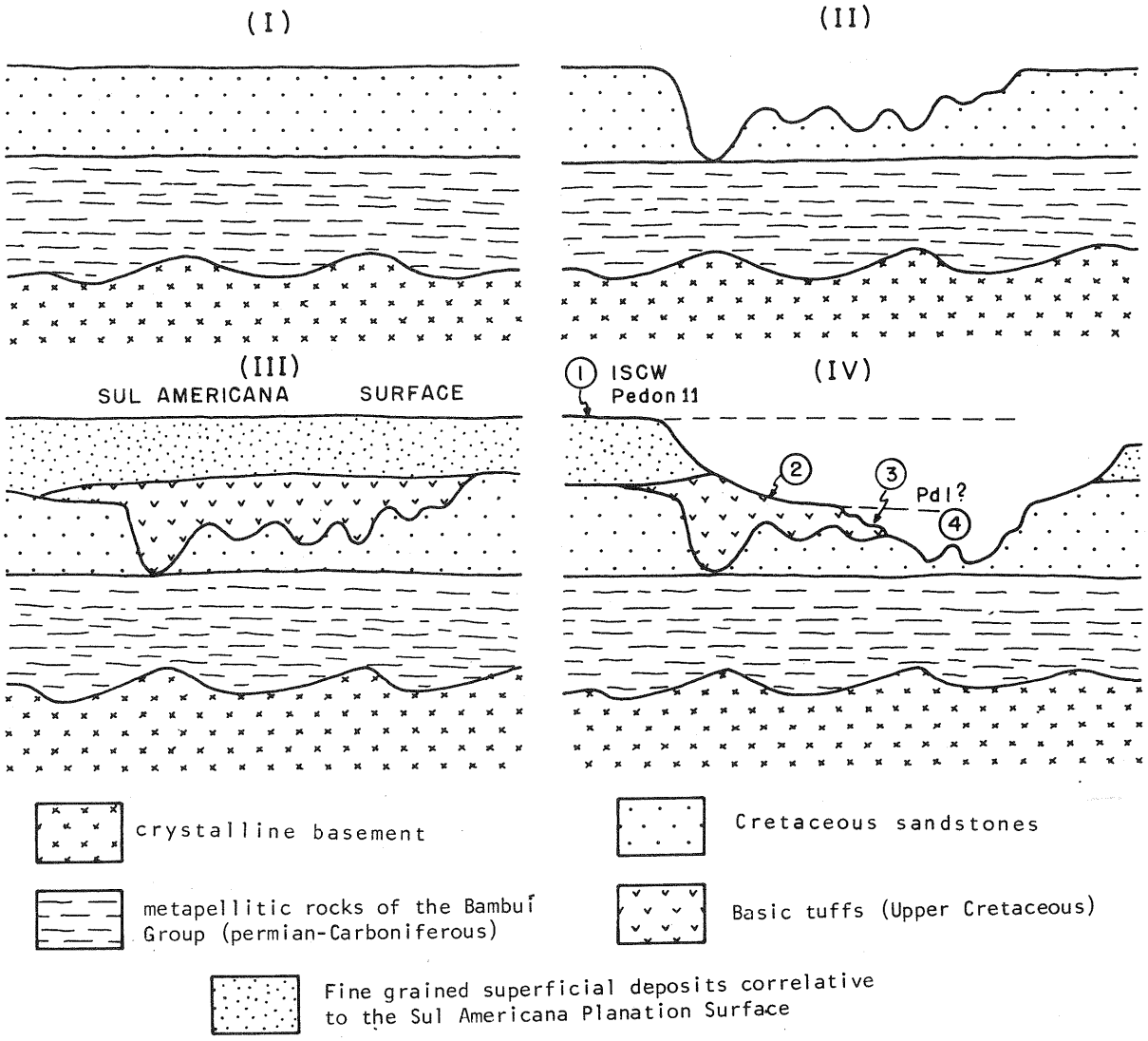


Fig. 9. Landscape evolution hypothetical model and soil distribution along the São Gotardo plateau: 1. Typic Acrothox (*Latossolo* var. *Una*), 2. Haplic Acrorthox (distrophic *Latossolo Roxo*), 3. Alfisols and Mollisols (*Terra Roxa Estruturada* and Reddish Brunizem), 4. Inceptisols and Entisols (Cambisols and various lithic soils) (adapted from Carmo, Curi, and Resende 1984).

induce a high rate of vertical water percolation, thus favoring the formation of oxic horizons instead of the commonly found argillic one, restricted to where considerable amounts of water flow laterally in the soil.

The Central Brazilian Highlands

The central Brazilian landforms are classic examples of the result of multiple erosion cycles (Feuer 1956; Cline and Buol 1975). The planation surfaces are on nearly level to gentle undulating plateau tops, known as *chapadas*, at elevations of about 1000 to 1200 m. The highest level is the most extensive and best-preserved remnant of the Sul Americana cycles.

The area is underlain by Precambrian crystalline metamorphic rocks, but younger Neocenozoic superficial deposits, related to local minor planations, are a common feature. The relative resistance to geologic erosion of these *chapadas* was explained by Lepsch et al. (in prep.) based on the following factors: (a) topographic situation on the major continental divide, being the last and least affected by erosion due to scarp retreat; (b) absence of widespread Quaternary denudational processes, such as glaciation, etchplanation, and orogenic movements; (c) low relief; (d) lateritic (or petroplinthite) concretions edging the plateau borders, decreasing scarp retreat rate; and (e) high permeability of the superficial deposits, even when very high in clay, preventing stream channel establishment.

The origin of the edaphic savanna or *cerrado* vegetation dominant on these plateaus has been interpreted by Queiroz Neto (1982) as a relict feature, from former dryer climates, which has been maintained for a long period due to relative surface stability and nutrient poor, very acid soils. These *cerrados* are now in a natural regressive process, since semideciduous forest can be found on the youthful adjoining valleys.

The ISCW pedons 18, 20, and 21 are examples of the Acrustox prevailing on the upper land-surface pertaining to the Sul Americana remnants and referred to by Feuer (1956) as the "first erosion surface." These sites, according to Bennema (1983), may have soils developed from in situ weathered rock. He argues that, on these oldest and more stable remnants, some presumptive very slow rate of erosion over the whole Pleistocene would remove the Sul Americana original superficial deposits. Although the ISCW pedons sampled do not present any clear evidence of lithological discontinuity, it would be necessary to do more specific research on this subject in order to verify Bennema's hypothesis.

The ISCW pedon no. 22 represents a Haplustox of the pediment like Feuer's (1956) "second erosion surface." Pedon 23 is an Aquox a few meters below pedon 22 that is commonly found on semipermanent groundwater and seepage affected areas. Pedogenetic relationships on a toposequence close to these pedons were by Cavalcanti (1977) and Rodrigues and Klamt (1978).

Above the Sul Americana plateau are a few high protruding remnants of yet older planation surfaces, referred to as Gondwana or post-Gondwana cycles (King 1956). The Serra de Sant'Ana, at about 1500 m height, is one of them. However, although sometimes referred as a pre-Sul Americana surface remnant, it does not present any level top terrain, and the mountain slopes there grade directly to their nearby creek valleys. The real surface has been destroyed, superficial deposits have been removed, only remnants of weathering zones remain, and in fact shallow soils with youthful characteristics are dominant in this area.

In the lower post-Sul Americana areas adjoining the *chapadas*, there is a diverse physiography that includes the several serial Pleistocene denudation cycles and recent valley incisions. Over the recent escarpment Inceptisols (some lithic) and petroplinthic Oxisols are common. Petroplinthic soils frequently can be found near the edges of most plateau surfaces (e.g., ISCW pedon 19) but are not common in the soil at distances of more than several hundred meters from escarpments between the planation surfaces (Cline and Buol 1973). According to Sombröek and Camargo (1983), it might be that many of these petroplinthites are relict of former groundwater laterite (possibly Plinthaquox and/or Plinthaqualts) surfaces that were truncated at times of large-scale erosion and the associated drop of the general groundwater level. Because petroplinthite is resistant to erosion, these soils now may be important elements in decreasing slope retreat rate, thus assisting in the endurance of the upland Oxisol areas.

Below the escarpments there are areas 300 to 400 m lower than the highest level surfaces at Brasília. The highest levels at this altitude may be either pedimentlike connected gentle slopes or independent gentle undulating hills whose Oxisol-dominated tops probably are related to early Pleistocene planation cycles. Pedons 15, 16, and 17 apparently are on these sites. These Oxisols are usually shallower and less weathered than the Acrustox from the highest *chapadas* related to Sul Americana cycles. The valley sides, as well as some adjacent rolling hills more related to erosional relief, generally have low CEC soils with argillic horizons. The parent material of these soils with argillic horizons is often a relatively shallow colluvium, and stonelines may appear in the soil profile as in ISCW pedon 16 and 17.

The landscapes for the Central Brazil Highlands, being good examples of polycyclic landscape evolution, including well-preserved remnants of the oldest surfaces and of several important Pleistocene geomorphic cycles, stand as a region of much relevance to Oxisol chronology and evolution weathering studies and are of great importance to the development of a morphogenetic soil classification system.

Acknowledgments

The authors express grateful appreciation to A.C. Moniz and A.M.C. Furlani of Instituto Agronômico for manuscript review and to R.B. Daniels of North Carolina State University for his helpful comments.

References

Beckmann, G.G. 1983. Development of old landscape and soils. *In* Soils: An Australian viewpoint. CSIRO Academic Press, Australia. Pp. 51-72.

Peinroth, F.H., G. Uehara, and H. Ikawa. 1974. Geomorphic relationships of

Oxisols and Ultisols on Kauai, Hawaii. *Soil Sci. Soc. Amer. Proc.* 38: 128-131.

Bennema, J. 1983. Oxisols in Brazil. *In* Proc. of the IVth Int. Soil Class. Work., Rwanda, 1981. ABOS-AGCD, Brussels. Pp. 111-143.

Bennema, J., M.N. Camargo, and C.S. Wright. 1962. Regional contrast in South American soil formation in relation to soil classification and soil fertility. *In* Trans. of joint meet. comm. IV and V intern. soil conf. New Zealand. Pp. 493-506.

Bigarella, J.J., and G.O. de Andrade. 1965. Contribution to the study of the Brazilian Quaternary. Spec. Pap., Geol. Soc. Amer. 84:433-351.

Buol, S.W. 1979. Geomorphology of Oxisols. *In* F.H. Beinroth and S. Paramananthan (eds.). Proc. II Intern. Soil Class. Work. Malaysia, Soil Survey Div., Land Dev. Dept., Bangkok, Thailand. Pp. 37-43.

Butler, B.E. 1959. Periodic phenomena in landscape as a basis for soil studies. CSIRO Aust. Soil Publ. no. 14.

Braun, O.P.G. 1982. Aspectos Geomorfológicos que afetam a interpretação de imagens de sensores remotos no Brasil. *In* Proc. II simposio Brasileiro de sensoriamento remoto, vol. 1. CNPq/INPE-Instituto de Pesquisas Espaciais. Brasília, DF., Brazil. Pp. 25-28.

Brown, E.H. 1968. Planation surface. *In* R.W. Fairbridge (ed.). The encyclopedia of geomorphology. Encyclopedia of earth sciences, vol. III. Dowden, Hutchington & Ross, Inc., Stroudsburg, PA.

Carmo, D.N., N. Curi, and M. Resende. 1984. Caracterização de latossolos da região do Alto Paranaiba (MG). *R. Bras. Ci. Solo*. Campinas 8:235-240.

Carvalho, A. 1976. Solos da região de Marília-Relações entre pedogênese e evolução do relevo. Ph.D. thesis. Instituto de Geociências USP. São Paulo, Brazil. 163p. (Mimeo.).

Carvalho, A., A. Chauvel, and N.M. Gonçalves. 1983. Alteration of basalt and formation of kaolinitic and gibbsitic material in the region of Ribeirão Preto (SP), Brazil. *In* Proc. of the II Int. seminar on laterization processes. São Paulo, USP. I. Astronômico Geofísico. São Paulo, Brazil. Pp. 477-489.

Cavalcante, A.C. 1977. Estudo de latossolos argilosos do planalto central do Brasil. MS thesis. Univ. Federal Rural do Rio de Janeiro, Brazil. 185p. (Mimeo.).

Cline, M.G., and S.W. Buol. 1975. Soils of the central plateau of Brazil and extension of results of field research conducted near Planaltina, Federal District. Ithaca, NY. Cornell Univ., (Mimeo.). 43p.

Coltrinati, L., and J.P. Coutard. 1978. A região do médio do rio Parateí—São Paulo. *In* Coloquio interdisciplinar Franco-Brasileiro "Estudo e cartografaçao de formações superficiais e suas aplicações em regiões tropicais." Vol. II. Guia de Excursões. Fac. Filosofia Ci. e Letras & I. Geografia. São Paulo, USP, Brazil.

Coltrinari, L., J.P. Coutard, and P. Nakashima. 1978. Itinerário da excursão ao Vale do Parateí - SP. *In* Coloquio interdisciplinar Franco-Brasileiro "Estudo e cartografação de formações superficiais e suas aplicações em regiões tropicais." Vol. II. Guia de Excursões, USP, São Paulo, Brazil.

Curi, N., and D.P. Franzmeier. 1984. Toposequence of Oxisols from the central plateau of Brazil. *Soil Sci. Amer. J.* 48:341-346.

Daniels, R.B., E.E. Gamble, and J.G. Cady. 1971. The relation between geomorphology and soil morphology and genesis. *Adv. Agronomy* 23:51-87.

De Martonne, E. 1940. Problemes morphologiques du Brèsil tropical Atlantique. Pp. 106-109. *In* Annales de geographie, gan. 49, no. 277. Pp. 1-27 and no. 278-279. Paris.

Demattê, J.L.I., and N. Holowaychuc. 1977. Solos da região de São Pedro, Estado de São Paulo. *R. Bras. Ci. Solo* Campinas 1(2-3):92-104.

EMBRAPA. 1981. Carta de solos do Brasil. EMBRAPA, Serviço Nacional de Levantamento e Conservação de Solos, Rio de Janeiro. (1:5,000,000 scale).

Feuer, R. 1956. An exploratory investigation of the soils and agricultural potential of the soils of the future Federal District in central plateau of Brazil. Ph.D. thesis. Cornell Univ., Ithaca, NY. 432p. (Mimeo).

Garner, H.F. 1974. The origin of landscape. Oxford Univ. Press, Paris, London. 134p.

King, L.C. 1956. A geomorfologia do Brasil Oriental. *R. Bras. Geografia*, 19:147-266.

— 1968. Gondwana landscape. *In* The encyclopedia of geomorphology. Dowden, Hutchison & Ross, Inc., Stroudsburg, PA.

— 1976. Planation remnants upon high lands. *Z. Geomorph. N.F.* 20(2):133-348.

Klamt, E., and M. Beatty. 1972. Gênese de uma sequência de solos na região do Planalto Médio Riograndense. *Pesq. Agrop. Bras.* Série Agronomia 7:99-109.

Lepsch, I.F., and S.W. Buol. 1974. Investigations in and Ultisol-Oxisol toposequence in São Paulo State, Brazil. *Soil Sci. Amer. Proc.* 38:491-496.

Lepsch, I.F., S.S. Buol, and R.B. Daniels. 1977. Soil landscape relationship in the occidental plateau of São Paulo State, Brazil. *Soil Sci. Soc. Amer. J.* 41:104-115.

Lepsch, I.F., M.N. Camargo, A. Christofoletti, and O.P.Braun. In prep. Soil landscape relations in eastern South America.

Mescherikov, Y.A. 1968. Plains. *In* The encyclopedia of geomorphology. Dowden, Hutchinson & Ross, Inc., Stroudsburg, PA. Pp. 850-855.

Moniz, A.C., and S.W. Buol. 1982. Formation of an Oxisol-Utisol transition in São Paulo, Brazil. I. Double layer water flow model of soil development. *Soil Soc. J.* 46:1228-1223.

Moormann, F.R., and A. van Wambeke. 1978. The soils of the lowland rainy tropical climates: Their inherent limitation for food production and related climatic restraints. *In* 11th Cong. of the Int. Soc. of Soil Sci. Proc. of plenary papers, vol. 2. Edmonton, Canada.

Oliveira, J.B. de, and H. do Prado. 1983. Levantamento pedológico semidetalhado do Estado de São Paulo: Quadrícula de Ribeirão Preto. I. Agronômico (Soil map on scale 1:100,000).

Peres F.A., J.L. Donzelli, and I.F. Lepsch. 1980. Relações solos geomorfologia em várzea do rio Mogi Guaçu (SP). *R. Bras. Ci. Solo*, Campinas 4:181-187.

Queiróz Neto, J.P., and S.F. Castro. 1974. Formações superficiais e Latossolo Vermelho Amarelo Húmico da area de Bragança Paulista, SP. *In* Proc. 28th cong. bras. geol. Porto Alegre, Brazil. Pp. 65-83.

Queiróz Neto, J.P. 1975. Pedogênese no planalto Atlântico-Contribuição a interpretação paleogeográfica dos solos da Mantiqueira Oxidental. Thesis. Dep. de Geografia FFCL-USP. São Paulo (Mimeo.).

— 1982. Solos da região dos cerrados e suas interpretações. *R. Bras. Ci. Solo*, Campinas 6:1-12.

Rodrigues, T.E., and E. Klamt. 1978. Mineralogia e Gênese de uma sequência de solos do Distrito Federal. *R. Bras. C. Solo*, Campinas 2:132-139.

Ruhe, R. 1969. Quaternary landscapes in Iowa. Iowa State Univ. Press. Amer. Iowa.

Sleeman, J.R., and I.F. Lepsch. In Press. Micromorphology of red basaltic soils from North Queensland, Australia and São Paulo, Brazil. CSIRO, Div. Soils Dic. Report. Australia.

Soil Survey Staff, SCS, USDA. 1975. Soil taxonomy: A basic system of soil classification for making and interpreting soil surveys. Agric. Hand. no. 436. SCS, USDA. U.S. Govt. Printing Office, Washington, D.C.

Sombröek, W.G., and M.N. Camargo. 1983. Groundwater laterite and ironstone soils in Brazil, with examples from the Amazon Region. In Proc. of the II intern. seminar on characterization processes. São Paulo. I. Astronômico Geofísico. USP, São Paulo, Brazil, Pp. 541-552.

Suguio, K., and J.J. Bigarella. 1979. Ambiente fluvial. *In* Bigarella et al. (eds.). Ambiente de sedimentação e sua interpretão e importância. Curitiba, Editora Un Paraná, Brazil.

Tie-Bi-Youan, H., I. Sakai, I.F. Lepsch, and A. Chauvel. 1983. Características e gênese de solos da Formação Pariquera-Açu. *R. Bras. Ci. Solo*, Campinas 7:183-190.

Titarelli, A.H.V. 1975. O vale do Parateí. Estudo Geocorfológico. IGEOG-USP, São Paulo, Brazil. Série Tese e Mon., 197p.

THE BRAZILIAN CLASSIFICATION OF LATOSOLS

M.N. Camargo, P.K.T. Jacomine, A.P. Carvalho, and J. Olmos I.L.[1]

Effective soil surveys in Brazil started in the 1950s. The extensive territory, the scarcity of soil scientists, and the urgent need for soil resources information directed at agricultural development led to opting for small scale, low intensity reconnaissance surveys. The need then arose for soil classification at relatively high categorical levels.

The reference base adopted, and later adapted, was the great group and suborder levels of the then official Soil Conservation Service, U.S. Department of Agriculture (SCS/USDA) system (Baldwin, Kellogg, and Thorp 1938) and added modifications (Thorp and Smith 1949). The noun *latosols,* applied to a grouping of tropical soils, has been inherited from a subsequent attempt toward modification of the SCS system (Kellogg 1949).

In the early days, the attempt to perform small scale, extensive, speedy soil surveys through prefixed legend very soon proved unsatisfactory. Thenceforth, the influence exerted by the open and evolving legend model, as required by the envisaged soil survey, imparted parallel adaptations in the reference soil classification scheme.

Within this context, reflexes in Latosols identification and discrimination have been of considerable concern, even more so at present, because of more complete knowledge of their known or hoped for distinctions, and because of their diversified distribution in the country. As major coexisting soils of common frequency within about one-third of the territory, Latosols occur from equatorial humid regions through tropical semiarid, semihumid regions, and subtropical humid mesothermal regions (perudic isothermic), even sometimes subject to light occasional snow falls (Fig. 1).

Course to Present

Initially, the Latosols, like the other main soil classes (great groups), were identified through correlation of soil profile morphological characteristics aimed at distinguishing broad mapping units (primarily soil and secondary relief landscape traits). The standing reference pedon was a specimen identified as modal by R.W. Simonson (pers. comm. 1954), now named a Typic Acrusthox according to *Soil Taxonomy* (Soil Survey Staff 1975). This being the case, the central concept established was pertinent to a highly weathered soil having a deep solum with slight to almost no textural differentiation from the surface downward; faintly expressed horizonation other than from A to B major horizons; and rather gradual to diffuse transitions. Moreover, throughout the very porous B horizon, outstanding in the soil profile due to its intense yellowish red color, the pedon exhibits soft (dry) very friable (moist) consistence, and peculiar undistinctive peds, its structure consisting of very small size aggregates.

The concept essentially had a morphological expression (Barros et al. 1958), undergoing improvement by Bennema, Lemos, and Vettori (1959), much of it being set in contradistinction to the Red-Yellow Podzolics great group (Lemos et al. 1960; Camargo et al. 1962), that is, soils characterized by latosolic B horizons versus textural B horizons. The concept formulation designed for African soils by Kellogg and Davol (1949) stood as a concurrent reference.

Since then, not much diversion has been allowed within the conceptual framing of the overall class of Latosols in Brazil. By and large, a lasting "sense of purity" has been attained by most of the soil surveyors, actually not numerous. A broader conception has been the preference of a few Brazilians, mainly bearing on lateritization/ferralitization processes and related classes of ferralitic soils (Commission de Pédologie et de Cartographie des Sols 1967).

With the progress of soil surveys in the country and the building of knowledge in the little known world of tropical soils, bits of information were added till the middle 1960s which were pertinent to implementation of analytical characterization and coupled to attempts to set apart various types of Latosols in the undeveloped category of subgroups. This has proceeded simultaneous with and through some shared pathways of development toward the 7th Approximation (Soil Survey Staff 1960) up to *Soil Taxonomy* (Soil Survey Staff 1975).

[1] Authors are Soil Researchers at Servico Nacional de Levantamento e Conservação de Solos, Empresa Brasiliera de Pesquisa Agropecuária (SNLCS, EMBRAPA), Rua Jardim Botânico 1024. Rio de Janeiro, Brazil 22460

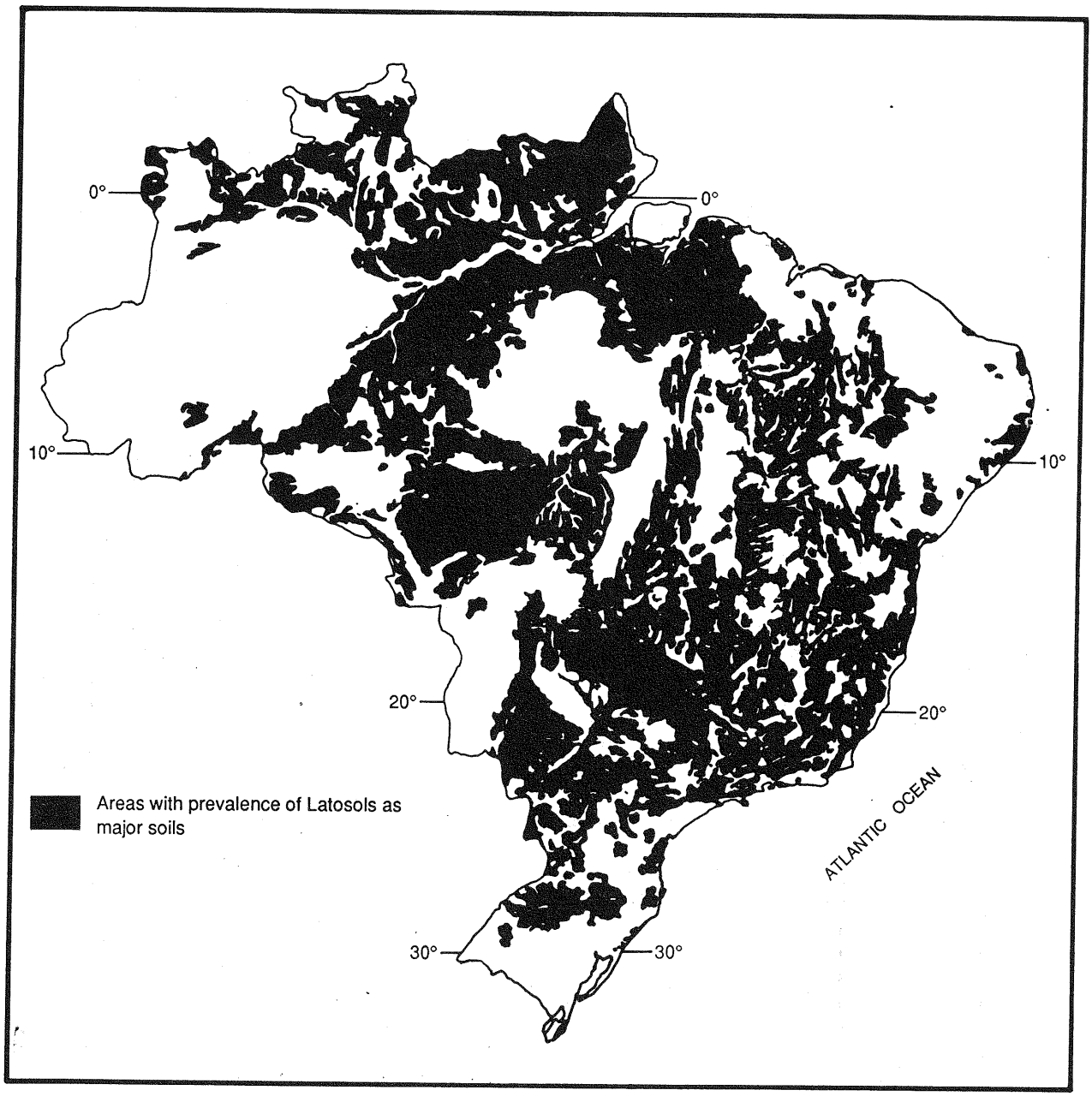


Fig. 1. General view of the territorial extent in Brazil where Latosols constitute the main coexisting soils (after Lepsch and Buol 1987).

Morphological and analytical data accumulation provided means to (1) more fully appraise the characterization of a possible central concept, as refers to the overall taxon of Latosols, (2) notice departures and conceive possible lower rank groupings, and (3) get familiar with ranges in variation and learn of relationships among analytical data produced by the methodology adopted.

With respect to analytical data, of particular concern with reference to latosolic B horizons has been: the sulfuric attack (EMBRAPA 1979), that is, treatment with H_2SO_4 solution 1:1 to obtain quantitative information on the secondary mineral constituents as expressed by the silica aluminum and silica sesquioxide molecular ratios (Vettori 1969; Duriez, Johas, and Barreto 1982); sample dispersion for particle-size analysis (Vettori 1969; EMBRAPA 1979) interferring mainly in the clay and silt percentages to the detriment of the CEC reported to 100 g of clay discounting for carbon contribution (Bennema 1966) and of the silt clay ratio criterion (Van Wambeke 1962) of importance still accounted for; the ΔpH from determinations in H_2O and N KCl (Alvahydo 1959; Bennema and Vettori 1960) and water dispersible clay (Bennema, Camargo, and Lemos 1958) drawing attention to the factors implied and its pedological expression (Bennema and Vettori 1960).

As soil surveys went into operation, the first attempts to discriminate types of Latosols were primarily based on conspicuous morphological differences among the latosolic B horizons of the various soils, and were allied to "supporting" environmental correlations, particularly those associated with differences in land use—apparent or known by experience—as well as with variations in the binomial relief-climate and weighty conditioning exerted by parent material as imposed by source rocks (Barros et al. 1958; Lemos et al. 1960).

In the early 1960s a tentative organization and consolidation of distinctive criteria to discriminate soil classes, based in previous experience with mapping units in the surveys, was carried out (Bennema and Camargo 1964), being mostly devoted to Latosols and Red-Yellow Podzolic soils. In the systematic trial the hierarchical pattern pertinent to the Latosol was based on diversity of development and essence of solum constitution, the leading criteria being: clay activity in the latosolic B horizon, as reflected by the silica-aluminum ratio and CEC of the clay fraction discounting for carbon contribution (Bennema 1966); base saturation of the solum; content of iron and aluminum constituents and their qualitative influence as displayed by color of the latosolic B horizon; and the humic character expressed by an overthickened rather dark A horizon.

Subsequent to the dissemination of the 7th Approximation (Soil Survey Staff 1960) and following the classification trial, additional criteria have been in effect comprising mainly distinctions of A horizons after the types of epipedons introduced by the 7th Approximation, the major grouping of textural classes, and some improvements in the recognition of intergrades. In this regard, a crucial problem occurred and still remains in the domain of the intergrades. It concerns the proper and needed criteria for easy distinction of Latosols and Red-Yellow Podzolics intermediate soil departures. On the other hand, not many problems were caused by interfaces to "intrazonal" great soil groups, that is, Low Humic Gleys and Ground Water Laterites (more recently encompassed by Plinthosols), but they were somewhat more troublesome to the Sol Brun Acide (presently part of Cambisols).

Along these lines, criteria applied to distinguish types of Latosols as lately summarized by Jacomine (1979) centered on red to yellow hues of B horizons as well as magnetic susceptibility coupled to nature and content of iron oxides; colors of quite low values and chromas related to relevant organic matter content in upper solum; sandier constitution imparted by parent material; underthickeness of the solum; high base status of the solum; oligotrophic nature of types almost devoid of nutrients; the "abnormal" cohesion of some; the anthropogenic modifications and accretions in the upper solum; or combinations of criteria given; and in addition the recognition of the intermediary nature related to other classes of soils. In terms of mapping units, adoption of phases provided complementary distinctions of distribution of Latosols, according to topographic forms of relief and pedo-climatic conditions, as reflected by major types of primary vegetation. More broadly, recent effort has been directed to the normalization of distinctive criteria for recognition of soil classes encompassing matters of pertinence to Latosols (Carvalho et al. 1986).

These developments have led to increased consideration of the major constituents of Latosols—inorganic and organic components of the solum; the secondary mineralogical makeup of the latosolic B horizon and relevant properties which express its stage of alteration and decomposition, or even recombination; the proportions in the latosolic B horizon of iron and aluminum oxides versus clay minerals and also among the oxides; and base status of the solum as reflected by desaturation intensity. Of future concern will be supplementary accounting for the intergraded character of Latosol departures bearing on solum thickness next to semi-weathered rock remains next to less resistant mineral particles; textural gradient from A to B major horizons and the distinctiveness of blocky peds in the B horizon possibly associated to clay skins; emergence of plinthite or its indurated succedent—petroplinthite; and a few other sets of properties indicative of other intergrade departures.

Definition of the Latosolic B Horizon: The Concept of an Overall Class of Latosols

After the trends leading to the 7th Approximation (Soil Survey Staff 1960), reckoning the relevance of the diagnostic character merited by expressive soil horizons in the realm of soil classification has been favored in the Brazilian classification of soil since the early 1960s. Arising from the embryonic concept stated by Kellogg (1949) and following implementation by Bennema, Lemos, and Vettori (1959), succeeding formulations (Lemos et al. 1960) and progressive refinements established the current definition of the latosolic B horizon.

In summary, the latosolic B horizon is a subsurface mineral horizon, exclusive of the textural B or natric B horizons, gley horizon, and plinthic horizon, which constitute evidence of an

advanced state of weathering, as shown by the complete or near complete alteration and decomposition of the less resistant primary and secondary minerals, intense desilication (otherwise preweathered parent material), leading to residual concentration of sesquioxides and/or 1:1 clay minerals, and coexisting with primary minerals moderate to highly resistant to weathering.

Holding close similarities with the nonhydromorphic and nonplinthic share of the oxic horizon of *Soil Taxonomy* (Soil Survey Staff 1975), it is a distinctive diagnostic B horizon which, exclusive of the criteria pertaining to textural B horizons, plinthic horizons, and gley horizons, meets these requirements[2]:

1. Contains in the fraction < 0.05 mm, as reported to the fine-earth fraction, < 4 percent of any easily weatherable primary minerals, or < 6 percent muscovite. Has only rather small proportions of silicate clay minerals less resistant to weathering than kaolinite, with some allowance for aluminum interlayered chlorite;
2. Has a silica-aluminum molecular ratio of the clay fraction, or referred to it ≤ 2.2 (often < 2.0);
3. Has an apparent cation exchange capacity (pH 7) of the fine-earth fraction of < 13 meq per 100 g clay after discounting for organic carbon contribution (Table 2);
4. Does not have more than 4 percent by volume of semiweathered rock fragments with altered constituents, or of rock structure remains;
5. Has texture of sandy loam or finer and silt-clay ratio ≤ 0.6 if clayey, or ≤ 0.7 if loamy;
6. Has a very fine to fine strong granular structure seemingly structureless, which may grade to subangular blocky, weak, or seldom moderately developed;
7. Has color often intense, of Munsell hues 2.5 Y or redder and chromas > 2, and if mottled has less than 15 percent by volume of plinthite or petroplinthite reddish bodies, and has less than 20 percent of mottles of chromas ≤ 2;
8. Is at least 50 cm thick (BA and BC horizons included);
9. Has transitions between subhorizons mainly diffuse or gradual, related to weak subhorizon differentiation.

Note that parameter(s) to exclude x-ray amorphous soil material are not developed, since uncertainties remain regarding occurrence of Andosols in Brazil.

In terms of general concept, as adopted in the Brazilian classification, Latosols are nonhydromorphic mineral soils that have a latosolic B horizon following any kind of diagnostic A horizon, but "turfoso" (histic) providing the requirements of Plinthosols are not met.

This class comprises soils that are rather developed, with mineral constitution of the solum which evidences the highly advanced weathered stage, being virtually devoid of primary and secondary mineral constituents less resistant to weathering. Hence these soils have low activity of coloidal mineral constituents, bear a low silica-aluminum molecular ratio (average expression of the whole secondary inorganic composition), and range from extremely weathered predominantly gibbsitic soils with values of about 0.1 to lesser weathered predominantly or entirely kaolinitic soil with values of about 2.0 rising up to 2.2. At the same time CEC values lower than 13 meq per 100 g clay (cf. Table 2) stand as an expression of the low activity, coloidal mineral constituents.

These soils are mostly rather deep (solum seldom < 1.5 m), ordinarily range from excessively to well drained, are composed of an A, B, C sequence of horizons, and show gradual or diffuse boundaries, particularly with subhorizons of the latosolic B.

Apart from the variable darkening in the A horizon, a colorful tendency prevails in the B, ranging mostly from yellowish brown to red tints (10 YR to 10 R hues).

The clay content shows a gradual increase downward in the solum; the increment from A to B is faint, the requirement for textural B horizon not being met. The silt-clay ratios are low (< 0.7), the higher rates tending to be related to decreasing clay content.

As a typical characteristic, mobility of clays is low, and, as expressed by the water dispersible clay, the flocculation rate in the latosolic B horizon is 100 percent or nearly so, rising atypically toward the A horizon by counterweighted influence of the organic matter (electro-negative charges surplus), or, occasionally, down the latosolic B horizon if the silica-aluminum and particularly the silica-sesquioxide ratio is rather low (electro-positive charges surplus), which is reflected by the pH, as pointed out by Bennema, Camargo, and Lemos (1958), Bennema and Vettori (1960), and Lemos et al. (1960). Atypical behavior might hold also for loamy-textured Latosols, more noticeably in those of coarser texture.

As a related feature, aggregates < 2 mm of granular shape impart a pseudostructureless appearance and a high porosity to the B horizon of the typical soils. Likewise, the wet consistence of the soil material is misleading—the initial low plasticity and stickiness of handled samples shows significant increase with intensified rubbing. Furthermore, consistence soft to slightly hard when dry and very friable to friable when moist is commonplace in typical Latosols.

Nevertheless, apart from the aforementioned typical pattern, the class also comprises soils that, in structure and consistence, stand as variant. Cohesion of B-horizon soil material may be stronger, structure may consist of moderately developed, subangular blocks, and consistence may range from very hard when dry, to firm when moist, with no deceptive character for the wet consistence.

Commonly, base saturation and exchangeable bases are low to extremely low in the solum, mainly in the latosolic B horizon. Some recharge of bases—cycling through vegetation—might concern primarily the A horizon. The soils concerned are usually strongly to extremely acid. High exchangeable aluminum saturation in the A horizon is very common, being variable in the B, tending to decreased proportions and eventual absence down the solum and the C horizon, being restrained by decreasing silica-aluminum and silica-sesquioxide molecular ratios, which raises the pH and the tendency to or prevalence of net positive charge.

High base saturation Latosols are scarce and are found primarily in climatic regions with a pronounced dry season, semiarid or not. They may also be found among the soil formed

[2] No requirement given is limited solely to a latosolic B horizon.

from basic rocks, even though under moister climatic conditions.

Major Classes of Latosols: Distinction from Related Major Classes of Soils

Recognition of the various major classes of Latosols has been based on differences in the soil material constituting the latosolic B horizon. This composition is seen as a consequence of their origin and the intrinsic changes accounting for their production. Sets of properties, believed to be indicative of the actual composition of latosolic B horizons, stand as discriminant criteria.

Seven main subdivisions of the overall class of Latosols are presently recognized (Table 1).

Further subdivision of classes, through poorly systematized lower ranks, have been established based on criteria as specified, according to the major class of Latosols.

Ferriferous Latosols—Humic character; intergradational with Cambisols and Pertoplinthosols; prominent or moderate A horizon; texture fine, very fine.

Dusky Red Latosols—Humic character; high or low base saturation or high aluminum saturation; intergradational with *Terra Roxa Estruturada* (textural B soil), Red-Yellow Podzolics, Cambisols, Plinthosols, Dark Red Latosols, Ferriferous Latosols; underthickened solum, prominent, moderate, or chernozemic A horizon; texture very fine, fine, or seldom loamy.

Red Dark Latosols—Humic character; high or low base saturation or high aluminum saturation; intergradational with Dark Red Podzolics, Red-Yellow Podzolics, Cambisols, Red-Yellow Quartz Sands; prominent, moderate, weak, or seldom chernozemic A horizon; texture very fine, fine, or loamy.

Red-Yellow Latosols—Humic character; low or seldom high base saturation or high aluminum saturation; intergradational with Red-Yellow Podzolics, Cambisols, Plinthosols, Red-Yellow Quartz Sands, Gleysols; underthickened solum; prominent, moderate, or weak A horizon; texture very fine, fine, or seldom loamy.

Yellow Latosols—Humic character; low or scarcely high base saturation (semiarid region) or often high aluminum saturation; intergradational with Yellow Podzolics, Plinthosols, Red-Yellow Quartz Sands, Gleysols, Red-Yellow Latosols; anthropogenic character of the A and B upper horizons; prominent, moderate, or weak A horizon; texture very fine, fine, or, loamy.

Brown Latosols—Humic or cryptohumic character; low base saturation or high aluminum saturation; intergradational with Cambisols, *Terra Bruna Estruturada,* Dusky Red Latosols, Red-Yellow Latosols, Gleysols; underthickened solum; texture very fine or fine.

Latosols Una *variation*—Humic or cryptohumic character; low base saturation or scarcely high aluminum saturation; intergradational with Cambisols, Plinthosols, Red-Yellow Latosols, Dark Red Latosols; underthickened solum; texture very fine or fine.

Supplemental adoption of phases according to main types of primary vegetation constitutes a contrivance for additional discrimination on the basis of pedo-climatic conditions, chiefly concerning soil moisture regime.

Notwithstanding the long prevailing necessity, no practical means has been devised for field distinction of the more typical Latosols—more weathered (~acric in *Soil Taxonomy*) from not so severely weathered Latosols.

The conjunction of features of the latosolic B horizon, comprising strong, fine to very fine granular structure, seemingly by structureless, soft and very friable dry and moist consistence, gradational wet consistence, plus renitency to steady pressure have not been entirely successful for exclusiveness. Nevertheless, much support for distinction is met by indicative sets of analytical properties, namely, quite low silica-sesquioxide and silica-aluminum molecular ratios, insignificant CEC per 100 g clay after discounting for organic carbon contribution, a tendency toward or positive pH, and the absence, or virtually so, of exchangeable aluminum.

Actually, the needed distinction among these older varieties has remained the major shortcoming in the distinction of major classes of Latosols.

The distinction of Latosol varieties is approached in the field by indentification which accounts for color, particularly of the latosolic B horizon; attraction of the dry, well-crushed sample to a hand magnet; high or low base saturation in conjunction with high aluminum saturation of the solum, inferred from field pH determination coupled to experience concerning agricultural use of the lands, observation of crops, and recognition of primary vegetation types; recognition of intergradational morphological features displayed by the soil profile; inspection of sample under a hand-lens in search of clayskins, glazes, and primary mineralogical particles; recognition of type of A horizon; and texture estimated by feel. Decisive indentification is obtained through analytical characterization.

The essentials of distinction between Latosols and other related major classes of soils comprise the following:

1. Distinction from low activity clay Red-Yellow Podzolics, Red Podzolics, and Yellow Podzolics—These soils have a textured B horizon (argillic horizon in *Soil Taxonomy*) sequent to an A, AB, E, or EB horizon. Besides, contrary to Latosols, these soils when dry commonly show faded colors in the A and in the transition to the textural B horizon, eventually characterizing an E horizon. The different facies attained by Latosol intergrades to Podzolic soils are (a) expressed mainly by textural differentiation—clay increase—between A and the still latosolic B horizon; (b) prevalence of weak or seldom moderate subangular and rarely angular blocky structure throughout the B, associated with no more than few and faint or scarce and moderate clayskins, the last if present preferentially in vertical faces; (c) upper B as above, preceding a lower B horizon, pseudostructureless, though formed by strong, fine to very fine granular structure.
2. Distinction from *Terra Roxa Estruturada*—The presence of a textural B horizon sequent to an A or AB is the distinguishing mark. Although these soils have a textural B horizon, the clay increase from A to B is mostly

Table 1. Distinction of Major Classes of Latosols

Classes recognized at present	Differentiae concerning the B horizon						
	Fe_2O_3[a] % wg. pertaining fract. < 2 mm. Referred to clayey soils[b]	Color (exclusive of BA)			Magnetic susceptibility[c] of dry, well-crushed sample < 2 mm	SiO_2-Al_2O_3 molecular ratio[a]	$SiOAl_2O_3$ & Fe_2O_3 molecular ratio[a]
		Hue	Value	Chroma			
Ferriferous Latosols	≥ 36 (72)[d]	Redder than 4 YR	≤ 3	≤ 6	Wholly attracted	0.1 to 0.9	
Dusky Red Latosols	40 to 18	Mostly redder than 4 YR	Mostly ≤ 3	≤ 6	Strongly to wholly attracted	0.2 to 2.0	
Dark Red Latosols	18 to 8	Mostly redder than 4 YR	≤ 4.5	Mostly ≤ 6	Weak to virtually no attraction	0.2 to 2.2	
Red-Yellow Latosols	Mostly 11 to 7	Yellower than 1.5 YR	Mostly > 4.5	≥ 6	Virtually no attraction	Mostly < 1.5	< 1.4
Yellow Latosols	Mostly < 7	Mostly yellower than 6 YR	≥ 5	≥ 4	same	1.5 to 2.2	> 1.4
Brown Latosols	> 11 (30)[d]	Mostly yellower than 3.5 YR and reddening downward	3 to 4	≥ 3	same	0.7 to 2.2	
Latosols *Una* variation	> 11 (30)[d]	Mostly yellower than 3.5 YR	4 to 5	Mostly ≥ 5	Strong to virtually no attraction	0.2 to 2.0	

[a] From attack by H_2SO_4 solution 1:1 (EMBRAPA 1979). Results pertaining to the clay fraction, though including sesquioxides contained in nodules, concretions, and coatings in fract. < 2 mm, plus negligible Fe_2O_3 in ilmenite occasionally present.
[b] Al_2O_3 - Fe_2O_3 molecular ration applicable to soils with less than 35% clay.
[c] Hand magnet.
[d] Higher known value.

small and faint, the concerned diagnostic horizon being chiefly characterized by having no less than common and distinct clayskins associated with moderate to strong subangular and even angular blocky structure.

3. Distinction from low clay activity Plinthosols—These soils have either: (a) a plinthic horizon[3] or its petric succedent horizon sequent to any A, AB, E, or EB horizon; (b) a plinthic horizon or its petric succedent horizon occurring within 60 cm of the soil surface, being preceded by a B horizon containing not enough plinthite or petroplinthite for plinthic or pertroplinthic, otherwise this preceding horizon shows many mottles tending to or of reduction colors in a red to yellow rather pale matrix, or vice-versa; (c) a plinthic horizon or its petric succedent horizon within 210 cm of the soil surface, being preceded till the base of the A by an E horizon or by a quite palid horizon having color tending to or of reduction, otherwise mottled with such colors.
4. Distinction from low activity clay Cambisols—These soils have in sequence to an A or AB a diagnostic incipient B horizon differing from a latosolic B primarily by meeting one or more of these requirements: (a) contain in the fraction < 0.05 mm, as reported to the fine-earth fraction, ≥ 4 percent easily weatherable primary minerals or ≥ 6 percent muscovite; (b) have meaningful proportions of clay mineral less resistant to weathering than kaolinite; (c) have either 5 percent or more by volume of semiweathered rock fragments with altered or nonaltered easily weatherable constituents, or have 5 percent or more of rock structure remains or saprolitic material.
5. Distinction from Red-Yellow Quartz Sands—The bare difference lays in the higher clay content by definition of Latosols, ordinarily > 15 percent.
6. Distinction from low activity Gleysols—The presence of a diagnostic gley horizon within 50 cm of the soil surface answers for the difference from Latosols.

Dissonance in Relation to *Soil Taxonomy*

From a comparative standpoint, notice that several attributes of Latosols and Oxisols are identical or similar, a conformance due to equivalence of some requirements set for both overall classes of soils, but equality does not happen, even when the highest categorical rank is considered.

Of relevance is the discordance of the Brazilian classification which is centered toward latosolic B and, further, the types of A horizons, in contradistinction to *Soil Taxonomy's* accounting for oxic horizons and types of epipedons—therefore their overlap.

However, differences prevailing chiefly arise from distinctions in criteria pertaining to latosolic B and oxic B horizons, as described in the following remarks.

1. Relevant hydromorphic conditions exclude latosolic B criteria—considered restrictive of one or more of the attributes recognized as typical of Latosols, implying in the nature of latosolic B horizon, namely residual concentration of sesquioxides being counteracted by iron oxides reduction and liability to migration and eventual removal; counteraction to desilication of soil material; high silt-clay ratio and low proportion of weatherable primary minerals since parent material in the case in view is mostly of aggraded nature.
2. Relevant plinthite either following the A horizon or sequent to intervening deferrified horizon(s) excluded from latosolic B, being recognized as characteristic of plinthic horizon.
3. Minimum thickness of 50 cm for latosolic B horizon versus 30 cm for oxic horizon.
4. Easily weatherable primary minerals in the sands, as reported to the fine-earth fraction, < 4 percent or < 6 percent of muscovite as criteria for latosolic B versus < 3 percent in the 20 to 200 micra fraction for oxic horizon.
5. Silt-clay ratio admitted as criteria for latosolic B and not for oxic horizon.
6. Divergent limits for CEC as explained in Table 2. Apart from the causes mentioned, standing divergences developed from the second higher categorical level, and necessarily down following classes. Naturally, they are the expression of discrepant differentia applied to class formation, that is moisture regime and humic character are taken into account for Oxisols, whereas attributes reflecting the essence of inorganic constitution of the soil material are applied to Latosols.

Thus, comparisons of Latosol and Oxisol descendant classes led to difficulties and confusing correlations at the second taxonomic level, the results being demonstrative of divergences, as shown in Table 3.

Future Perspective

Compelled by the need to overcome enduring deficiencies, aggravated by the amount of information gained through soil surveys, and induced by changes in concepts envisioned for soil groupings, the soil classification frame has been subjected to a critical reappraisal since 1978, which has led to decisions favoring reformulation and achievement of a formal framing of soil classification of the country, a process under development.

The fundamental thought behind the classification of Latosols has persisted from the present framing, as detailed in the foregoing exposition.

Present trends towards a reformulated classification of Latosols can be illustrated by the trial delineation which follows.

CATEGORY I. CLASS 8—SOILS WITH LATOSOLIC B UNDERLAYING A OR AB HORIZONS

Base: Well-advanced evolution, intense weathering of constituents, diffuse residual concentration of sesquioxides and/or resistant silicate clay minerals, negligible argilluviation, impoverishment, ferrolysis, gleyzation, or plinthitization.

Criteria: Development of latosolic B underlying an AB or any kind of A horizon but histic, allied to small clay increase from A to B, if any.

[3] ≥ 15 cm thick and ≥ 15 percent by volume plinthite.

Table 2. Comparison of CEC Limits as Adopted for Soil Classification in Brazil and in *Soil Taxonomy*

Distinction intended in Brazilian classification	Brazilian SNLCS CEC Values: Organic carbon contribution subtracted	Brazilian SNLCS CEC Values: No subtraction	NSSL-SCS USDA CEC values (no subtraction)	Distinction intended in *Soil Taxonomy*
	(meq per 100 grams of clay)			
High activity/low activity clay soils	24	27	42	Nihil
Limit latosolic B horizon	13	16	24	Limit oxic subgroups
Nihil	8	10	16	Limit oxic horizon
Limit typic latosolic B horizon, i.e., highly weathered types	6.5	8.5	14	Nihil

CATEGORY II. CLASSES

8.1 Very low content of iron (< 7 percent) and aluminum oxides, virtually kaolinitic (xanthic).

8.2 "Aluminous" soils, medium to high content of iron oxides, and either chiefly kaolinitic or sesquioxidic (helvic).

8.3 Medium to low content of iron oxides (< 18 percent) and either chiefly kaolinitic or sesquioxidic (xanthic or rhodic).

8.4 High content of iron oxides (> 18 percent) and either chiefly kaolinitic or sesquioxidic (mostly rhodic).

8.5 Very high content of iron oxides (≥ 36 percent) and virtually devoid of kaolinite or other silicate clay minerals (rhodic).

CATEGORY III. (PARTITION OF CLASS 8.3)

	Organic content	Base saturation	Main mineralogy
8.3.1	High	Dissaturated	Kaolinitic rather than sesquioxidic
8.3.2	Same	Same	Sesquioxidic rather than kaolinitic
8.3.3	Medium to low	Same	Kaolinitic rather than sesquioxidic
8.3.4	Same	Slightly unsaturated	Same
8.3.5	Same	Nearly saturated	Same
8.3.6	Same	Dissaturated	Sesquioxidic rather than kaolinitic

CATEGORY IV. (PARTITION OF CLASS 8.3.6)

8.3.6.1 Typic (Pro henatitic, namely rhodic)

8.3.6.2 Pro goethitic (nonrhodic)

8.3.6.3 Intergrades with class 8.3.4 (cambic)

8.3.6.4 Intergrades with class 12 (gleyic)

As shown, fundamental similitude is held with the present-day classification of Latosols. The needed operational possibilities, to provide feasible distinction of acric from nonacric Latosols, remain a major shortcoming.

The framing of a formal proposal for the classification of Latosols is not firmly set. The whole reformulation of the soil classification system designed for Brazil is in progress, and achieving a prototype for experimental operation may be possible by 1988.

References

Alvahydo, R. 1959. Influência da composição coloidal inorgânica do solo na diferença de pH determinado em água e cloreto de potássio. Tese para provimento de cátedra. Escola Nacional de Agronomia, Rio de Janeiro.

Baldwin, M., C.E. Kellogg, and J. Thorp. 1938. Soil classification. *In* Soils and men. U.S. Dep. Agr. Yearbook of Agr. U.S. Govt. Printing Office, Washington, D.C.

Table 3. Approximate Equivalent Between the Brazilian Classification of Latosols and Oxisols in *Soil Taxonomy* (Soil Survey Staff 1975)

Present Brazilian classification	*Soil Taxonomy*	
Major classes of Latosols	Great groups mainly related[1]	Great groups secondarily related[1]
Ferriferous Latosols	Acrohumox; Acrorthox	
Dusky Red Latosols	Acr, Hapl, Eutr Orthox & Ustox; Acrohumox	Umbriorthox; Haplohumox; Dystropepts; Dystrochrepts
Dark Red Latosols	Acr, Hapl, Umbri Orthox; Acr, Hapl, Eutr Ustox; Acrohumox	Umbriorthox; Eutrorthox; Haplohumox; Dystrochrepts Dystr, Ust Tropepts
Red-Yellow Latosols	Acr, Hapl, Umbri Orthox; Acr, Hapl Ustox; Acrohumox	Sombriorthox; Hapl, Sombri Humox; Eutrustox; Torrox; Dystr, Ust Tropepts
Yellow Latosols	Hapl, Acr, Orthox & Ustox	Hapl, Acr Humox; Torrox; Dystr, Ust Tropepts
Brown Latosols	Hapl, Acr Humox; Acr, Umbri Orthox	Sombrihumox; Sombriorthox Dystr, Humi Ochrepts
Latosols *Una* variation	Acr, Sombri Orthox; Acrohumox	Acr, Sombri Ustox; Sombri humox; Dystropepts

[1] Always *pro parte*

Barros, H. C., J. L. Drumond, M. N. Camargo, P.O.C. Lemos et al. 1958. Levantamento de reconhecimento dos solos do Estado do Rio de Janeiro e Distrito Federal. Comissão de Solos, S.N.P.A. Bol. N. 11. Ministério da Agricultura, Rio de Janeiro.

Bennema, J. 1966. The calculation of CEC for 100 grams clay with correction for organic carbon. *In* Report to the government of Brazil: Classification of Brazilian soils. FAO Rpt. EPTA 2197. Rome.

Bennema, J., M. N. Camargo, and R.C. Lemos. 1958. Conceituação e distinções preliminares de Latossolos brasileiros. Comunicação á IV Reunião Latino-Americana de Fitotecnia, Santiago.

Bennema, J., and M. N. Camargo. 1964. Segundo esboço parcial de classificação de solos brasileiros. Divisão de Pedologia e Fertilidade do Solo, D.P.E.A., Ministério da Agricultura, Rio de Janeiro (mimeo.).

Bennema, J., R. C. Lemos, and L. Vettori. 1959. Latosols in Brazil. Proc. 3rd Interafrican Soils Conference. Dalaba.

Bennema, J., and L. Vettori. 1960. The influence of the carbon/clay and silica/sesquioxides ratios on the pH of Latosols. *In* Transactions, 7th Int. Cong. of Soil Sci. (Madison, WI), vol 4: 244-250.

Camargo, M. N., C. Hirano, F. G. de Freitas, P.K.T. Jacomine et al. 1962. Levantamento de reconhecimento dos solos da região sob influência do reservatório de Furnas. Comissão de Solos S.N.P.A. Bol. no. 13. Ministério da Agrticultura, Rio de Janeiro.

Carvalho, A. P., J. Olmos I.L., P.K.T. Jacomine, and M. N. Camargo. 1986. Critérios para distinção de classes de solos e fases de unidades de mapeamento. Serviço Nacional de Levantamento e Conservação de Solos. EMBRAPA. Rio de Janeiro (not published).

Commission de Pédologie et de Cartographie des Sols. 1967. Classification des sols. Grinon, ENSA.

Duriez, M.A.M., R.A.L. Johas, and W. O. Barreto. 1982. Método simplificado para determinação dos valores Ki e Kr na terra fina. Serviço Naional de Levantamento e Conservação de Solos. Bol. Pesq. no. 2. EMBRAPA. Rio de Janeiro.

EMBRAPA. Serviço Nacional de Levantamento e Conservação de Solos. 1979. Manual de métodos de análise de solo. Rio de Janeiro.

Jacomine, P.K.T. 1979. Conceituação sumária de classes de solos e critérios para subdividí-las. Serviço Nacional de Levantamento e Conservação de Solos, EMBRAPA. Rio de Janeiro (mineo.).

Kellogg, C. E. 1949. Preliminary suggestions for the classification and nomenclature of great soil groups in tropical and equatorial regions. Commonwealth Bur. Soil Sci. Tech. Comm. 46:76-85.

Kellogg, C. E., and F.D. Davol. 1949. An exploratory study of soil groups in

the Belgian Congo. INEAC Sér. Scientifique no. 46. Bruxelles.

Lemos, R. C., J. Bennema, R. D. dos Santos, J. Olmos I.L. et al. 1960. Levantamento de reconhecimento dos solos do Estado de São Paulo. Comissão de Solos, S.N.P.A. Bol. no. 12. Ministério da Agricultura. Rio de Janeiro.

Lepsch, I. F., and S.W. Boul. 1987. Oxisol-landscape relationships in Brazil. *In* Proc. VIIIth Int. Soil Class. Workshop. EMBRAPA, Serviço Nacional de Levantamento e Conservação de Solos. Rio de Janeiro.

Soil Survey Staff, USDA, SCS. Soil classification, a comprehensive system, 7th approximation. Soil Conserv. Serv., U.S. Dep. Agr. U.S. Govt. Printing Office, Washington D.C.

———. 1975. Soil taxonomy. U.S. Dep. Agr. Handb. no. 436. U.S. Govt. Printing Office, Washington, D.C.

Thorp, J., and G. D. Smith. 1949. Higher categories of soil classification: Order, suborder, and great soil groups. *Soil Sci.* 67:117-126.

Van Wambeke, A. 1962. Criteria for classifying tropical soils by age. *J. of Soil Sci.* 13(1):124-132.

Vettori, L. 1969. Métodos de análises de solos. Equiqe de Pedologia e Fertilidade do Solo. Bol. Iéc. no. 7. Ministério da Agricultura. Rio de Janeiro.

Vettori, L., and H. Pierantoni. 1968. Análise granulométrica; novo método para determinar a fração argila. Equipe de Pedologia e Fertilidade do Solo. Bol. Téc. no. 3. Ministério da Agricultura. Rio de Janeiro.

AGRONOMIC AND ENGINEERING ASPECTS OF OXISOLS

AGRONOMIC CONSIDERATIONS OF MODERN AGRICULTURE ON OXISOLS

W.J. Goedert and E. Lobato[1]

Abstract

Agriculture is continuously expanding toward the tropics, and the use of Oxisols is becoming more important for food production. Most Oxisols have excellent mechanical conditions for cropping but low fertility status and, therefore, present severe constraints for modern agriculture. However, research data have demonstrated that such constraints can be overcome by proper soil and crop management. Any soil management strategy should be based on neutralizing part of the effects of soil acidity and building up the fertility status, as well as protecting the soil against erosion. The type of management and productivity is closely related to the level of investment made in the farm. Positive economic returns have been obtained with these kinds of soils. On the other hand, the intensive use of Oxisols may cause substantial changes in the soil profile, mainly in the upper horizons. These changes can modify the soil classification, especially concerning its potential for agriculture.

The world population is increasing, which emphasizes the need for increasing food and raw materials production. The participation of Oxisols in this process is important, since they comprise a large proportion of the agricultural soils in the world, especially in the tropical region.

The intensive use of Oxisols for agriculture is relatively recent, and the technology for sustained food production on these soils is still in a very early stage of development. However, experience has shown their high agricultural potential.

The general purpose of this paper is to discuss agronomic features of the utilization of Oxisols for intensive agriculture. Most of the discussion will be based on the research results obtained for Oxisols of the savanna region of Brazil.

Oxisols Characterization

The Oxisols, like any soil, exhibit favorable and unfavorable features for intensive agriculture. The scope of this section is to discuss these features, based mainly on the profiles described during this workshop. In summary, the favorable features are:

1. The soils are deep and well drained with a thick A horizon (usually more than 20 cm) and a total depth above 300 cm;
2. Absence of stones on the soil surface;
3. Variable clay content, but a few soils are too sandy;
4. High porosity and loose for mechanical work;
5. Relatively high organic matter content of the A horizon and consequently a reasonable potential of N supply (Most ion exchange capacity of these soils originates from the organic components); and
6. Low content of exchangeable Na and no salinity problems.

On the other hand, the main unfavorable features of distrophic Oxisols are:

1. Most Oxisols are highly weathered, with low values of Ki and Kr. The clay fraction is dominated by low activity minerals (kaolinite, gibbsite, and iron oxides);
2. Low cation exchange capacity. The value for "T" is higher only in the upper horizon. The exchange capacity at the soil pH is very low;
3. The soils are acid, with Al^{3+} predominating in the exchangeable pool (i.e., high values of Al saturation);
4. The clay mineralogical composition favors absorption of anions, especially phoshate;
5. The sum of bases (Ca, Mg, and K) and the base saturation (S) are very low and decrease with soil depth. The low content of Ca is an important constraint to root growth and, therefore, has to be considered in any soil management scheme;
6. The amount of plant available nutrients is low. Phosphorus deficiency is, commonly, the single most wide spread production constraint, but other nutrients may become deficient such as Ca, K, Zn, N, Mg, S, and B; and
7. The water holding capacity is usually low, even in clayey soils.

In summary, the Oxisols present good physical conditions for agriculture but serious constraints in relation to some chemical properties, especially with the ion exchange pool.

[1] Authors are Researchers at Centro de Pesquisa Agropecuária dos Cerrados (CPAC). Cx. Postal 70.0023. 73300, Planaltina, DF., Brazil.

Enviromental Characterization

The potential use of a soil for agriculture and its management are also related to features that cannot be observed in a soil profile, such as the landscape, the kind of vegetation, the climate, and the availability of resources.

The topography of the area is predominantly flat or gently undulated, and, therefore suitable for intensive mechanized agriculture.

The vegetation varies from pure grassland to forest. Under humid forest most of the nutrients of the ecosystem are located in the aereal part of the vegetation, and a sustained production system must take this into consideration. Under savanna, this aspect is not so important.

The climate is usually favorable for most crops. Average monthly temperature may vary from 21 to 27°C. The total annual rainfall is variable from one area to another, but in most areas is more than 1500 mm. Its distribution is characterized by distinct wet and dry seasons. The length of the dry season varies from about 2 to 6 months. Short-term droughts may occur during the rainy season and may be detrimental to crop growth because of high evapotranspiration rates, low soil available water retention capacity, and adverse soil chemical conditions for root growth. During the rainy season, rainfall intensity is usually high, with high erodibility power. The management of soils must consider these aspects.

Another aspect that should be considered is the infrastructure available (transport, market, technical assistance, etc.). It is quite impossible to practice an intensive agriculture without a simultaneous development of infrastructure facilities. Machinery, seed, and amendments (lime, fertilizers, pesticides, etc.) must be readily available.

In summary, an analysis of the profile data and of the general features of the environment where Oxisols are located indicates the high potential of these soils for intensive agriculture.

The constraints related to the chemical aspects (acidity and low nutrient status) can be overcome by soil and crop management.

Management of Oxisols

Any soil management strategy of distrophic Oxisols must be based on neutralizing part of the effects of soil acidity and building up the soil fertility status. In addition, constant attention must be given to protecting the soil against erosion. In areas where short-term droughts occur, the soil management scheme has to be concerned with minimizing their effects on plant growth.

The transformation of a virgin land into a cultivated area usually requires a series of practices which chronologically follow the general sequence: clearing, liming, fertilizing, and cropping.

Clearing

Most of the work in this step consists of eliminating (or incorporating), partially or totally, the vegetation cover. The way to clear land varies with the kind of vegetation and with the final objective of the farmer. In any case, it is very important to maximize the incorporation of the organic matter from the vegetation into the soil.

One traditional method for clearing is the slash-and-burn system. More recently mechanized systems have been used. The effects of these systems on soil properties is not well known, and most of the published information was obtained on humid tropic regimes (Seubert, Sanchez, and Valverde 1977).

Research data on mechanical clearing are scarce; however, experience indicates that care must be taken to minimize compaction. The upper layer of the soil must not be removed by the machinery, since most of the organic matter and nutrients are located in this part.

Protection against erosion includes a series of practices which vary mainly with soil characteristics and topography. When necessary, terraces have to be built from the first year. Traditionally, the native vegetation is concentrated in strips perpendicular to the lines of higher slope of the land. After a few years it is burned, giving place to terraces.

In summary, clearing operations will induce modifications in the soil profile, especially in the upper layer. Incorporation of organic matter and erosion control are of most concern to avoid deterioration of the soil.

Liming

The constraint of soil acidity is being solved by plant breeding and soil management. There has been a substantial amount of work on breeding and selecting varieties of crops and pasture plants tolerant to aluminum.

Liming is a common practice on Oxisols. Several experiments have been conducted to evaluate liming effects on soil properties and crop performance. Some of this work was reviewed by Lathwell (1979a), Miranda, Mielnickzuk, and Lobato (1980), and Kamprath (1984). A typical yield response to lime, obtained on a Dark Red Latosol (similar to profile n. 22) is illustrated by Figure 1. The total yield of seven crops was

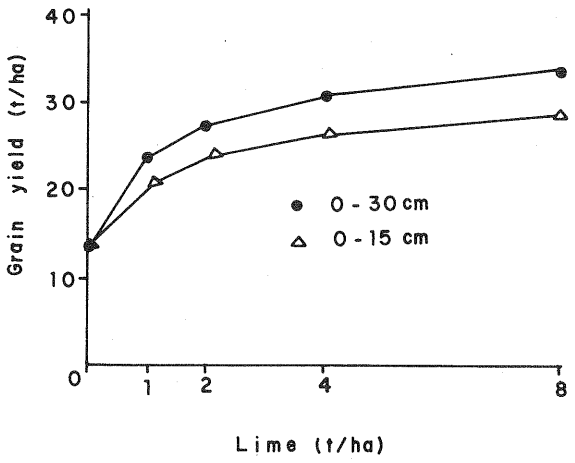


Fig. 1. Crop performance as a function of rates of lime applied before the first crop, at two depths, on a Haplustox. A total of seven crops were grown in the experiment. The first three, the fifth, and the sixth were corn, the fourth was sorghum, and the seventh was soybean (Miranda, Mielnickzuk, and Lobato 1980 Goedert 1983).

approximately doubled by an application of 2 t/ha of dolomitic limestone and positive responses were obtained up to 8 t/ha. Long residual effect of liming was also evident, even for the smallest rate of liming (Miranda, Mielnickzuk, and Lobato 1980).

From the same experiment, the effect of liming on soil properties is shown in Table 1. As expected, changes in soil pH and in the exchangeable cation pool were closely related to lime rates. Soil pH and exchangeable Ca + Mg increased initially but decreased at all rates during the following 5 years. The change in pH can be partly explained by residual acidity of N fertilizers applied during the experiment. Exchangeable Al and Al saturation increased with time, but became no higher than the initial level.

The benefits from liming are related to changes of both Al and (Ca + Mg) status, but other effects such as the influence of lime on the cation exchange capacity and on the phosphate sorption capacity also may be important.

The rates of lime required are closely related to the kind of farming system. Lime recommendations are usually based on exchangeable Al and Ca + Mg. Recently, the criterion of base saturation is being tested.

As mentioned earlier, there is a need to enhance root growth in volume and depth. The root system is often confined to the topsoil because the subsoil presents a chemical barrier to root development, either due to Al toxicity or extreme Ca deficiency, or both. One solution would be the deep incorporation of lime (and possibly phosphate) which, as shown in Figure 1, is effective. However, this operation is expensive and requires specialized equipment.

Another alternative is to promote downward movement of Ca and Mg. Figure 2 shows the subsoil conditions 40 months after liming (lime rates and crop responses presented in Fig. 1). The decrease in Al saturation with depth was the main explanation for an observed better root development of maize (Bouldin 1979).

Recent experiments showed that calcium moves down the profile more quickly when $CaCl_2$ or $CaSo_4$, instead of $CaCo_3$, were mixed with the topsoil layer (Ritchey et al. 1980). Sulphate is the most suitable anion because chloride leads to calcium loss. These findings help to explain the better crop performances obtained when single superphosphate was compared with other calcium-phosphorus fertilizers not containing gypsum (EMBRAPA/CPAC 1980). Although the effects of calcuim sulphate addition to *cerrado* soils need further evaluation, it already has been recommended to farmers, either as a component of regular fertilizers or as gypsum.

Fertilization

As mentioned earlier, most Oxisols present a low nutrient status, phosphorus deficiency being the single most widespread production constraint. In addition, other nutrients may become critical, especially after a few years of cropping.

Phosphorus. The total P content of Oxisols is low and, when the clay fraction is dominated by iron and aluminum oxides, the adsorption capacity of these soils may be very high (Le Mare 1982). As a consequence, the plant available P is usually much below the level required for most crops, as can be observed for most profiles described during this workshop.

The typical crop responses to P fertilization in virgin Oxisols (Fig.3) show that for obtaining maximum yields, a range of P application rates are required according to the crop. The performance of all crops without addition of P is poor, and large responses are obtained with this nutrient.

Figure 3 illustrates the high potential of these soils for agricultural production, once P deficiency is corrected, and that high initial applications of 100-200 kg P/ha are needed to achieve such yields in the first year of cropping. The cost of phosphate can be as high as the price of the land in some parts of the region. Hence, improved methods must be found to make the most efficient use of the applied phosphate.

Potentially, the best approach is to: (1) minimize phosphorus fixation; (2) determine the best fertilizer rates and placement methods; (3) evaluate local cheap sources of P; and (4) enhance P uptake by plants by their assocation with soil organisms, such as mycorrhiza (Goedert 1983).

In practice, a positive interaction has been found with liming and P fertilization. In acid Oxisols, high yields can be obtained only when the effects of acidity are decreased and when P is

Table 1. Effect of Lime on Properties of a Dark Red Latosol, near Brasilia (soil samples 0-15 cm depth)

Lime applied in 1972 (t/ha)	pH (1 : 1 H_2O)		Exch. Al. (meq/100g)		Exch. Ca+Mg (meq/100g)		Al saturation (%)	
	6[a]	66[a]	6[a]	66[a]	6[a]	66[a]	6[a]	66[a]
0	4.7	3.9	1.1	1.5	0.6	0.3	63	80
1	5.0	4.2	0.9	1.1	1.1	0.6	45	61
2	5.1	4.3	0.5	1.0	1.5	1.0	25	46
4	5.6	4.8	0.2	0.4	3.1	2.1	6	15
8	6.3	5.2	0.0	0.1	4.4	4.0	0	2

[a] Months after lime incorporation to the 0-15 cm layer.
Source: Sanchez and Salinas (1981).

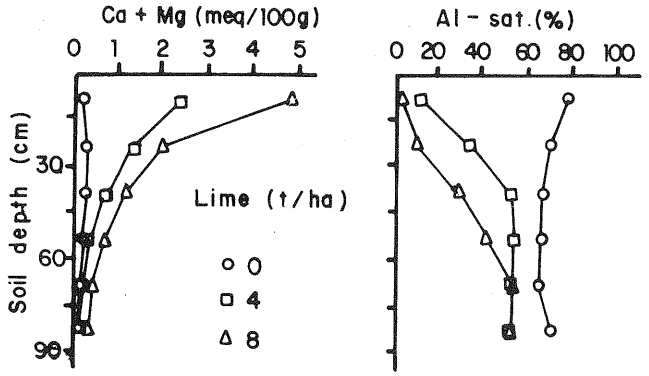


Fig. 2. Residual effects of lime on exchangeable Ca, Mg, and % Al saturation in a Dark Red Latosols, 40 months after lime application to the top 15 cm (Sanchez and Salinas 1981).

applied above a certain level (EMBRAPA/CPAC 1976).

A reasonable amount of work has been done in Oxisols to determine crop and pasture responses to P fertilization rates and placement (Lathwell 1979b; Miranda, Mielnickzuk, and Lobato 1980; Sanchez and Salinas 1981; Goedert 1983). Comparison of the effects of P applications over 10 years is provided by an experiment established on a high P sorbing Oxisol (similar to profile n. 22). Band and broadcast applications of P produced similar results on a long-term basis, that is, the total yield obtained after 10 years is almost the same for any combination of placement methods of the same amount of P applied (Lobato 1980). In conclusion, in the long run the important factor is the total amount of P applied, independent of the method of application.

Another important aspect revealed by P fertilization experiments on Oxisols is the high sorbing soils. This high residual value makes P fertilization economic, as discussed later.

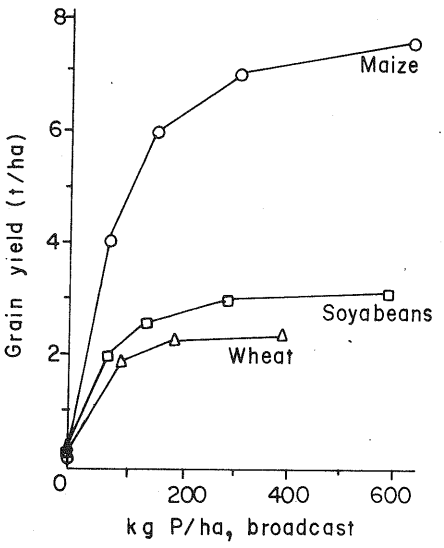


Fig. 3. Typical crop responses to phosphate fertilizer on virgin *cerrado* clay soils (Lobato 1980).

Phosphate fertilizer recommendation schemes are usually organized as a function of the levels of extractable P, the soil texture, and the kind of farming system. In these schemes, one important variable is the source of phosphate. When local rock phosphates are available, they may be useful for improving soil P status. However, most of the phosphates known in tropical areas are of low solubility and low agronomic effectiveness.

The P uptake by plants can be enhanced by their association with soil organisms such as mycorrhizal fungi. These associations are commonly found in native environments, but the efficiency of the process can be improved by the introduction of some exotic species. However, to take full advantage of this phenomenon, several problems have to be solved, such as the technology to produce massive quantities of inoculum and to inoculate mycorrhiza on a practical basis, in large areas (Mosse and Hayman 1980; Miranda 1981, 1982; Yost and Fox 1982; Miranda, Sousa, and Miranda 1984; Sano 1984).

Other Nutrients. Most Oxisols have medium to high contents of organic matter and hence of nitrogen. It has been observed that 60-80 $kg.ha^{-1}a^{s}$ of N are released from organic matter decomposition following lime and phosphate application to these soils (Grove 1979; EMBRAPA/CPAC 1981). Although nitrogen may not be of major immediate concern, the increasing removal of N by intensive cropping and by leaching (the soils are highly permeable and rainfall intensity is high) may reduce N availability in the soil. The main lines of research have been based on biological N fixation, crop associations, and mineral fertilization (Peres and Suhet 1986).

Potassium is also a very important nutrient. Most Oxisols have less than 0.15 meq K/100 g which is considered to be the critical level for grain crops. Crop responses are frequent for soils with less than 50 ppm K (extracted by the Mehlich procedure). Usually K is included in a NPK fertilizer formula, used as maintenance localized application at sowing time (Vilela and Ritchey 1985).

Crops on Oxisols often show deficiency of sulfur and micronutrients, especially zinc. Soil reserves of copper, boron,

and molybdenum may also be inadequate (McClung, Freitas, and Lott 1959; Lopes and Cox 1977). Among the micronutrients, only lack of zinc has caused yield depression under field conditions, especially with nonlegume plants and in limed soils. Field data for crop response to rates of zinc application or to levels of extractable Zn from the soil are scarce, but the addition of 3 kg Zn/ha has been shown to overcome Zn deficiency (EMBRAPA/CPAC 1976; Galrão 1984).

Cropping

Once the effects of soils acidity are minimized and the fertility status improved, areas of Oxisols can be cropped with almost any crop which is adapted to regional climatic conditions. However, the type of cropping system and the level of yield are closely related to the total amount of amendments (especially limestone and fertilizers) used and the kind of soil management.

If the final goal is to establish pasture for grazing, there is no need for a full correction of soil acidity since most tropical forage species commonly show tolerance to Al (Spain 1979). Also these plants usually have a higher capacity to extract nutrients from the soil system, which implies maximum yields with lower levels of fertilization when compared to most annual crops. On the other hand, when the objective is a continuous cropping system with species such as soybean or corn, high yields can only be obtained after the level of the soil fertility is above a threshold. This level, as discussed later, is also a function of the economic situation.

Soil Management and Economic Features

Researchers as well as good farmers have demonstrated that, once we overcome the limitations imposed by low soil fertility and eventual water stress, we can get yields as high as or even higher than those obtained in some other soils.

Independent of the productivity, there are costs in the production system which are fixed, such as soil preparation, seeds, pesticides, labor, and so on. To pay for these costs a minimum production must be obtained above which some yield is still required for paying the variable costs and to give economic return to the activity.

Fertilizer is the one factor that can appreciably increase productivity when working with infertile soils. However, this is not the only factor responsible for agricultural production.

Considering the high cost of the production factors, especially the inputs, efficiency is a must. When talking about efficiency, usually we are talking about high productivity. To reach the required productivity, rural administration plays an important role. In other words, a clever combination of production factors is a permanent challenge. Figure 4 shows that to reach low levels of productivity (PL_1) there are several possible combinations among crop management levels (variety, time of planting, plant population, etc.) and fertilizer levels. As we increase production level to PL_2, the possible combinations among the considered production factors decrease. To get higher productivity, expressed by PL_3, the alternative combinations decrease in number and a minimum fertilizer level A and a crop management level K are required.

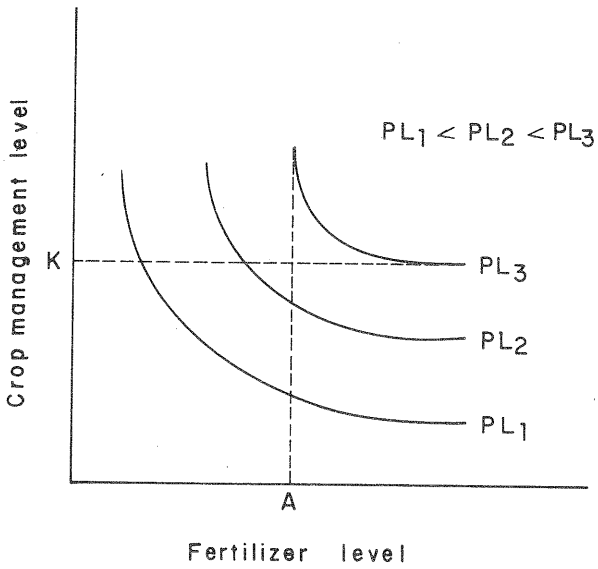


Fig. 4. Productivity as a function of fertilizer and crop management levels (Goedert, Scolari, and Lobato 1986).

As we increase productivity the utilization of technology and the administration of production factors become more critical.

As an example, Figure 5 represents the potential response of soybeans to phosphate application. Two levels of management are considered: actual and advanced. The latter includes better soil preparation; a greater amount of limestone, seeds, and inoculant of better quality; time of planting adequate to the variety; integrated control of pests; and so on. In this example the average yield of 1.7 ton/ha is represented by point A. Among several possibilities for increasing this productivity, the simplest way is to increase the rate of P application to reach point B, on the same level of management. This point is given by calculating the rate of maximum economic return at the same management level. Even though the prices vary with time, we may predict possible economical average productivity of about 2.5 ton/ha. This shows that the regional productivity has been limited, to a great extent, by the level of phosphate usually applied. Alternatives to improve the efficiency of phosphate fertilization are given by the points C, D, and E. Increasing management level may, sometimes, be represented by a simple replacement of a variety. Point C shows that it is possible to maintain the same level of productivity (A) by decreasing phosphate level and improving management level. A productivity level greater than A can be obtained through better management (D) or with simultaneous increasing of phosphate application (E).

Production Possibilities

The contribution of *cerrados* Oxisols to the country production of rice, edible beans, corn, soybeans, wheat, and cassava in 1984 was 24 percent of the total, resulting from the cultivation of 26 percent of the total area planted with those

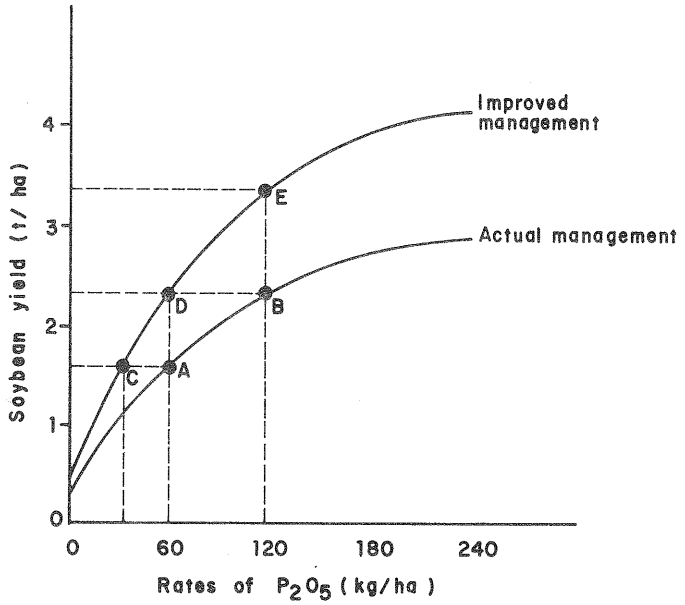


Fig. 5. Soybean response to phosphate fertilization in acid Oxisols (Goedert 1985).

crops. So, one fourth of the area yielded about one fourth of the production giving, roughly, the same national average.

However, average productivity for most of the crop is quite low. There is no doubt that, with proper assistance based upon the present available knowledge, a two- to fivefold increase in those productivities (Table 2) could be obtained. Notice that some farmers are getting good yields. Research plots may show yields even higher.

Due to the extension and the heterogeneity of areas covered by Oxisols, the potential for diversification of agricultural production is not limited to the half-a-dozen crops listed on Table 2. Grains, beef, fruits, fibers, timber, and horticulture are among the possible alternatives for use of this area. Concerning humid tropics regions, the best options include several perennial crops, such as rubber, oilpalm, cocoa, and so forth.

Economic Implications

The residual effect of lime and phosphate application is quite considerable. The normal rate of lime incorporation to reach pH 5.5 may last for at least 5 years before another liming is needed. The effect of an application of 160 kg P_2O_5/ha on a clayey Oxisol increased yield of corn during 10 crops before complete depletion of available phosphorus (Lobato 1980). This residual effect is a function, among other factors, of the amount of lime and phosphate applied.

The investment required to build up soil fertility can be made at once, in the first year, followed by annual maintenance applications to compensate for the amount of nutrient taken up by the crops. Another alternative is to apply annually levels of nutrients (especially phosphate) greater than those required for maintenance such that residuals will be accumulated, year after

Table 2. Present and Potential Productivity of Some Important Grain Crops in *Cerrado* Areas (1984)

Crops	Average Yield		Good farmers	Research plots
	Cerrados	Brazil		
	(t/ha)			
Rice	1.1	1.7	3.0	4.8
			8.0[a]	9.0[a]
Corn	1.6	1.7	7.0	13.0
Beans	0.4	0.5	2.0	4.0
Soybeans	1.7	1.7	4.0	4.8
Wheat	1.4[b]	1.2[b]	2.5	3.0
			5.4[a]	7.7[a]

[a] Irrigated.
[b] Average of 1983.

Table 3. Cost for Transforming One Hectare of *Cerrado* Oxisol in Highly Productive Agricultural Soil

Items	Total Cost (US$/ha)	(%)
Inputs (lime, phosphorus, potassium, micronutrients)	340	42.5
Land clearing	140	17.5
Other investments	120	15.0
Total	600	
Average land price (native)	200	25.0
Total cost of 1 ha of improved soil	800	100.0

Source: D.D.G. Scolari (pers. comm.).

year, until reaching the desired level of fertility and productivity.

The cost to transform one hectare of *cerrado* Oxisol (land clearing, inputs, and other investments), as an average, is three times higher than the price of the virgin area. However, adding up these costs plus the cost of the land we have a total of about US$800 per hectare (Table 3).

Comparing the final cost of this highly productive hectare, after soil fertility build up, with the cost of one hectare in some traditional agricultural areas of Brazil, the *cerrado* Oxisol may cost as low as one-tenth of the price of the traditional area.

After this initial investment the maintenance application of fertilizers is about the same as anywhere else.

Implications of Intensive Use on Soil Profile Characteristics

The removal of the original vegetation cover, followed by liming, fertilization, and cropping, will result in substantial changes of several soil profile features, especially on the plow layer. Some of these changes may affect soil classification

Porosity, erodibility, and water retention capacity are among the physical properties commonly modified by continuous cropping. Concerning soil morphology, the most immediate consequence is the formation of an Ap horizon, with high porosity. The continuous use of heavy machinery or the inadequate use of any machinery may result in the development of a compacted layer just below the plowed layer, which may have drastic negative effects on root growth and consequently on water and nutrient uptake by plants. Another consequence is the decrease in water infiltration with increasing risks of soil erosion through runoff.

The organic matter (OM) content usually decreases after cropping, but the final level of OM will be a function of the kind of soil management, especially regarding the incorporation of crop residues. The decrease in the total OM content, apparently, may reduce the water-holding capacity.

Drastic changes in the chemical features of the soil can be observed after the addition of lime, fertilizers, and other amendments. The soil properties more affected are: pH, exchangeable cations, (S), exchangeable Al and Al saturation, availability of nutrients (especially phosphate), and capacity to absorb anions.

Table 1 illustrates some effects of liming on the exchangeable pool of the topsoil. The changes are closely related to lime rates and vary with time after lime incorporation. Exchangeable Al and Al saturation may decrease to values close to zero. The inverse will occur with exchangeable Ca and Mg, and with base saturation (V). In other words, the plow layer of a distrophic Oxisol may exhibit eutrophic behavior.

In addition, liming will affect cation exchange capacity (CEC) and the soil capacity to absorb anions, such as phosphate. Because variable charge minerals predominate in the clay fraction of these soils, lime will affect pH dependent charges, thus increasing CEC, measured at soil pH (ECEC). An estimate of the magnitude of this effect can be obtained from Table 1, by comparing the sum of exchangeable Ca, Mg, and Al for various lime levels. This sum, which roughly represents the ECEC, more than doubled as the pH rose from 4.7 to 6.3. As a consequence, limed soils have greater retention of nutrient cations.

Furthermore, the changes in the soil charge balance and the additon of a large amount of hydroxil ions into soil solution may result in a decrease of the soil P sorption capacity. Le Mare and Goedert (1983) found that the addition of lime to increase the pH to about 6 decreases by about 30 percent the amount of P absorbed nonexchangeably in a Dark Red Latosol.

The additon of lime may also affect soil properties below the plow layer. Since most Oxisols exhibit low exchange capacity, the movement of ions into and through the soil profile may cause significant changes in the ionic pool (mainly in the solution and exchangeable pool) of the horizons below plow

layer. One illustration was already discussed concerning the downward movement of Ca, after liming (Fig. 2). Five years after liming the exchangeable Ca increased significantly down to a 60 cm depth and the Al saturation was reduced.

The movement of ions in the soil profile will depend on several factors, such as rainfall intensity, soil clay content and mineralogy, and the amount and kind of ions added through soil management and cropping.

In addition to chemical and physical changes may occur modifications in the soil biological composition and activity, but very little information is available in this area.

In conclusion, the intensive use of Oxisols for agriculture, in the long run, may modify the genetic classification of the soil and undoubtedly will change its potential for agriculture. A virgin distrophic Oxisol, with severe limitations for intensive cropping, can be transformed into an excellent soil for agriculture.

References

Bouldin, D.R. 1979. The influence of subsoil acidity on crop yield potential. *Cornell Intern. Agric. Bull.* 34, Cornell Univ., Ithaca, NY.

EMBRAPA/CPAC. 1976. Relatório Técnico Anual do Centro de Pesquisa Agropecuária dos Cerrados 1975-1976. Planaltina-DF, Brazil.

—. 1980. Relatório Técnico Anual do Centro de Pesquisa Agropecuária dos Cerrados 1978-1979. Plantatina-DF, Brazil.

—. 1981. Relatório Técnico Anual do Centro de Pesquisa Agropecuária dos Cerrados 1979-1980. Plantatina-DF, Brazil.

Galrão, E.Z. 1984. Efeito de micronutrientes e do cobalto na produção e composição química do arroz, milho e soja, em solo de cerrado. *R. Bras. Ci. Solo* 8:111-116

Goedert, W.J. 1983. Management of the cerrado soils of Brazil: A review. *J. of Soil Sci.* 34:405-428.

—. 1985. Management of acid tropical soils in the savannas of South America. *In* Inaugural workshop of the acid tropical soils management network, IBSRAM. Brasilia, Brazil.

Goedert, W.J., D.D.G. Scolari, and E. Lobato. 1986. Estratégia de uso e manejo do solo. *In* W.J. Goedert (ed.). Solos dos cerradosTecnologias e estratégias de manejo. EMBRAPA e Editora NOBEL. São Paulo, Brazil.

Grove, T.L. 1979. Nitrogen fertility in Oxisols and Ultisols of the humid tropics. *Cornell Intern. Agric. Bull.* 36. Cornell Univ. Ithaca, NY.

Kamprath, E.J. 1984. Crop response to lime on soils in the tropics. *In* Soil acidity and liming. Agronomy Monograph no. 12 (2nd edition). Am. Soc. Agron., Madison, WI.

Lathwell, D.J. 1979a. Phosphorus response on Oxisols and Ultisols. *Cornell Intern. Agric. Bull.* 33. Cornell Univ. Ithaca, NY.

—. 1979b. Crop response to liming of Ultisols and Oxisols. *Cornell Intern. Agric. Bull.* 35. Cornell Univ. aca, NY.

Le Mare, P.H. 1982. Sorption of isotopically exchangeable and non-exchangeable phosphate by some soils of Colombia and Brazil, and comparisons with soils of southern Nigeria. *J. of Soil Sci.* 33:691-707.

Le Mare, P.H., and W.J. Goedert. 1983. Effects of liming on sorption and desorption of phosphate by some acid soils of South America. Proc. of IMPHOS 3rd international congress of phosphorus compounds. Brussels. Institut Mondial du Phosphat. Casa Blanca, Marrocos.

Lobato, E. 1980. Adubação fosfatada em solos sob vegetação de cerrado. EMBRAPA/Centro de Pesquisa Agropecuária dos CerradosPlanaltina-DF, Brazil.

Lopes, A.S., and F.R. Cox. 1977. A survey of the fertility status of surface soils under "cerrado" vegetation in Brazil. *Soil Sci. Soc. of Amer. Proc.* 4:742-747.

McClung, A.C., L.M.M. Freitas, and W.L. Lott. 1959. Analysis of several Brazilian soils in relation to plant responses to sulphur. *Soil Sci. Soc. of Amer. Proc.* 23:221-224.

Miranda, J.C.C. 1981. Ocorrência de fungos endomirrizicos nati vos em um solo de cerrado do Distrito Federal e sua influência na absorção de fósforo por *Brachiaria decumbens* Stapf. *R. Bras. Ci. Solo* 5:102-105.

—. 1982. Influência de fungos endomicorrizicos inoculados a campo na cultura de sorgo e soja em um solo sob cerrado. *R. Bras. CEolo* 6:19-23.

Miranda, J.C.C., D.M.G. Souza, and L.N. Miranda. 1984. Infuência de fungos endomicorrizicos vesiculo-arbusculares na absorcao de fósforo e no rendimento de matéria seca de plantas de sorgo. *R. Bras. Ci. Solo* 8:31-36.

Miranda, L., J. Mielnickzuk, and E. Lobato. 1980. Calagem e adubacao corretiva. *In* V Simpósio sobre o cerrado. Brazilia-DF, Brazill. Pp. 521-578.

Mosse, B., and D.S. Hayman. 1980. Mycorrhiza in agricultural plants. *In* P. Mikola, (ed.). Tropical mycorrhiza research. Oxford Univ. Press. Pp. 214-230.

Peres, J.R.R., and A.R. Suhet. In press. Adubação nitrogenda no Planalto Central. *In* P.C. Rosand (ed.). Adubação nitrogenada no Brasil.

Ritchey, K.D., D.M.G. Sousa, E. Lobato, and O.C. Sousa. 1980. Calcium leaching to increase rooting depth in a Brazilian savannah Oxisol. *Agron. J.* 32:40-44.

Sanchez, P.A., and J.G. Salinas. 1981. Low-input technology for managing Oxisols and Ultisols in tropical America. *Advan. in Agron.* 34:280-398.

Sano, S.M. 1984. Influência de endomicorrizas nativas do cerra do no crescimento de plantas. *R. Bras. Ci. Solo* 8:25-29.

Seubert, C.E., P.A. Sanchez, and C. Valverde. 1977. Effects of land clearing methods on soil properties and crop performance in an Ultisol of the Amazon jungle of Peru. *Trop. Agric.*, Trin. 54:307-322.

Spain, J.M. 1979. Pasture establishment and management in the Llanos Orientales. *In* P.A. Sanchez and L. Tergas (eds.). Pasture production in acid soils of the tropics. CIAT, Cali, Columbia. Pp. 167-176.

Vilela, L., and K.D. Ritchey. 1985. Potassium in intensive cropping systems on highly weathered soils. *In* R.D.Munson (ed.). Potassium in agriculture. Am. Soc. Agron. Madison, WI.

Yost, R.S., and R.L. Fox. 1982. Influence of mycorrhiza on the mineral contents of cowpea and soyabean grown in an Oxisol. *Agron. J.* 74:475-481.

OXISOLS ACIDITY AND FERTILITY EVALUATION: A NEED FOR SUITABLE MANAGEMENT

A.S. Lopes and N. Curi[1]

Abstract

A majority of Oxisols, which occupy a large portion of the potentially arable land in the world, are considered marginal for agricultural production due to several constraints, as for example soil acidity and low natural fertility. However, examples of success in sustained agriculture on these soils demonstrate that, with adequate technology and rational use of lime and fertilizers, it is highly feasible to use these soils on a continuous basis. To increase the probability of success of agricultural production in these soils, it is necessary to quantify their possible nutritional constraints as a crucial point to reduce or eliminate them throughout suitable management. In this sense this paper deals with a review of the basic principles of soil acidity and the necessity of their interrelationships with cation exchange properties of Oxisols in order to estimate adequate rates of lime. It also presents critical comparison among three common criteria for lime recommendation (exchangeable aluminum, SMP at pH 6.0, and base saturation elevation), their limitations and advantages. In terms of evaluation of primary and secondary macronutrients, micronutrients, P adsorption, Al toxicity, and cation exchange properties a general discussion of the possible more suitable laboratory methods is presented. The final goal is to achieve an adequate reference base that can integrate pedology with soil fertility and allow further extrapolation of research findings to farmers' fields.

Oxisols, which occupy a large portion of the potentially arable land in the world, are considered, in most cases, marginal for agricultural production. However, examples of success in sustained agriculture on these soils demonstrate that, with adequate technology and rational use of lime and fertilizers, it is feasible to use these highly weathered soils on a continuous basis, while aiming to reduce food shortages in the third world. Since the most widespread constraints to agricultural use of these soils are related to acidity and low natural fertility, special attention must be given to adequately quantify these constraints, evaluate the intensity of their occurrence, and suggest management technology to reduce or eliminate them for food crop production.

This paper deals with the following objectives: (1) to review the basic principles of soil acidity and their interrelationships with cation exchange properties of Oxisols; (2) to make a critical evaluation of common criteria to recommend rates of lime for Oxisols; and (3) to suggest some fertility parameters to compose a reference base on knowledge of fertility status of these soils as a support for suitable management.

Soil Acidity Evaluation

Basic Concepts

Soil acidity basic concepts are well known in both temperate and tropical regions. In order to adequately evaluate and make use of these parameters one should remember their implications in terms of different rates of lime and suitable management of acid tropical soils, while aiming at reduction or elimination of soil acidity as a constraint to agricultural production.

In this sense the basic principles of soil acidity cannot be considered in isolated terms, being obvious the necessity of interrelationships with basic concepts of cation exchange capacity (CEC) to achieve the desired goals.

The main components of soil acidity in relation to the active solid fractions of the soil—organic matter, clay minerals, oxides, oxyhydroxides, and hydroxides of Fe and Al—are shown in Figure 1 (van Raij and Quaggio 1984).

These components are defined by Kinjo (1983) as: (a) active acidity; (b) exchangeable acidity; (c) nonexchangeable acidity; and (d) potential acidity or total acidity.

(a)*Active acidity* is given by the concentration of H^+ in the soil solution and is expressed in terms of pH.

(b)*Exchangeable acidity* refers to exchangeable Al plus H^+ adsorbed on the colloidal surface by electrostatic forces and extracted by a neutral unbuffered salt solution like 1N KCl. Since very little exchangeable H^+ exists in mineral soil (Coleman and Thomas 1967; Coulter 1969), exchangeable acidity and exchangeable Al are considered almost equivalents.

(c)*Nonexchangeable acidity* is the amount of the titrator that still remains in the soil after the exchangeable acidity has been

[1] Authors' present address: Departamento de Ciência do Solo, Escola Superior de Agricultura de Lavras (ESAL). Caixa Postal 37. CEP 37.200, Lavras, Minas Gerais, Brazil.

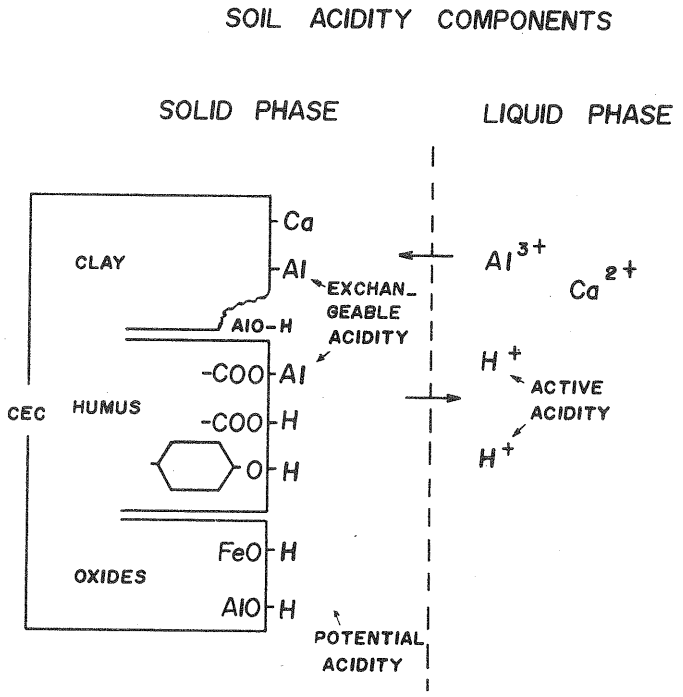


Fig. 1. Diagrammatical representation of soil acidity components, according to van Raij and Quaggio (1984).

removed with a neutral unbuffered salt solution. This type of acidity is represented by H^+ in covalent bonds with organic and mineral soil fractions.

(d)*Potential acidity* or *total acidity* refers to the total H^+ in covalent bonds plus exchangeable Al and H extracted with a buffered salt solution at a given pH. In the Brazilian soil classification system this acidity is determined at pH 7.0 (EMBRAPA 1979), and in *Soil Taxonomy* at pH 8.2 (Soil Survey Staff 1975). By subtracting the values of exchangeable acidity from the potential acidity, one can obtain the nonexchangeable acidity.

A suitable representation concerning soil acidity basic concepts, CEC, and pH can be visualized in Figure 2, according to van Raij (1981). It is necessary to stress that the *potential cation exchange capacity* (*T*) is defined as the quantity of cations adsorbed at pH 7.0 or pH 8.2, according to the Brazilian soil classification system or *Soil Taxonomy*, respectively. Potential CEC can be obtained by the addition of the *summation of bases* (*S*) plus $H^+ + Al^{3+}$ at pH 7.0 or 8.2, and it is generally expressed in meq/100 g or meq/100 cm^3:

$$S = Ca^{2+} + Mg^{2+} + K^+ + Na^+,$$
$$T = \text{potential CEC} = S + (H^+ + Al^{3+}).$$

The fraction of the potential CEC occupied by exchangeable bases is referred to as base saturation (V%) and calculated by the formula:

$$V\% = 100\,\frac{S}{T}.$$

By subtracting the value of base saturation from 100 percent one can obtain the *acid saturation* of M% value:

$$M\% = 100 - 100\,\frac{S}{T} = 100 - V\%\,.$$

When dealing with the concept of effective CEC (*t*), that is, the cation adsorption capacity near the natural soil pH value, this parameter can be calculated by the following expression:

$$t = \text{effective CEC} = S + Al.$$

The fraction of the effective CEC occupied by exchangeable Al or exchangeable acidity is identified as *percentage of aluminum saturation* (m%):

$$m\% = \frac{100 \times Al^{3+}}{S + Al^{3+}} = \frac{100 \times Al^{3+}}{t}\,.$$

By subtracting the value of Al saturation from 100 percent, one can obtain the *percentage of base saturation* of the effective CEC or v% value.

Since the cation exchange process is dynamic and alteration of quantity of bases adsorbed to the colloidal complex alters the pH, the importance of taking these facts into consideration when dealing with liming needs of Oxisols is obvious. According to Thomas (1982), the potential acidity is related to the potential liming level and to the potential CEC, while the exchangeable acidity deals with the immediate liming level and existing CEC.

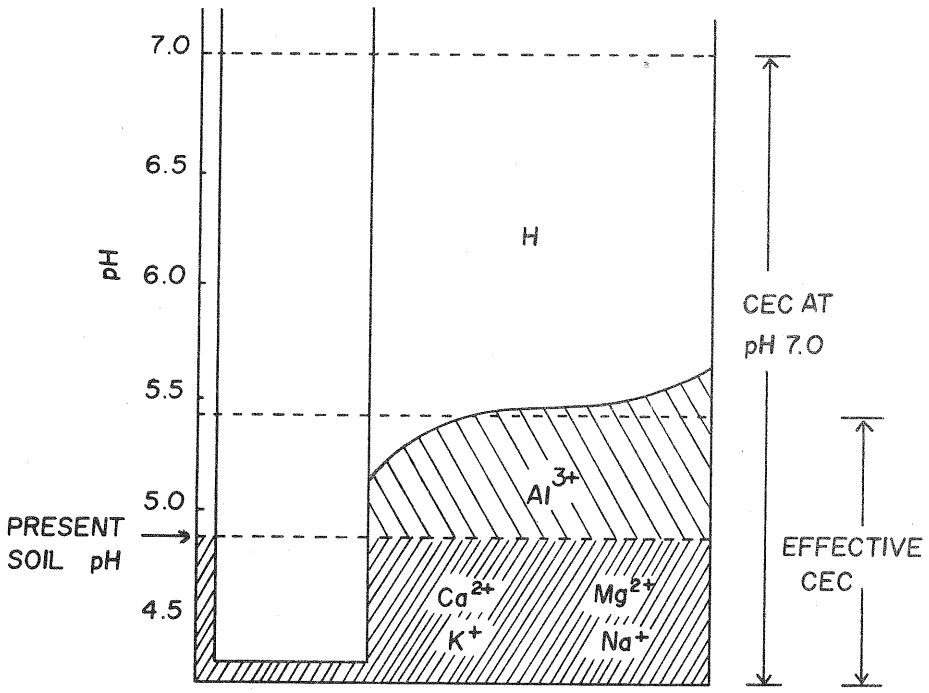


Fig. 2. Diagrammatical representation of CEC as a reservoir in which the pH indicates the level of exchangeable bases. Source: van Raij (1981).

Criteria for Lime Recommendation on Oxisols

The importance of suitable evaluation of soil acidity parameters increases because of the interrelationships of these parameters with assessment of adequate rates of lime to overcome soil acidity as a constraint to agricultural production in most Oxisols.

Given the relevance of this subject, a deeper discussion will be given considering the following liming recommendation criteria: (1) exchangeable Al; (2) buffer SMP; and (3) base saturation elevation.

Exchangeable Al criterion. The original basis for this method was the paper by Daikuhara (1914) where the author suggested the evaluation of exchangeable Al, extracted by 1N KCl following titration with NaOH, as a parameter for soil acidity evaluation. Exchangeable Al has been suggested as the criterion for determining the amount of lime to apply to acid soils (Mohr 1960; Kamprath 1967, 1970; Reeve and Sumner 1970). General diffusion of this method took place after the work of Coleman, Kamprath, and Weed (1959), and mainly after the findings that the predominant cation in acid soils with pH below 5.0 was aluminum rather than hydrogen (Coleman and Thomas 1967). By that time it was established that exchangeable acidity affecting plant growth was the one which could be extracted by a neutral unbuffered salt solution. At pH 5.5 or above, soils contain essentially no exchangeable aluminum (extracted by KCl). The international spreading of this method in the tropics was observed after Kamprath (1967), through the work developed by the International Soil Testing Project, coordinated by North Carolina State University. That author stated that liming rates for mineral soil should be calculated by the expression:

(a) meq Al^{3+}/100 cm^3 x 2 = ton of lime/ha.

Several modifications of this method were introduced in Brazil involving directly or indirectly the concept of exchangeable aluminum as summarized by Lopes (1984):

(b) 2 - (meq Ca^{2+} + Mg^{2+}/100 cm^3) = ton of lime/ha;

(c) (2 x meq Al^{3+}/100 cm^3) + 2 - (meq Ca^{+} + Mg^{2+}/100 cm^3) = ton of lime/ha;

(d) Y - (meq Ca^{2+} + Mg^{2+}/100 cm^3) x f = ton of lime/ha; or

(e) meq Al^{3+}/100 cm^3 x f = ton of lime/ha,

where:

Y = 2 for sandy soils with less than 1.5 percent organic matter,

Y = 3 for other soils,

f = 1.5 for acidity tolerant crops,

f = 2 for acidity nontolerant crops.

Criterion (a) is utilized in Central Brazil for soil with high levels of exchangeable Al and low levels of exchangeable Ca + Mg. Criterion (b) is recommended for soils low in exchangeable Al and Ca + Mg. Criterion (c) is a combination of (a) and (b) recommended for crops requiring more Ca^{2+} + Mg^{2+} and is the method generally used in the *cerrado* area in central Brazil (CFSEMG 1978; CEFSG, no date; EMBRATER 1979).

Criteria (d) and (e) were, until 1983, used by the Instituto Agronômico de Campinas (IAC), São Paulo State, being the option of recommendation by expression (d) or (e) as a function of the one that reaches the higher rate of lime (Ultrafertil 1978).

Some considerations about the original exchangeable Al concept as a criterion for determining rates of lime for Oxisols is desirable at this stage. According to Lopes (1984), some limitations of this method are as follows:

1. Does not directly consider variations in soil texture and organic matter, and, consequently, there are no variations in rates of lime according to soil-buffering capacity;
2. Does not consider variations in degree of tolerance to pH problems and Al, Fe, and Mn toxicity among plant species and varieties; rates of lime calculated by this criterion are not sufficient to overcome Mn toxicity problems;
3. Does not allow adequate generation of pH-dependent charges, since the pH 5.3 to 5.6 that follows lime application calculated by this method is not enough to maximize the occurrence of this phenomenon;
4. The residual effect of the liming is smaller, since the rates are approximately half of the rates recommended by the SMP pH 6.0 method (Fig. 3);
5. Negligible effect in diminishing Al, Fe, and Mn toxicity in subsurface layers, as a function of lower rates applied and consequently lower downward movement of micropulverized lime particles;
6. Smaller global efficiency for N, P, K, Ca, Mg, and S, since at pH 5.5 this efficiency is 65 percent, as compared to 75 percent at pH 6.0 and 94 percent at pH 6.5 (Alcarde 1983).

Some advantages of the exchangeable Al criterion can be summarized as follows:

1. Fewer possible problems in terms of unbalance of micronutrients (mainly B, Cu, and Zn) in Oxisols with low reserves due to the low amounts in the parent material, high weathering and leaching losses, or both;
2. Smaller investments in short periods of time as a result of generally smaller rates of lime applied;
3. Probably is a suitable method for the technology level of farming systems in some specific regions, soils, and crop conditions.

An improvement of the exchangeable Al criterion, including the critical aluminum saturation required by a particular crop, variety, or farming system was proposed by Cochrane, Salinas, and Sanchez (1980) as a method to determine the amount of lime required for Oxisols and Ultisols:

$$\text{Lime required (ton } CaCO_3 \text{ eq/ha)} = 1.8|Al\text{-}RAS\ (Al + Ca + Mg)|/100:$$

where RAS = critical percent of aluminum saturation.

According to those authors, when compared with actual field data, the predictability of this equation is excellent.

Buffer SMP criterion. The buffer SMP method (Shoemaker, McLean, and Pratt 1961) is presently utilized in the states from south Brazil. It is simple to incorporate into routine soil analysis

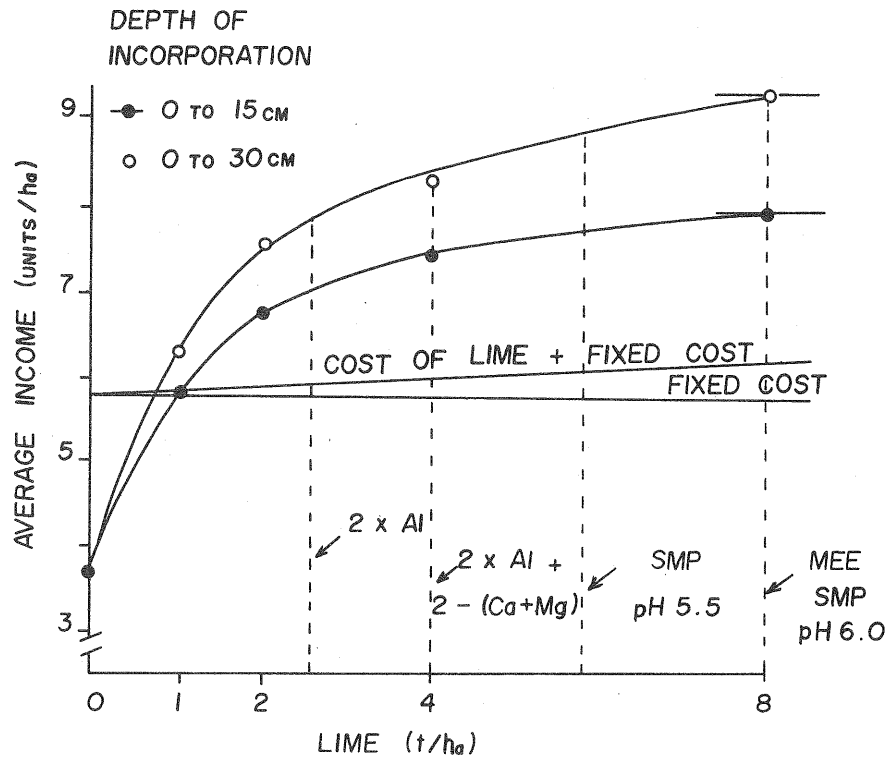


Fig. 3. Average income (units/ha) of seven crops—or five corn, one sorghum, and one soybeans—as a function of lime rates applied in 1972 on a dystrophic, clayey, Dark Red Latosol (Oxisols). MEE = Maximum Economic Efficiency. Source: Miranda, Mielniczuk, and Lobato (1980).

since it consists in determining the pH_{SMP} of a suspension (soil, water, and a buffer solution) and getting the amount of lime needed to increase the soil pH to 6.0 by using a table. The table is organized by using a collection of soil samples that must represent the region. The samples are incubated with $CaCO_3$ and then a relation between the values of pH_{SMP} and lime required to bring the pH in H_2O to 6.0 is established (Quaggio 1985).

Limitations of this method for Oxisols, according to Lopes (1984), are as follows:

1. Does not consider variations in degree of tolerance to pH problem and Al, Fe, and Mn toxicity among crop species and varieties;
2. Greater possibility of nutritional unbalance in terms of micronutrients (mainly B, Cu, and Zn), requiring more theoretical background to solve possible induced problems;
3. Greater investments in short periods of time as a result of greater rates of lime required;
4. More intense acceleration in the decomposition of organic matter, due to higher pH values inducing higher microbial activity;
5. Tendency to form smaller aggregates, diminishing infiltration rates—that can be beneficial in certain cases—and increasing erosion problems as a result of increasing runoff.

The advantages of the buffer SMP to pH 6.0 method would be the reverse of the limitations of the exchangeable Al method previously presented, with the exception of item (2) that continues as a limitation for both methods.

Base Saturation Elevation Criterion. The fact that there is a relationship between soil pH and base saturation has been observed by many authors (Cantani and Gallo 1955; Comissão de Solos 1960; Combeau, Ollat, and Quantin 1961; van Raij, Saccheto, and Ique 1968; Castro, Barreto, and Anastácio 1972; Camargo and van Raij 1975; Quaggio 1983).

The original paper in Brazil concerning this method was that of Cantani and Gallo (1955), working with data of 85 samples from São Paulo State (Fig. 4). Based upon this relationship, an equation was developed by those authors and later on adapted by van Raij (1981), and van Raij and Quaggio (1983) as follows;

$$\text{Lime required} = \frac{T(V_2 - V_1)}{100} \times f,$$

where: T = cation exchange capacity at pH 7.0,

V_1 = base saturation of the soil at pH 7.0 = 100 x S/T,

where: S = summation of bases = $Ca^{2+} + Mg^{2+} + K^{+} + Na^{+}$,

V_2 = base saturation at pH 7.0, desired for a given crop,

f = correction factor for the lime quality = 100/PRNT,

where PRNT takes into account the chemical efficiency and particle size of the lime.

Some limitations of this methodology can be summarized as follows:

1. The base saturation (V%) is taken in relation to a value of

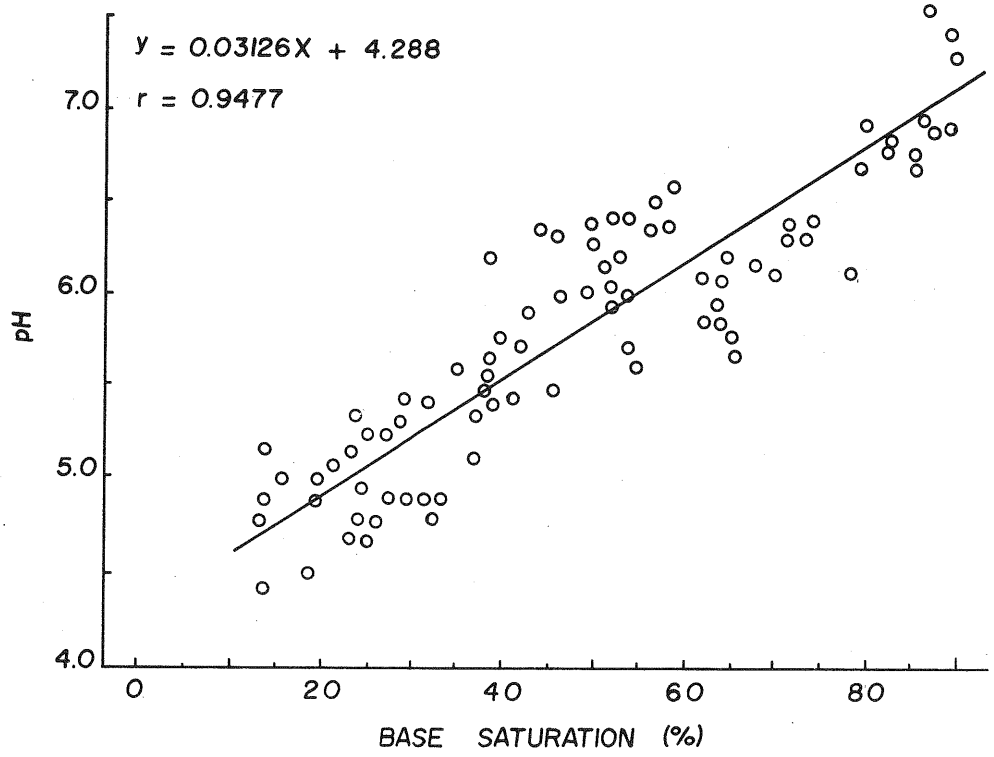


Fig. 4. Relationship between pH and base saturation of 85 samples of soils from São Paulo State. Source: Catani and Gallo (1955).

CEC at pH 7.0 that is still considered too high for a comparison basis for most soil in the tropical region;
2. Requires specific calibration studies to estimate the ideal value of V% for specific crops and varieties. This requires time and a considerable data collection;
3. Requires modifications in routine analyses for fertility purposes in order to include $H^+ + Al^{3+}$ to be added to $Ca^{2+} + Mg^{2+} + K^+ + Na^+$, aiming to estimate CEC at pH 7.0, and calculate V%;
4. Higher rates of lime by this method can have some deleterious effects on the nutritional balance in terms of micronutrients (mainly B, Cu, and Zn).

However, some advantages of this system must be considered as a basis for re-examination of the general idea that the exchangeable aluminum criterion is the one indicated for "tropical" soils:

1. It is a more flexible and scientific criterion that takes into account the ideal crop or variety base saturation for maximum economic efficiency;
2. It integrates the factors that affect the buffer capacity of the soil (texture, mineralogy, organic matter content), since these parameters affect the evaluation of CEC at pH 7.0;
3. Allows greater residual effect of the liming practices, possibly allowing also greater effect on subsurface layers, since the rates of lime are considerably higher than rates based on the exchangeable aluminum criterion (Table 1);
4. Allows greater global efficiency for N, P, K, Ca, Mg, and S since the higher rates of lime recommended lead to a greater final pH value than that attained by the rates based on the exchangeable aluminum criterion;
5. Inclusion of $H^+ + Al^{3+}$ for routine purposes, which is necessary for the use of the base saturation elevation criterion, allows also an estimate of pH-dependent charges in Oxisols, with all practical implications from the knowledge of this parameter. This can be obtained by subtracting effective CEC (t) from CEC at pH 7.0 (T);
6. Certainly it is a more suitable method for a high input technology approach already practiced in many areas of Oxisols for grain crops production.

Many laboratories in Brazil have already incorporated the determination of H+ + Al3+ for routine purposes. The time consuming extraction of $H^+ + Al^{3+}$ by Ca-acetate buffered at pH 7.0 (Vettori 1969; EMBRAPA 1979) has been substituted by evaluation of the equilibrium pH of a buffer SMP solution with the soil. Since these parameters are well correlated (van Raij, Cantarella, and Zullo 1979; Quaggio and van Raij 1982; and pers. observ.), one only needs to incorporate an additional pH reading to routine analyses in order to be able to estimate $H^+ + Al^{3+}$ with all beneficial implications from the knowledge of this variable.

Evidences for Re-examination of Soil Acidity Evaluation and Recommendation of Lime Rates on Oxisols

There are no long-term studies involving residual effects and including economic data on lime use for Oxisols. However, a few data available concerning this subject allow us, at least, to show that rates of lime based upon exchangeable aluminum are not always the best approach for these soils.

Data presented in Table 2 from the paper of Quaggio (1985), based upon 10 field experiments conducted during several years at different locations, with different soils and crops, indicated that the exchangeable aluminum criterion subestimated the lime needs for optimization of crop yields, while rates estimated by SMP pH 6.0 and base saturation methods led to productions very close to maximum yields. Calculations of lime rates for maximum economic efficiency for some of these results from São Paulo State and also including data from the *cerrado* area and south Brazil, suggest that for Oxisols rates estimated by exchangeable aluminum criterion are about half of the optimum rates (Table 1)(Mielniczuk 1983).

Calculations of lime needs according to the criteria of exchangeable aluminum and base saturation (from the hypothesis that the rate of lime needed should account for 70 percent base saturation of the CEC at pH 7.0), based upon soil chemical analyses of the upper layer of the Oxisols described in the field trip of the VIIIth International Soil Classification Workshop (ISCW) is presented in Table 3. The considerable differences in rates according to these criteria, jointly with the results presented in Tables 1, 2, and 3, and Figure 3, suggest, at least, a review in concepts to recommend rates of lime for Oxisols. This review is mainly necessary for some grain crops which are not tolerant to acidity and aluminum and/or manganese toxicity, cultivated under advanced high input technology, and mainly where the natural reserves and availability of lime are not limiting. Oxisols systems in central Brazil are definitely included in this category.

Fertility Evaluation

Nitrogen Deficiency

Available N is defined as N in the root zone in a form readily absorbed by plant roots (Scarsbrook 1965). This N is derived from various sources. In production agriculture, it is dominantly from fertilizers, biological N2 fixation, and mineralization of organic N from wastes, crop residues, and soil organic matter (Keeney 1982). In most Oxisols in the intertropical regions, a significant amount of soil organic N is mineralized during a growing season, mostly due to favorable temperature and moisture environments.

Bremner (1965) states that proposed laboratory indices of soil N availability can be split into biological and chemical tests. Beyond furnishing a valid index of soil N availability, a laboratory index method should be simple, rapid, reproducible, and should not be affected by sample pretreatment; the latter requirements in essence rule out biological methods (Keeney 1982).

Usually, total nitrogen and organic carbon are poorly correlated with nitrogen response in the field. Because of the lack of a better method, many laboratories use these measures to provide some information to farmers (Sanchez 1976). Some methods for directly evaluating inorganic nitrogen have been successful under greenhouse conditions, by using 0.01 M

Table 1. Rates of Lime for Maximum Economic Efficiency (MEE) of Some Crops of Crop Sequences in Brazil

Place	Soil	Crop	pH	Al^{3+}	Rates of lime		
					Al x 2	SMP pH 6.0	MEE
				(meq/100 cm^3)	----------(t/ha)----------		
Lagoa Vermelha, RS	Durox[a]	Wheat	4.9	1.5	3	8.1	8.1
		Soybeans					12.4
		Wheat-soybeans					10.8
Vacaria, RS	Vacaria[a]	Wheat	4.7	2.4	4.8	10.6	9.9
		Soybeans					13.3
		Wheat-soybeans					12.0
Planaltina, DF	LVE[a]	Corn-sorghum-soybean	4.9	1.9	3.8	8.0	8.0
Mococa, SP	PVA (Red-Yellow Podzolic)	Corn	4.6	1.1	2.2	6.0	8.5
São Simão, SP	LVE[a]	Soybeans	4.9	1.1	2.2	2.8	4.5

[a] Oxisols.
Source: Adapted from Mielniczuk (1983).

Table 2. Crop Responses to Liming in Acid Soils of São Paulo State, Brazil (comparison among efficiency of three criteria for lime recommendation)

Crop	Soil	Observed yield		Estimated yield		
		Without lime	Maximum with lime	Al = 0	BS (%)	SMP pH 6.0
		(ka/ha)				
Cotton	LR[a]	538	1,561	846	1,726	1,743
Cotton	LR[a]	1,463	2,823	1,600	2,394	2,274
Peanut	LE[a]	2,162	2,578	2,380	2,430	2,372
Potato	Cambisol (Inceptisol)	6,721	20,083	13,816	17,692	19,440
Sunflower	PVA (Red-Yellow Podzolic)	900	2,490	1,393	1,672	1,561
Corn	PVA (Red-Yellow Podzolic)	3,292	5,917	4,012	5,157	5,128
Corn	Cambisol (Inceptisol)	208	3,398	2,028	3,504	3,551
Soybeans	LVA[a]	494	1,462	1,072	1,710	1,669
Soybeans	LR[a]	1,720	2,658	1,973	2,577	2,540
Triticale	Cambisol (Inceptisol)	302	2,357	1,531	2,336	2,491

[a] Oxisols.

Source: Adapted from several authors by Quaggio (1985).

Table 3. Selected Chemical Properties of the Top Layer of 23 Soil Profiles Described in the Field Trip of the VIIIth International Soil Classification Workshop (ISCW) and Rates of Lime Estimated by Exchangeable Al and Base Saturation Criteria

Pedon number	pH H_2O	Al^{3+}	$Ca^{2+}+Mg^{2+}$	$H^+ + Al^{3+}$	S	T	BS	Rates of lime	
								Al x 2	BS 70%
		----------(meq/100g)----------					(%)	-------(t/ha)------	
VIII ISCW-1	4.1	2.0	0.3	7.1	0.4	7.5	5.3	4.0	4.8
VIII ISCW-2	5.0	2.9	1.8	17.7	2.0	19.7	10.1	5.8	11.8
VIII ISCW-3	5.1	0.3	6.8	8.2	7.1	15.3	46.4	0.6	3.6
VIII ISCW-4	5.8	0.1	6.2	5.4	6.3	11.7	53.8	0.2	2.0
VIII ISCW-5	6.6	0.0	14.9	3.0	15.9	18.9	84.1	0.0	0.0
VIII ISCW-6	5.5	0.3	6.7	5.3	6.9	12.2	56.5	0.6	1.6
VIII ISCW-7	5.9	0.0	7.8	5.7	8.1	13.8	58.7	0.0	1.6
VIII ISCW-8	6.2	0.0	8.4	3.3	9.2	12.5	73.6	0.0	0.0
VIII ISCW-9	4.9	0.6	0.1	4.2	0.2	4.4	4.5	1.2	2.9
VIII ISCW-10	5.2	0.3	0.3	2.2	0.4	2.6	15.4	0.6	1.4
VIII ISCW-11	5.2	0.5	0.7	9.2	0.9	10.1	8.9	1.0	6.2
VIII ISCW-12	4.9	1.3	0.3	7.3	0.4	7.7	5.2	2.6	5.0
VIII ISCW-13	5.4	0.6	0.8	2.7	0.9	3.6	25.0	1.2	1.6
VIII ISCW-14	6.8	0.0	11.2	2.3	11.7	14.0	83.6	0.0	0.0
VIII ISCW-15	5.6	0.1	4.5	5.0	4.8	9.8	49.0	0.2	2.0
VIII ISCW-16	6.0	0.0	5.5	4.8	5.7	10.5	54.3	0.0	1.6
VIII ISCW-17	5.9	0.0	6.1	5.4	6.2	11.6	53.4	0.0	1.9
VIII ISCW-18	4.6	1.0	0.1	7.2	0.2	7.4	2.7	2.0	5.0
VIII ISCW-19	4.8	1.4	0.4	10.2	0.5	10.7	4.7	2.8	7.0
VIII ISCW-20	5.0	1.4	0.5	11.4	0.7	12.1	5.8	2.8	7.8
VIII ISCW-21	5.1	1.0	1.4	11.1	1.6	12.7	12.6	2.0	7.3
VIII ISCW-22	5.0	0.9	2.0	6.3	2.3	8.6	26.7	1.8	3.7
VIII ISCW-23	4.6	2.4	1.0	7.5	1.2	8.7	13.8	4.8	7.5

$CaCl_2$, or 1N KCl as extractant solutions (Lathwell, Dubey, and Fox 1972); however, no correlation with field response has been conducted in humid tropical areas.

More recently, working with five Ultisols out of eight soil materials, Fox and Piekielek (1978) found that the ultraviolet (UV) absorption by 0.01M $NaHCO_3$ soil extract at 260 nm was well correlated with the N-supplying capability of these tested soils. The authors also concluded that this method is as rapid, simple, and inexpensive as the methods currently used to measure availability of other essential nutrients in the soil.

If further field studies show that this test is as well correlated with the N-supplying capability of Oxisols in tropical areas as it was for the soils tested it could serve as a reference basis for this nutrient problem in terms of routine soil testing.

Top priority should be given to find out a reliable reference basis for N availability in Oxisols.

Phosphorus Deficiency

Acid tropical soils, including most of the Oxisols, normally possess limited phosphorus reserves and/or have high adsorption capacity (Dabin 1980). Economic application of phosphate fertilizers should allow these reserves to be increased economically and gradually to improve the general low soil fertility. Adequate interpretation of the results of P analysis is definitely an important step in solving the P-deficiency problem.

Taking into account the various methods of measuring available P (the term labile P is preferred, Dabin 1980), the results must be accompanied by the name of the method used, and, in addition, the data must be calibrated with crop production in the field. The methods that furnish the highest correlations with plant growth and yields are admitted to be the most suitable ones. Their feasibility is basically dependent upon soil, climate, and plant environments.

In terms of routine analysis for soils in the intertropical regions, the methods employing acid extractants have been commonly used. These methods appear to be less effective for tropical soils high in sesquioxides, where labile P consists mainly of Al-P and Fe-P (Dabin 1980). The Mehlich-3 method (CH_3COOH, NH_4NO_3, NH_4F, HNO_3, and EDTA at 1:10 soil:solution ratio) seems to extract more P than Mehlich-1 (0.05 N HCl + 0.025N H_2SO_4) and has a broader range of applicability (F.R. Cox, pers. comm.). Mehlich-1 has serious limitations for soils derived from mafic rocks and areas previously fertilized with natural rock phosphates (pers. observ.), and also for lowland soils (Grande, Curi, and Quaggio 1986). The Mehlich-3 method should be one of the options for evaluating P status on Oxisols in the tropics. Although more difficult to use for routine purposes, anionic resin methods (van Raij and Quaggio 1983) have given excellent results for these soils and should be further tested. Anionic resin methods are already incorporated into many routine soil analyses laboratories in São Paulo State, Brazil. According to Dabin (1980), anionic resin methods are slightly superior to those using isotopic techniques (E and L values).

Potassium Deficiency

According to Boyer (1972), Oxisols of the humid tropics are usually deficient in available K. In general, effective availability of K is decreased by high pH, strongly reducing soil conditions, and low soil moisture regimes (Kemmler 1980).

Soil testing and fertilizer trials are used in many countries to obtain knowledge toward overcoming potassium deficiency. Careful examination of crop response to soil test data is needed and has already been done in some ongoing long-term fertilizer experiments (Kemmler 1980). In many cases, K needs can no longer be adequately overcome by the soil supply.

Under tropical conditions, in order to evaluate the K status of soils, unbuffered 1N ammonium acetate is used in most cases. In some Latin American countries, for routine purposes, "available" K is extracted by Mehlich-1 (0.5 N HCl + 0.025N H_2SO_4) extractant solution. According to Kemmler (1980), the usual soil analysis does not satisfactorily describe that actual availability of K. Information on the exchangeable K (quantity factor) reveals nothing about the K concentration in the soil solution (intensity factor). The great advantage of the use of 1N ammonium acetate is that most of the other exchangeable cations can be extracted at the same time. To improve soil test interpretation for potassium, the soil analysis report should, at least, contain details on soil texture, inorganic CEC (as an indicator of clay composition), and pH, as well as soil permeability and soil-water regime.

The method of electro-ultrafiltration (Németh 1972, 1978, 1979), which measures the desorption rate and its change with time for K and many other nutrients, should receive more attention in order to evaluate the K status on tropical soils. From the results obtained by this method one can infer the K concentration in the soil solution, the quantity of exchangeable K, K fixation, buffering, and K reserves. According to Kemmler (1980), this method is the only one which provides a thorough insight into the K dynamics (and that of other nutrients) of soils.

Phosphorus Fixation

It is well established that Fe- and Al-oxyhydroxides have a vital influence on P adsorption-desorption by the soil material. Consequently, P adsorption tends to be high and solution concentration tends to be low in most acid tropical soils where these oxidic components are abundant. Dabin (1980) reports that the quantity factor (adsorbed P) must play a major role in plant nutrition and that the high temperature in tropical soils leads to a faster solution replacement, concomitantly with a faster decomposition for organic and inorganic reserves of low solubility. Because the P availability in soils is a function of the relationship between quantity and intensity, P-requirement estimates can be attained from adsorption isotherms.

Likewise, knowledge of the degree of reversibility of P adsorption by soil constituents is of great agronomic significance, because desorption is a limiting step for the uptake of P by crops (Cabrera et al. 1981). Under tropical conditions such knowledge is even more important, due to the extremely low values for available P (Curi 1983).

Not all measurements of fixation capacity are standardized. They depend upon the soil:solution ratio, time of contact, temperature, shaking velocity, and the method of evaluation of adsorption data. It seems that for Oxisols the criterion working

satisfactorily includes: (a) a soil:solution ratio of 1:20 rather than 1:10; (b) a period of 12 hours of contact by shaking, and (c) the adsorption data being evaluated assuming two types of sites by applying the Langmuir two-surface equation (S. Barber, pers. comm.; Gualberto 1984; Curi and Franzmeier 1984; Souza 1985; Curi et al. 1986; Curi and Camargo 1986).

If one thinks about determining P desorption, the samples previously used for P adsorption can be shaken for 12 hours with 0.01 M $CaCl_2$ (1:20), centrifuged, and the amount of P desorbed taken as that present in the solution after shaking. It appears that four desorption extractions could give a reasonable insight into the P release in relation to time.

Under the agronomic and practical point of view, an adequate estimate of P-adsorption capacity of Brazilian Oxisols samples has been obtained by using indicator parameters, usually found in soil survey reports, such as: percent Fe_2O_3 from sulfuric acid digestion (Lopes 1977; Lopes and Cox 1979; Curi et al. 1986), percent Al_2O_3 from H_2SO_4 digestion (Lopes 1977; Lopes and Cox 1979), SiO_2/R_2O_3 molecular ratio (Curi and Camargo 1986), and clay content (Camargo, van Raij, and Grohmann 1974; Lopes 1977; Lopes and Cox 1979; Curi and Camargo 1986). Revalidation of these findings for Oxisol samples throughout the tropics would be suggested as a priority for more insight into the evaluation of P status in these soils.

Calcium and Magnesium Deficiency and Low Cation Exchange Capacity

Particularly in Oxisol ecosystems, the low amounts of Ca and/or Mg, as well as other nutrients, and a low effective CEC are well known to be major fertility constraints which often account for the poor crop productivity on these soils. Evaluation of these parameters in subsurface layers should receive special attention. Recent findings on Oxisols in Brazil associated poor root development in depth with Al toxicity and also with low levels of exchangeable and soil solution Ca, down the profile (Ritchey, Silva, and Costa 1982; Ritchey, Silva, and Sousa 1983). Consequently, it is extremely important to quantify these parameters, especially in areas subject to short periods of water stress during the rainy season. Technology to increase rooting depth should receive top priority, in order to achieve agricultural development on these soils.

Although unbuffered ammonium acetate only provides information about the quantity factor (exchangeable form), its advantage, as previously mentioned, is that Ca, Mg, K, Na, and Al can be extracted simultaneously, and it appears feasible, especially in the case of less developed tropical areas. Ca, Mg, Na, and Al can also be extracted with unbuffered 1N KCl. An estimate of "exchangeable" K has been attained by determining soluble K in 0.05N HCl + 0.025N H_2SO_4, which is also used for P extraction.

To complete the picture in terms of cation exchange capacity evaluation in these soils, it is probably necessary to determine H + Al by using a buffered extractant solution at pH 7.0. Calcium acetate buffered at pH 7.0 is used routinely for pedology purposes in Brazil (EMBRAPA 1979).

As previously mentioned, for routine soil testing purposes H + Al can be estimated by measuring the equilibrium pH of a buffered SMP solution with the soil (van Raij, Cantarella, and Zullo 1979; Quaggio and van Raij 1982). The advantage in getting values for H + Al is that one can calculate the CEC at pH 7.0 by the summation of Ca + Mg + K + Na + (H + Al). This parameter, if compared with the effective CEC (summation of Ca + Mg + K + Na + Al), would definitely be important in estimating pH-dependent charges and would allow further and deeper knowledge of the behavior of these soils. For example, one can estimate base saturation (BS) at pH 7.0. This parameter is necessary to calculate rates of lime according to the new methodology used now in some states of Brazil (Quaggio 1983; Quaggio, van Raij, and Malavolta 1983), as previously discussed.

Sulfur Deficiency

Blair, Mamaril, and Ismunadji (1980) claim that Oxisols which occupy large areas of the tropics have low total S contents because of low S amounts in the parent materials, extreme weathering and leaching losses, or both.

In terms of soil testing for S status, the methods used to extract S from soil can be grouped in four categories: soluble sulfates, soluble and adsorbed sulfates, total and organic S, and microbiological methods. The second group normally is better correlated with S status than the first one. According to Blair, Mamaril and Ismunadji (1980), there is a need for correlation studies in tropical areas with specific crops, sulfur extractants, and methods. In general, adsorbed sulfate is removed by neutral or slightly alkaline extractants and by extractants containing a strong replacing ion, such as a phosphate.

Two extractant solutions are suggested by Blair, Mamaril, and Ismunadji (1980): (a) sodium bicarbonate at pH 8.5 used by Bardsley and Kilmer (1963), which is also a common extractant used to evaluate available P, and (b) calcium-phosphate, because the divalent Ca does not cause dispersion of clay and organic matter, which may occur when potassium or sodium is used. For laboratories with limited equipment, the barium sulfate turbidimetric method is the practical and commonly used procedure. The instability of the barium sulfate precipitate can be overcome by the use of stabilizers (Blair, Mamaril, and Ismunadji 1980).

Micronutrients

Zn, B, Cu, and Mo are the most common deficiencies in Oxisols in the tropics, whereas Fe deficiency and Mn toxicity are relatively localized (Lopes 1980). One of the major problems in assessing the micronutrients situation in tropical and subtropical crop production is the diversity in soil testing procedures, according to Sillanpää and Vlek (1985). They mention that as many as 15 different extraction techniques are presently in use. Within a continent, and even within a country, researchers often select soil test methods on the basis of analytical tools and/or personal preference, sometimes based on recommendations by specialists from abroad. These latter authors also mention that the lack of proper calibration of these soil tests within the region imposes difficulties in interpreting the data. Worldwide coordination appears to be needed in establishing unified methodologies for soil testing.

A worldwide sampling of Oxisols of diverse physiographical, climatic, and landscape characteristics and

evaluation of micronutrients (total and available) in the laboratory and greenhouse are desirable. The approach followed by Sillanpää (1982) is an excellent guide in this regard, however, since soil-testing laboratories in the tropics have not made wide use of acid extractants with chelates, such as the ammonium acetate with EDTA at pH 4.65 used by that author, inclusion of acid extractants is suggested (Lindsay and Cox 1985).

If one is required to recommend an extractant for available Fe, Mn, Zn, and Cu that should be applicable to routine laboratory analyses of acid soils of the tropics, as Oxisols, one would likely think about Mehlich-1 (0.05N HCl + 0.025N H_2SO_4), with inclusion of other soil properties as appropriate (Lindsay and Cox 1985). This does not eliminate the need for inclusion of extractants as chelates and others for research purposes and refinement of the studies involving micronutrients. In this sense the Mehlich-3 method, which employs CH_3COOH, NH_4NO_3, NH_4F, HNO_3, and EDTA at 1:10 soil:solution ratio, has a stronger extracting capability and a broader range of applicability than Mehlich-1 and should be tested further in terms of Oxisols (F.R. Cox, pers. comm.).

Available B is usually determined by hot water extractant (Dible, Troug, and Berger 1954); however, 0.05N HCl has shown some promise (Lindsay and Cox 1985), and some studies should be conducted by using the Mehlich-3 method too. The traditional method for determination of Mo is still the ammonium oxalate pH 3.3 (Grigg 1953; Lindsay and Cox 1985). Research data to support this method for Oxisols are scarce.

In terms of research data, because modern methods of soil analysis for micronutrients are available now as ICP (inductively coupled plasma-atomic emission spectrometry), total trace element determinations could be performed by this technique, using solutions generated by mixed-acid digestion (Lechler, Roy, and Leininger 1980). Utilizing this method, some data concerning Oxisols are already available (Curi 1983).

It should be stressed at this point that estimates of available micronutrients in relation to soil properties that affect their content, with detailed soil description and characterization and climatic condition, can be an adequate approach to extrapolation of scientific knowledge in this field (Lopes 1980). In this sense, adequate characterization of micronutrient status of stored samples collected for soil survey purposes can be a valuable diagnostic tool.

Other Parameters

Organic matter percentage, pH in H_2O, and particle-size analysis are some other parameters that must complete the list in terms of reference bases for fertility evaluation of Oxisols. One should not forget, however, that parameters for adequate evaluation of acidity and fertility of Oxisols are only part of the complete picture for management of these soils. Climatic, physical, biological, and agronomic aspects should not be forgotten when one aims at suitable management of Oxisols in terms of agricultural production.

References

Alcarde, J.C. 1983. Desaproveitamento de fertilizantes pela agicultura brasileira. *Caderno Agrícola*, Ano II, no. 4.

Bardsley, C.D., and V.J. Kilmer. 1963. Sulphur supply of soils and crop yields in the southeastern United States. *Soil Sci. Soc. Amer. Proc.* 27:197-199.

Blair, G.J., C.P. Mamaril, and M. Ismunadji. 1980. Sulfur deficiency in soils in the tropics as a constraint to food production. *In* Priorities for alleviating soil-related constraints to food production in the tropics. IRRI and Cornell Univ. Ithaca, NY. Pp. 233-251.

Boyer, J. 1972. Soil potassium. *In* National Academy of Sciences. Soils of the humid tropics. Washington, D.C. Pp. 102-135.

Bremner, J.M. 1965. Nitrogen availability indexes. *In* C.A. Black, D.D. Evans, L.E. Ensminger, J.L. White, and F.E. Clark (eds.). Methods of soil analysis, part 2. *Agronomy* 9:1324-1345.

Cabrera, F., P. de Arambarri, L. Madrid, and C.G. Toca. 1981. Desorption of phosphate from iron oxides in relation to equilibrium pH and porosity. *Geoderma* 26:203-216.

Camargo, O.A. de, and B. van Raij. 1975. Relações entre o alumínio trocável, bases trocáveis e pH dos solos. Anais do XV Congresso Brasileiro de Ciência do Solo, Campinas. Pp. 95-101.

Camargo, O.A. de, B. van Raij, and F. Grohmann. 1974. Fixação de fósforo em solos avaliada pelo índice de Bache e Williams e sua correlação com outras propriedades. *Cienc. Cult.* 28:681-685.

Castro, A.F., W.O. Barreto, and M.L.A. Anastácio. 1972. Correlação entre o pH e saturação de bases de alguns solos brasileiros. *Pesq. Agropec. Bras.* 7:9-17.

Catani, R.A., and J.R. Gallo. 1955. Avaliação da exigência de calcário dos solos do Estado de São Paulo, mediante correlação entre o pH e a porcentagem de saturação de bases. *Rev. Agric.* 30:49-60.

CEFSG-Comissão Estadual de Fertilidade do Solo - Goiás. Recomendações de fertilizantes para Goiás - 4a aproximação.

CFSEMG-Comissão de Fertilidade do Solo do Estado de Minas Gerais. 1978. Recomendações para o uso de corretivos e fertilizantes em Minas Gerais - 3a aproximação. EPAMIG, Belo Horizonte.

Cochrane, T.T., J.G. Salinas, and P.A. Sanchez. 1980. An equation for liming acid mineral soils to compensate crop aluminum tolerance. *Trop. Agric.* 57:133-140.

Coleman, N.T., E.J. Kamprath, and S.B. Weed. 1959. Liming. *Adv. in Agron.* 10:475-522.

Coleman, N.T., and G.W. Thomas. 1967. The basic chemistry of soil acidity. *In* R.W. Pearson and F. Adams (eds.). Soil acidity and liming. *Agronomy* 12:1-41.

Combeau, A., C. Ollat, and P. Quantin. 1961. Observações sobre certas características dos solos ferralíticos - Relações entre os resultados da análise dos solos e os rendimentos. *Fertilité* 13:27-40.

Comissão de Solos. 1960. Levantamento de reconhecimento dos solos do Estado de São Paulo. Centro Nacional de Ensino e Pesquisas Agronômicas. Boletim no. 12. Rio de Janeiro, Brazil.

Coulter, B.S. 1969. The chemistry of hydrogen and aluminum ions in soils, clay minerals, and resins. *Soil Fertil.* 32:215-223.

Curi, N. 1983. Lithosequence and toposequence of Oxisols from Goiás and Minas Gerais states, Brazil. Ph.D. thesis. Purdue Univ., Lafayette, Ind.

Curi, N., and O.A. de Camargo. 1986. Phosphorus adsorption characteristics of Brazilian Oxisols. *In* Proc. VIIIth Int. Soil Class. Work. SMSS/ EMBRAPA/UPR, Brazil.

Curi, N., O.A. de Camargo, G.A.A. Guedes, and J.V. Silveira. 1986. Sorção de fósforo em materiais de Latossolos do Brasil Sudeste e Sul. Anais da III Reunião de Classificação, Correlação de Solos e Interpretação da Aptidão Agrícola. September 1984. EMBRAPA/SNLCS, Rio de Janeiro, Brazil.

Curi, N., and D.P. Franzmeier. 1984. Toposequence of Oxisols from the Central Plateau of Brazil. *Soil Sci. Soc. Amer. J.* 48:341-346.

Dabin, B. 1980. Phosphorus deficiency in tropical soils as a constraint on agricultural output. *In* Priorities for alleviating soil-related constraints to food production in the tropics. IRRI and Cornell Univ., Ithaca, NY. Pp. 217-232.

Daikuhara, G. 1914. About acid mineral soils. *Bull. Imp. Agr. Exp. Stat.* Japan, 2:1-40.

Dible, W.T., E. Truog, and K.C. Berger. 1954. Boron determination in soils and plants. *Anal. Chem.* 26:418-421.

EMBRAPA. Serviço Nacional de Levantamento e Conservação de Solos. 1979. Manual de métodos de análise de solo. Ministério da Agricultura, Rio de Janeiro, Brazil.

EMBRATER. 1979. Manual Técnico. Abertura e Manejo de Cerrados. MG, MT, GO e DF.

Fox, R.H., and W.P. Piekielek. 1978. A rapid method for estimating the nitrogen-supplying capacity of a soil. *Soil Sci. Soc. Amer. J.* 42:751-753.

Grande, M.A., N. Curi, and J.A. Quaggio. 1986. Disponibilidade de fósforo pelos extratores de Mehlich e resina, em solos cultivados com arroz irrigado. *R. Bras. Ci. Solo* 10:45-50.

Grigg, J.L. 1953. Determination of the available molybdenum of soils. *J. Sci. Tech.* 34:405-414.

Gualberto, V. 1984. Caracterização física, química e mineralógica de alguns latossolos, com altos teores de ferro, da Amazônia e do Planalto Central. M.S. thesis. Univ. Federal de Viçosa.

Kamprath, E.J. 1967. Soil acidity and response to liming. Tech. Bull. no. 4, Intern. Soil Testing Series, NCSU Agric. Exp. Stat.

———. 1970. Exchangeable aluminum as a criterion for liming leached mineral soils. *Soil Sci. Soc. Amer. Proc.* 24:252-254.

Keeney, D.R. 1982. Nitrogen-availability indices. *In* A.L. Page, R.H. Miller, and D.R. Keeney (eds.). Methods of soil analysis, part 2. *Agron.* 9:711-733.

Kemmler, G. 1980. Potassium deficiency in soils of the tropics as a constraint to food production. *In* Priorities for alleviating soil-related constraints to food production in the tropics. IRRI and Cornell Univ., Ithaca, NY. Pp. 253-275.

Kinjo, T. 1983. Conceitos de acidez de solos. *In* B. van Raij et al. (coord.). Simpósio sobre Acidez e Calagem no Brasil. Soc. Bras. de Ciêncai do Solo, Campinas, SP, 1982. Pp. 23-31.

Lathwell, D.J., H.D. Dubey, and R.H. Fox. 1972. Nitrogen supplying power of some tropical soils of Puerto Rico and methods for its evaluation. *Agron. J.* 64:763-766.

Lechler, P.J., W.R. Roy, and R.K. Leininger. 1980. Major and trace element analysis of 12 reference soils by inductively coupled plasma-atomic emission spectrometry. *Soil Sci.* 130:238-241.

Lindsay, W.L., and F.R. Cox. 1985. Micronutrients soil testing for the tropics. *In* P.L.G. Vlek (ed.). Micronutrients in tropical food crop production. Developments in plant and soil sciences, vol. 14, Boston, MA. Pp. 169-200.

Lopes, A.S. 1977. Available water, phosphorus fixation, and zinc levels in Brazilian cerrado soils in relation to their physical, chemical, and mineralogical properties. Ph.D. thesis. North Carolina State Univ., Raleigh, NC.

———. 1980. Micronutrients in soils of the tropics as constraints to food production. *In* Priorities for alleviating soil-related constraints to food production in the tropics. IRRI and Cornell Univ., Ithaca, NY. Pp. 277-298.

———. 1984. Solos sob "cerrado": características, propriedades e manejo. Associação Brasileira para Pesquisa da Potassa e Fosfato, 2a ed., Piracicaba.

Lopes, A.S., and F.R. Cox. 1979. Relação de características físicas, químicas e mineralógicas com fixação de fósforo em solos sob cerrado. *R. Bras. Ci. Solo* 3:82-88.

Mielniczuk, J. 1983. Economicidade da calagem. *In* B. van Raij et al. (coord.). Simpósio sobre Acidez e Calagem. Soc. Bras. Ciência do Solo, Campinas, SP, 1982. Pp. 63-77.

Miranda, L.N. de, J. Mielniczuk, and E. Lobato. 1980. Calagem e adubação corretiva. *In* D. Marchetti and A.D. Machado (coord.). V Simpósio sobre o cerrado, Brasília, DF, 1979. Pp. 523-578.

Mohr, W. 1960. A influência da acidez sobre a fertilidade dos solos. Anais do I Congresso Nacional de Conservação do Solo, Campinas, SP. Pp. 61-76.

Németh, K. 1972. The determination of desorption and solubility rates of nutrients in the soil by means of electro-ultrafiltration (EUF). *In* Intern. Potash Inst. Potassium in soil. Berne, Switzerland. Pp. 171-180.

———. 1978. Limitations of present soil test interpretation for K and suggestions for modification. A. European experience. *In* Potash Res. Inst. of India. Proc. symposium on potassium in soils and crops, New Delhi, India. Pp. 95-111.

———. 1979. The availability of nutrients in the soil as determined by electro-ultrafiltration (EUF). *Adv. in Agron.* 31:155-188.

Quaggio, J.A. 1983. Critérios para calagem em solos do Estado de São Paulo. M.S. thesis. Escola Superior de Agricultura "Luiz de Queiróz."

———. 1985. Respostas das culturas à calagem. *In* E. Malavolta (coord.). Seminário sobre corretivos agrícolas. Fundação Cargill, Campinas. Pp. 121-157.

Quaggio, J.A., and B. van Raij. 1982. Alternativas de uso do tampão SMP para determinar a necessidade de calagem em solos. Instituto Agronômico, Campinas.

Quaggio, J.A., B. van Raij, and E. Malavolta. 1983. Alternativas de uso da solução tampão SMP para determinar a necessidade de calagem em solos (Abstract). XIX Congresso Brasileiro de Ciência do Solo, Curitiba.

Reeve, N.G., and M.E. Sumner. 1970. Lime requirement of Natal Oxisols based on exchangeable aluminum. *Soil Sci. Soc. Amer. Proc.* 34:595-598.

Ritchey, K.D., J.E. Silva, and U.F. Costa. 1982. Calcium deficiency in clayey B horizons of savannah Oxisols. *Soil Sci.* 133:378-382.

Ritchey, K.D., J.E. Silva, and D.M.G. Sousa. 1983. Relação entre o teor de cálcio no solo e desenvolvimento de raízes avaliado por um método biológico. *R. Bras. Ci. Solo* 7:269-275.

Sanchez, P.A. 1976. Properties and management of soils in the tropics. John Wiley & Sons, NY.

Scarsbrook, C.E. 1965. Nitrogen availability. *In* W.V. Bartholomew and F.E. Clark (eds.). Soil nitrogen. *Agronomy* 10:481-502.

Shoemaker, H.E., E.O. McLean, and P.F. Pratt. 1961. Buffer methods for determining lime requirement of soils with appreciable amounts of extractable aluminum. *Soil Sci. Soc. Amer. Proc.* 25:274-277.

Sillanpää, M. 1982. Micronutrients and the nutrient status of soils: A global study. FAO Soils Bull. 48. Food and Agric. Organization of the United Nations, Rome.

Sillanpää, M., and P.L.G. Vlek. 1985. Micronutrients and the agroecology of tropical and mediteranean regions. *In* P.L.G. Vlek (ed.). Micronutrients in tropical food crop production. Developments in plant and soil sciences, vol. 14. Boston, MA. Pp. 151-167.

Soil Survey Staff, SCS, USDA. 1975. Soil taxonomy: A basic system of soil classification for making and interpreting soil surveys. USDA Agric. Handb. no. 436. U.S. Govt. Printing Office, Washington, D.C.

Sousa, J.A. 1985. Relações entre formas de ferro e sorção de fósforo em Latossolos sob cerrado do Planalto Central. M.S. thesis. Escola Superior de Agricultura de Lavras.

Thomas, G.W. 1982. Exchangeable cations. *In* Page et al. (eds.). Methods of soil analysis, part 2. *Agronomy* 9:159-165.

Ultrafertil. 1978. Guia de adubação Ultrafertil. van Raij, B. 1981. Avaliação da fertilidade do solo. Instituto da Potassa & Fosfato, Instituto International da Potassa, Piracicaba.

van Raij, B., H. Cantarella, and M.A.T. Zullo. 1979. O método tampão SMP para determinação da calagem de solos do Estado de São Paulo. *Bragantia* 38:57-69.

van Raij, B. and J.A. Quaggio. 1983. Méthodos de análise de solo para fins de fertilidade. Boletim Técnico no. 81, Campinas.

———. 1984. Uso eficiente de calcário e gesso na agricultura. *In* W. Espinoza and J.A. Jorge (eds.). Anais do simpósio sobre fetilizantes na agricultura Brasileira. EMBRAPA-DEP, Documentos 14, Brasília, DF, Brazil. Pp. 323-346.

van Raij, B., M.T.D. Saccheto, and T. Igue. 1968. Correlações entre o pH e o grau de saturação de bases nos solos com horizonte B textural e horizonte B latossólico. *Bragantia* 27:193-200.

Vettori, L. 1969. Métodos de análise de solos. Equipe de pedologia e fertilidade do solo. Boletim Técnico no. 7. Ministério da Agricultura, Rio de Janeiro, Brazil.

CRITICAL EVALUATION OF DIFFERENT PHOSPHORUS EXTRACTIONS ON OXISOLS[1]

B. van Raij[2]

Abstract

Phosphorus in Oxisols follows the general behavior of the element in other soils. Concentrations in soil solution are low, due to the low solubility products of phosphorus compounds existing in soils and to the strong adsorption power of soil particles for phosphates. Extraction of phosphorus is done with a variety of solutions which rely on the solvent action of acids, on anion replacement, and on complexing or hydrolysis of cations binding P. The solutions used are in general specific for some combined forms of phosphorus and might extract phosphates from soils which are not plant available. Anion exchange resin extraction has also been evaluated, and results obtained, as shown in the literature, are in general better related to P uptake by plants than the results given by other methods. The advantages of the ion-exchange resin extraction for soil phosphorus are discussed. In the state of São Paulo, Brazil, an ion exchange procedure to determine soil phosphorus has been used in routine soil testing since 1983. Results are shown that confirm the superiority of the method over the one used formerly, based on acid extraction of soil P. For the surface samples of the 22 key pedons selected for the field trip, more results obtained by the resin method were in higher classes of interpretation of soil P, as compared with results obtained by Mehlich's method.

A diversity of extracting procedures are used for phosphorus throughout the world, which is by itself a demonstration that there are no widely accepted procedures to determine this nutrient in soils. Reviews on the subject were made by Nelson, Mehlich, and Winters (1953), Bingham (1962), Thomas and Peaslee (1973), van Raij (1978) and Kamprath and Watson (1980). Most methods rely on the solvent action of acids, anion replacement by ions as acetate, citrate, lactate, sulfate, and bicarbonate, complexing of cations binding P, especially by fluoride, and hydrolysis of cations binding P using $NaHCO_3$ solution buffered at pH 8.5 (Kamprath and Watson 1980).

[1] Contribution from the Section of Soil Fertility and Plant Nutrition, Instituto Agronômico, Caixa Postal 28, 13100 Campinas-SP, Brazil.

[2] Soil Scientist and Chief of Section. Research fellow of the Brazilian National Organization of Scientific and Technological Development.

Phosphorus in Oxisols

For Oxisols, the principles of phosphorus extraction valid for other soils can also be applied. Specific aspects might, however, exist and demand improved approaches to phosphorus extraction.

In soils, phosphorus is found combined in inorganic compounds with iron, aluminum, and calcium and in organic matter. In Oxisols, soils that are in general acid, the P-Fe and P-Al are predominant among the inorganic forms (Bahia Filho and Braga 1975).

The availability of organic phosphorus is dependent on mineralization processes, which cannot be predicted by soil testing. Thus, the extraction of soil P to assess availability usually deals with phosphorus in inorganic forms.

The solubility products of most inorganic compounds of phosphorus found in soils are usually very low. Furthermore, the oxidic surfaces of the clay particles of Oxisols adsorb strongly phosphate ions from solution. Consequently, phosphorus concentrations in soil solution are low, of the order of less than one tenth of a milligram P per liter. Since plants obtain phosphorus from the soil solution, the amounts existing in solution at any time are not sufficient to provide adequate plant nutrition. To assure this, part of the phosphate existing in the solid phases moves into solution. An overall simplified equilibrium of soil P can be written as

$$P_{fertilizer} \xrightarrow{\text{fast}} P_{solution} \xrightarrow{\text{slow}} P_{labile} \longrightarrow P_{nonlabile}$$

Extracting procedures for soil phosphorus in general try to determine some values that are related to the so-called "available phosphate." In Oxisols, as in other soils under cultivation, fertilizers of different types are added. This introduces another difficulty for soil testing, if residues of fertilizers are not completely soluble or plant available.

Often water-soluble phosphate added to soil, especially in laboratory tests, which becomes adsorbed on the solid particles, is called "fixed" phosphorus. This is a misleading term, since

part of the P applied can be converted to soil solution P, and can be recovered by crops even years after application (Yost et al. 1981; Couto, Leite, and Kornelius 1985). The term *labile P* is often used to refer to phosphorus existing in the solid phase that can transfer to the soil solution. Labile phosphate was initially used to qualify isotopically exchangeable P (McAuliffe et al. 1948; Larsen 1952), but is now used in a broader sense (Larsen 1967, 1974). It is an important fact that the transformation of labile forms of soil phosphates in nonlabile forms is a slow process (Barrow 1980).

"Available phosphorus" and "labile phosphorus" are concepts invented to make the understanding of plant uptake from soils easier. However, the determination of analytical values to give practical meaning to these concepts has proven to be very difficult, maybe even more so in Oxisols than in other soils.

Conventional Extractants of Soil Phosphorus

In most regions of the world, including tropical countries, different solutions are used to extract soil P, including 0.5 N $NaHCO_3$ at pH 8.5 (Olsen 1953), 0.025N HCl + 0.030N NH_4F (Bray and Kurtz 1945), 0.025N H_2SO_4 + 0.050N HCl (Nelson, Mehlich, and Winters 1953), and many others. Extensive reviews about methods for determining soil P were published among others by Nelson, Mehlich, and Winters (1953), Bingham (1962), Thomas and Peaslee (1973), van Raij (1978) and Kamprath and Watson (1980).

In Brazil actually two methods are recommended. The so-called Mehlich extractant, 0.025N H_2SO_4 + 0.050N HCl (Nelson, Mehlich, and Winters 1953) is recommended in all states except São Paulo. In this state an ion-exchange resin procedure was introduced in 1983 (van Raij and Quaggio 1983; van Raij, Quaggio, and da Silva 1986), replacing the extraction with 0.05N H_2SO_4 (Catani and Gargantini 1954), a method that produced results essentially equal to the results of Mehlich's method.

The acid extracts in use in Brazil, either 0.025N H_2SO_4 + 0.050N HCl or 0.050N H_2SO_4, have the advantage of very clear extracts. However, being acid, they do not seem to be the best choice for Oxisols, soils that present the available forms of phosphorus mainly in the Fe-P and Al-P forms, which become more soluble at higher pH values.

The low efficiency of conventional extractants for P has long been known for tropical soils. Jenkins (1966) mentioned that a common feature of many of the soils of Central and East Africa was that even when phosphorus was known to be adequate for plant growth, very little was recovered by commonly used methods of extraction. The same happens for Oxisols from Brazil when acid extractants are used, as will be shown latter.

There are so many papers published about extractants of soil P and dealing with many different subjects that comparisons are not easily made. Van Raij (1978) tried a comparison listing the results from 42 papers of the international literature, in which P uptake by plants in pot tests was correlated with P determined in soils by different methods. Considering the values of percent variation (r^2) to rate the methods, the result of the comparison is given in Table 1.

Not all methods were tested in all cases. Even so, the superiority of the anion exchange resin method seems obvious, with 63 percent of the cases rated in first place and 21 percent in second place. The Olsen method, which is the method most widely used throughout the world, was first in 39 percent of the cases and second in 22 percent. In 13 cases the resin method and Olsen's methods were compared, and in only one case was Olsen's method slightly superior. The other methods are inferior to the two methods discussed to evaluate the availability of soil P.

Table 1. Comparison of Extractants for Soil P, Rated by the Percent Variation (r^2) Associated with the Correlation between Values of Soil P and P Uptake by Plants in Pot Tests

Method	Number of cases in which it was tested	Number of cases in which it rated	
		1st	2nd
Olsen	36	14	8
Bray 1	31	5	7
Resin	19	12	4
Bray 2	15	1	5
Water	15	3	3
Morgan	14	1	3
Mehlich	13	3	2
Truog	10	2	3
0.01 M $CaCl_2$	12	1	3
E value	13	2	2
Egrier	9	2	1
L value	8	2	4

Source: Review by van Raij (1978).

Although this information is not specific for Oxisols, several of the reviewed papers deal with soils of tropical regions.

A similar comparison was made by Anghinoni and Wolkweiss (1984) for research conducted in Brazil. Mehlich's method was tested in 11 cases but was the best in only 1 case; Olsen's method was tested in 7 cases and first in 4; the method Bray 1 was tested in 6 cases and best in 2; the resin method was the best in all 4 cases in which it was tested.

The superiority of the resin method for soil P seems so striking that special attention shall be given to it. This is done also because an important development in soil testing, involving the use of ion exchange resin to determine phosphorus, is under way in a region in which the predominant soils are Oxisols. Roche et al. (1980) also recommend a resin method to determine soil P in tropical regions.

Phosphorus Extraction with Ion-Exchange Resin

In one of the first papers published on the use of anion exchange resin for the extraction of soil P, Amer et al. (1955) suggested that the extraction with anion exchange resin is more analogous to P withdrawal by plant roots than the process of isotopic exchange. This is so because the anion exchange resin provides a sink for soil P, without exerting destructive influence on soil, as is the case of several chemical extractants.

The anion exchange resin to determine soil phosphorus was introduced in routine soil testing in Rhodesia (Saunder and Meterlerkamp 1962) and in England (Cooke and Hislop 1963) but is not used in these places anymore. The reasons for stopping the use of the resin method are not known, but the difficulties of its use in routine laboratories might have been of influence. Probably the major difficulty was the need to grind the soil samples prior to extraction, in order to allow the separation of the resin from soil by sieving. This problem was overcome by van Raij, Quaggio, and da Silva (1986), who used the prior disaggregation of the soils by shaking with water and a glass marble before adding the resin.

In former work, the anion exchange resin was saturated with chloride ions and results varied with the ratio of resin to soil, which affected the pH of the suspension and, consequently, the amounts of phosphorus extracted. Sibbesen (1978) has shown that bicarbonate saturated resin gave results that were much less affected by varying the ratio of resin to soil, because the buffering action of bicarbonate ions allowed for more stable pH values of the soil-resin suspensions. In other work, Vaidyanathan and Talibudeen (1970) have shown that the addition to the anion exchange resin of a cation exchange resin saturated with a monovalent cation increased the extraction of phosphorus.

The method proposed by van Raij and Quaggio (1983) and van Raij, Quaggio, and da Silva (1986) uses a mixture of cation and anion exchange resins, saturated with sodium bicarbonate, thus taking advantage of the favorable effects of bicarbonate ions and the mixture with cation exchange resin on the extraction of soil P. Furthermore, in the same extracts for phosphorus, the exchangeable amounts of potassium, calcium, and magnesium are also determined.

The method was compared with the extraction of P with 0.05N H_2SO_4, for soil samples of 28 field experiments of cotton. In Figure 1 the correlation between 0.05N H_2SO_4 and relative yields of cotton shows one of the negative features of this type of extractant for the soils studied, which were mostly Oxisols. In the example it is almost impossible to predict the degree of response to applied phosphorus if values of soil P are around 5 mg dm^{-3}.

The extraction with the ion-exchange resin procedure was much more effective to predict responses to applied phosphorus. In Figure 2 it can be seen that, in some cases, the values of extractable P were about 10 times higher as compared with the acid extractant. Furthermore, the relationship between soil P and relative yields was closer, with a higher correlation coefficient.

Results for the Oxisols of the Field Trip

The samples of the surface subhorizon of the 22 soils have been analyzed by the two procedures actually in use in this country. The extraction by the Mehlich extractant is described by EMBRAPA (1979) while the extraction by the resin procedure is described by van Raij and Quaggio (1983) and van Raij, Quaggio, and da Silva (1986).

The results, given in Table 3, were classified in the scale of interpretation given in Table 2. The scale of interpretation in both cases was obtained by calibration curves relating soil P values and relative yields for field experiments. The partition in classes was done by defined limits of relative yields, as given in Table 2 and explained elsewhere (van Raij 1981). The limits for the resin method are presently used in the state of São Paulo for fertilizer recommendations (van Raij, da Silva, and Bataglia 1985). For Mehlich's method, the scale of interpretation of the method based on the extraction with 0.05N H_2SO_4 was used (van Raij 1981), considering that both methods give comparable results.

The use of the two methods for the determination of soil P has important practical consequences. By the use of Mehlich's extractant, 16 soil samples were rated as having very low P content, 4 as having low contents and 1 as having medium content. With the resin method the distribution was of 8 as very low, 9 as low, 3 as medium, 1 as high and 1 as very high. The consequences for practical use of soil testing are obvious. Much more phosphorus should be recommended by Mehlich's method.

In some cases, the differences are very high. For example, in the case of soil 4, Mehlich's method produces a value of 3 mg dm^{-3}, rated as very low, while by the resin method the value is 17 mg dm^{-3}, rated as medium. For soil number 7, the comparison is of 14, a medium value, with 213, a very high value.

These cases certainly require a reflection about soil testing for phosphorus, both from the practical and scientific points of view. The resin method in advisory soil testing is now a reality. Only in the laboratory of Instituto Agronômico, almost 50,000 samples have been analyzed. Furthermore, about 20 other soil-testing laboratories of the state of São Paulo have adopted the method, including the major colleges of agriculture, which is a demonstration of the wide acceptance of the resin method.

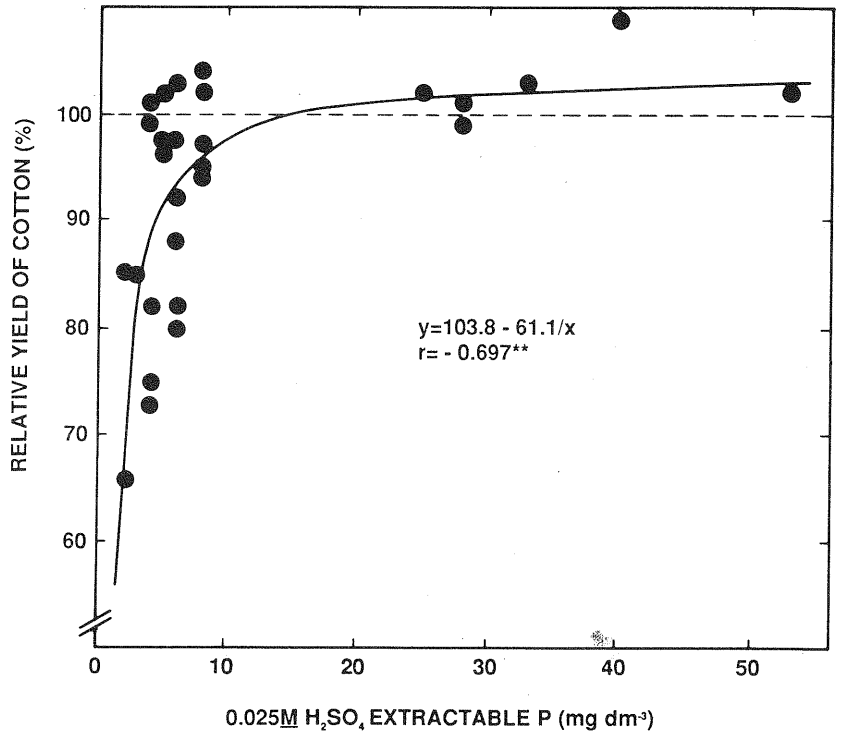


Fig. 1. Relation between values of 0.05N H_2SO_4 extractable P and response of cotton to applied phosphorus in 28 field experiments (from van Raij, Quaggio, and da Silva 1986).

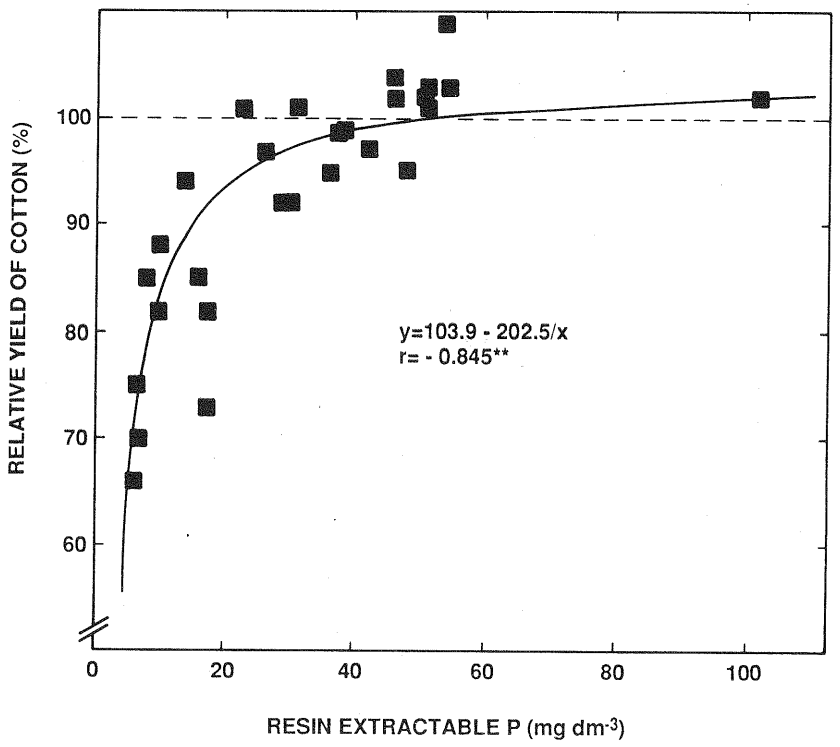


Fig. 2. Relation between values of resin extractable P and response of cotton to applied phosphorus in 28 field experiments (from van Raij, Quaggio, and da Silva 1986).

Table 2. Limits of Classes of Soil Contents

Phosphorus content	Average relative yields	Limits of soil P	
		Mehlich	Resin
	(%)	----------(mg dm^{-3})----------	
Very low (vl)	0-70	0-3	0-6
Low (l)	71-90	4-7	7-15
Medium (m)	91-100	8-15	16-40
High (h)	100	16-30	41-80
Very high (vh)	100	> 30	> 80

Table 3. Results of Phosphorus as Determined by Extraction with 0.050N HCl + 0.025N H_2SO_4 and with Ion-Exchange Resin, and Classification of the P Contents

Profile number	Horizon	Depth (cm)	Extractable phosphorus	
			0.050N HCl + 0.025N H_2SO_4[a]	Resin
			(mg dm^{-3})	(mg dm^{-3})
2	Avp	0-23	2 vl	5 vl
3	Avl.	0-10	4 l	9 l
4	A e l	0-4	3 vl	17 m
5	A e P	0-13	< 0.5vl	7 l
6	A E P	0-18	4 l	10 l
7	Apl	0-11	14 m	213 vh
8	Avl	0-16	4 l	23 m
9	Aep	0-18	20 h	67 h
10	Avl	0-15	1 vl	4 vl
11	A e pl	0-12	1 vl	4 vl
12	A e l	0-10	1 vl	8 l
13	A e	0-10	1 vl	8 l
14	A e p	0-12	2 vl	6 vl
15	Avp	0-25	4 l	22 m
16	A e p	0-13	2 vl	7 l
17	Ac	0-9	1 vl	6 vl
18	Avp	0-23	1 vl	5 vl
19	A e pl	0-15	1 vl	5 vl
20	Avpcl	0-20	1 vl	7 l
21	A e	0-10	1 vl	6 vl
22	A e p	0-10	3 vl	8 l
23	Avpl	0-18	2 vl	9 l

[a] Determined by SNLCS.
Note: vl=very low; l=low; m=medium; h=high; vh=very high.

References

Amer, F., D.R. Bouldin, C.A. Black, and F.R. Duke. 1955. Characterization of soil phosphorus by anion exchange resin adsorption and 32 P-equilibration. *Plant and Soil* 6:391-408.

Anghinoni, I., and S.J. Wolkweiss. 1984. Recomendação de uso de fertilizantes no Brasil. *In* W. Espinoza and A.J. de Oliveira (eds.). Anais do Simposio sobre fertilizantes na agricultura brasileira. Brasília, EMBRAPA-DEP. Pp. 179-204.

Bahia Filho, A.F.C., and J.M. Braga. 1975. Fósforo em latossolos do Estado de Minas Gerais: II - Quantidade de fósforo e fósforo "disponível". *Rev. Ceres* 22:50-61.

Barrow, N.J. 1980. Evaluation and utilization of residual phosphorus in soils. *In* F.E. Khasawneh, E.C. Sample, and E.J. Kamprath (eds.). The role of phosphorus in agriculture. Amer. Soc. Agron., Madison, WI. Pp. 333-359.

Bingham, F.T. 1962. Chemical soil tests for available phosphorus. *Soil Sci.* 94:87-95.

Bray, R.H., and L.T. Kurtz. 1945. Determination of total, organic available forms of phosphorus in soils. *Soil Sci.* 59:39-45.

Cabala, F.P., and M.B.M. Santana. 1972. Comparação de extratores químicos de fósforo em solos do sul da Bahia. *Turrialba* 22:19-26.

Catani, R.A., and H. Gargantini. 1954. Extração de fósforo do solo pelo método Neubauer e por métodos químicos. *Bragantia* 13:55-62.

Cooke, I.J., and J. Hislop. 1963. Use of anion exchange resin for the assessment of available soil phosphate. *Soil Sci.* 96:308-311.

Couto, W., G.G. Leite, and E. Kornelius. 1985. The residual effect of P and lime on the performance of four tropical grasses in a high P-fixing oxisol. *Agron. J.* 77:539-542.

EMBRAPA. 1979. Manual de análise de solo. SNLCS. Rio de Janeiro, Brazil.

Jenkins, W.L. 1966. The relationship between "labile soil phosphorus" and the aluminum and iron-bound phosphorus in tropical soils. *Plant and Soil* 24:407-422.

Kamprath, E.J., and M.E. Watson. 1980. Conventional soil and tissue tests for assessing the phosphorus status of soils. *In* F.E. Khasawneh, E.C. Sample, and E.J. Kamprath (eds.) The role of phosphorus in agriculture. Am. Soc. Agron., Madison, WI. Pp. 433-469.

Larsen, S. 1952. The use of P32 in studies on the uptake of phosphorus by plants. *Plant and Soil* 4:1-10.

——— 1967. Soil phosphorus. *Adv. Agron.* 19:151-210.

——— 1974. Phosphorus: A limiting factor in future food production. *Neth. J. Agric. Sci.* 22:270-274.

McAuliffe, C.D., N.S. Hall, L.A. Dean, and S.B. Hendrichs. 1948. Exchange reactions between phosphates and soils. Hydroxylic surfaces of soil minerals. *Soil Sci. Soc. Amer. Proc.* 12:115-123.

Nelson, W.L., A. Mehlich, and E. Winters. 1953. The development, evaluation and use of soil tests for phosphorus availability. *In* W.E. Pierre and A.G. Norman (eds.). Soil and fertilizer phosphorus in crop nutrition. Agronomy 4. Academic Press, New York. Pp. 153-158.

Olsen, S.R. 1953. Inorganic phosphorus in alkaline and calcareous soils. *In* W.E. Pierre and A.G. Norman (eds.). Soil and fertilizer phosphorus in crop nutrition. Agronomy 4. Academic Press, New York. Pp. 89-122.

Roche, P., L, Grière, D. Babie, H. Colba, and P. Fallavier. 1980. Phosphorus in tropical soils: Assessing deficiency levels and phosphorus requirements. Scientific Publication No. 2. IMPHOS, World Phosphate Inst., Paris. 48 p.

Saunder, D.H., and H.R. Meterlerkamp. 1962. Use of an anion-exchange resin for determination of available soil phosphorus. International Soil Conference, New Zealand. Paper C 19.

Sibbesen, E. 1978. An investigation of the anion-exchange resin method for soil phosphate extraction. *Plant and Soil* 50:305-321.

Thomas, G.W., and D.E. Peaslee. 1973. Testing soil for phosphorus. *In* L.M. Walsh and J.D. Beaton (eds.). Soil testing and plant analysis. Soil Sci. Soc. Amer., Madison, WI. Pp. 115-132.

Vaidyanathan, L.V., and O. Talibudeen. 1970. Rate processes in the desorption of phosphate from soils by ion exchange resins. *J. Soil Sci.* 21:173-183.

van Raij, B. 1978. Seleção de métodos de laboratório para avaliar a disponibilidade de fósforo em solos. *R. bras. Ci. Solo* 2:1-9.

——— 1981. Avaliação da fertilidade do solo. Piracicaba. Instituto da Potassa & Fosfato, Instituto Internaciaonal da Potassa. 142 p.

van Raij, B. and A. van Diest. 1980. Phosphate supplying power of rock phosphates in an oxisol. *Plant and Soil* 55:97-104.

van Raij, B., C.T. Feitosa, and N.M. da Silva. 1984. Comparação de quatro extratores de fósforo de solos. *Bragantia* 43:17-29.

van Raij, B. and J.A. Quaggio. 1983. Métodos de análise de solo para fins de fertilidade. Boletim Técnico 81. Instituto Agronômico. Campinas, Brazil.

van Raij, B., J.A. Quaggio, and N.M. da Silva. 1986. Extraction of phosphorus, potassium, calcium and magnesium from soils by an ion exchange resin procedure. *Comm. Soil Sci. Plant Anal.* 17:547-566.

van Raij, B., N.M. da Silva, and O.C. Bataglia. 1985. Recomendações de adubação e calagem para o Estado de São Paulo. Boletim Técnico 100. Instituto Agronômico. Campinas, Brazil. 107 p.

Yost, R.S., E.J. Kamprath, C.C. Naderman, and E. Lobato. 1981. Residual effects of phosphorus applications on a high phosphorus adsorbing oxisol of central Brazil. *Soil Sci. Soc. Amer. J.* 45:540-543.

DIFFICULTIES IN THE APPLICATION OF *SOIL TAXONOMY* IN BRAZIL AND THE BRAZILIAN EXPERIENCE WITH BUILDING UP OXISOLS' FERTILITY

N. Curi and A.S. Lopes[1]

The importance of Oxisols worldwide is related to the fact that this order of soils occupies 22 percent of the earth's land surfaces, occurring mostly in tropical regions (calculated by M. Drosdoff on the basis of Aubert and Tavernier's map, 1972, in Sanchez 1976).

Besides the importance of these soils in geographical extent, one must consider their place in terms of food production in the future with an aim to increase agricultural production by 60 percent in the year 2000 in areas already under cultivation, and to use 200 million new hectares of land not now incorporated in the production process (Dudal 1980).

Keeping in mind the need for suitable characterization, classification, and utilization of Oxisols, this paper has the following objectives: (a) to discuss the main difficulties in the use of *Soil Taxonomy* in terms of Brazilian Oxisols; (b) to propose for further testing a revision in *Soil Taxonomy*; and (c) to make a summary of the Brazilian experience in building up the fertility of Oxisols.

Difficulties of Using *Soil Taxonomy* with Brazilian Oxisols

Beyond the fact that *Soil Taxonomy* is still very incipient in terms of tropical soils, other problems exist.

Soil Moisture and Temperature Regimes

Field observations of soil conditions related to moisture and temperature are frequently lacking, and many criteria depend on seasonally changing variables, which need observations for extended periods of time (Van Wambeke 1981). The application of soil moisture and temperature regimes in the absence of precise data make class separations, even at high categories (suborder) problematic (Resende 1979).

Soil Profile Versus Landscape

Soil Taxonomy places very low emphasis on the soil as a three dimensional body. Only for some Aquic great groups is the use of the shape of the soil as a family differentia proposed; level is assumed in families of Aquic soils if no slope modifier is used in the family name (Soil Survey Staff 1975). This makes the classes without a three-dimensional aspect very incomplete in terms of agricultural use information. There is special importance in the soil profile and little in the landscape (Resende 1979).

Soil Color

Since soil color is a reliable indicator of iron oxide mineralogy, and other important soil properties covary with color, it seems that soil color should be used as a differentiating characteristic at a relatively high categorical level in *Soil Taxonomy* for Oxisols (Curi and Franzmeier 1984). Thus further testing was proposed of a revision whereby color would be used at the great group level and cation-retention capacity and base saturation might be used at the subgroup level instead of the great group level. According to this arrangement, Rhodustox would be established and listed early in the key of Ustox to represent the redder Ustox, those with hues redder than 5YR in which hematite generally predominates. Haplustox would be listed later in the key to include the yellower soils that did not meet the requirements of some of the other great soil groups. The acric subgroups of these great groups might include soils with low cation retention capacity.

Similar classification changes would seem appropriate in Orthox and other suborders. This grouping of soils recognizes that soil color is associated with some very important soil characteristics, as reflected in the Brazilian system. That proposal is similar to one considered by ICOMOX (International Committee on Classification of Oxisols) (Eswaran 1979), except that Rhodorthox would be listed earlier in the key, to include more of the red soils that also had some other distinctive features, and that Curi and Franzmeier's proposal requires Rhodorthox to be redder than 5YR instead of 5YR or redder. Kämpf and Schwertmann (1983) proposed that

[1] Authors' present address: Departamento de Ciência do Solos, Escola Superior de Agricultura de Lavras. Caixa Postal 37. CEP 37200- Lavras, Minas Gerais, Brazil.

soil color, as a function of hematite content, be used as a differentiating characteristic at the family level in *Soil Taxonomy*.

Properties Which Covary with the Parent Rock

Even in the case of Oxisols there are many reasons for the separation of soils that originated from different kinds of rock. This is a very pertinent problem to Brazil and it is not considered in *Soil Taxonomy*. Dusky Red Latosols are separated from other Latosols because they originated from mafic rocks. Such separation is well justified. For example, the dystrophic Dusky Red Latosol (LRd) and the dystrophic Dark Red (LEd) of the central plateau of Brazil are two distinct classes. Although dystrophic (<50 percent base saturation of the CEC determined at pH 7.0), LRd soils formed from mafic rocks are richer in total P, Fe, and trace elements essential for plant and animal nutrition than LEd soils formed from other rocks. Table 1 shows the results of total chemical analysis of Oxisols which represent different degrees of mixing from basaltic rock (M1) to sandstone (M3).

Apparently some soil properties inherited from the parent rocks influence the fertility of these soils. M1 is richer in TiO_2, Fe_2O_3, FeO, Cu, Co, and Zn than are M2 or M3. Co is abundant in the clay fraction of samples M1 and M2, especially in M1. The coarse fraction of M1 and M2 contributes substantially to the trace element content of these soils.

The analysis of magnetite (apparently intergrown with ilmenite) from the coarse fraction of M1 reveals very high amounts of all the analyzed elements, in agreement with the findings of Sidhu, Gilkes, and Posner (1978, 1980), that magnetite is an important source of trace elements in soils and rocks. Therefore, as magnetite is slowly weathered these trace elements would be slowly released to the soil solution, maintaining a bufferlike capacity of such elements. This slow release of trace elements becomes crucial in Oxisol conditions in which abundant pluviometric precipitation, high temperature, generally good drainage, and high leaching potential tend to deplete such weathered and old soils of these trace elements.

It appears that in Brazilian conditions mafic rocks contain much higher amounts of trace-element-rich magnetite than do other kinds of rock; therefore, the parent rocks could function as indicators of richness or poorness of the trace elements associated with them.

Similarly, Red-Yellow Latosols (LV) developed from gneiss are not separated from Yellow Latosols (LA) developed from Barreiras group (unconsolidated continental sediments which occur as a narrow and long band along the Atlantic coast) in and level in *Soil Taxonomy* (M. Resende, pers. comm.). Although the clay fraction of both soils has a fairly high kaolinite content, the latter soils are very much lower in gibbsite and Fe_2O_3 content, which covary with the nature of their parent material (very low in Fe). As a result, Yellow Latosols are the least permeable of the Brazilian Latosols, but present the maximum of coherence among particles, revealing higher run-off volume and laminar erosion as its sole erosion form (Resende 1985).

Allic Character

With respect to soil fertility parameters, in accordance with Kamprath (1980), crop production is drastically reduced when Al saturation of the active cation exchange sites is greater than

Table 1. Total Chemical Analysis of Some Soil Samples, Dialized Clay Fraction, and Magnetite Apparently Intergrown with Ilmenite from the Coarse Fraction[a]

	Concentration					
Sample	TiO_2	Fe_2O_3	FeO	Cu	Co	Zn
	(%)			(ppm)		
M1[b]	9.35	29.68	3.16	225	96	152
M1-DC	1.68	18.66	n.d.[f]	182	112	78
M2[c]	6.12	15.44	1.24	82	80	56
M2-DC	2.22	21.11	n.d.	85	96	42
M3[d]	2.64	7.04	0.27	30	n.d.	21
M3-DC	3.09	23.10	n.d.	70	n.d.	49
MT + Il - M1[e]	32.38	41.06	15.36	670	160	584

[a] All samples are from Oxisols under forest vegetation in the Minas Gerais Triangulo area. Source: Resende et al. (1986).
[b] M1 = Bo2 horizon from basalt. DC = dialized clay fraction.
[c] M2 = Bo2 horizon from basalt-sandstone.
[d] M3 = Bo2 horizon from sandstone.
[e] MT + Il-M1 = Magnetite apparently intergrown with ilmenite separated from the coarse fraction of M1 soil.
[f] n.d. = not detected.

60 percent and tends to be optimum when this value is nil. In *Soil Taxonomy* base saturation of the surface soil is used only with the great group Eutrorthox, and in all other instances the base saturation of a subsurface horizon is used. In this sense one cannot draw any specific conclusion about the base saturation of the surface horizon except for one great group. The Brazilian soil classification system recognizes and names soils or layers with Al saturation ≥ 50 percent (allic character) and uses terms such as epiallic or endoallic for specifying surface or subsurface problems related to this constraint (M.N. Camargo, pers. comm.). When the whole profile presents this situation the term *allic* is used alone. This terminology would fill the gap previously mentioned (Lopes, Smyth, and Curi 1986).

Revision in *Soil Taxonomy*

Based upon these preconsiderations, we are proposing for further testing a revision in *Soil Taxonomy* whereby soil color would be a more meaningful great group differentiating characteristic than cation-retention capacity (Acrorthox) and base saturation (Eutrorthox) criteria. The latter characteristics might be used at the subgroup level instead of the great group level. Perhaps the new key to great groups of the Orthox suborder could be: CEA. Rhodorthox, with hues redder than 5YR (hematite tends to predominate the Fe mineralogy); CEB. Sombriorthox; CEC. Gibbsiorthox; CED. Umbriorthox; CEE. Haplorthox, with 5YR hues and yellower (goethite is the main form of iron oxide). The new proposed subgroups for Rhodorthox would be: (a) cation-retention capacity (from NH_4Cl) or extractable bases plus extractable aluminum > 1.5 meq/100 g clay and base saturation (by NH_4OAc) < 35 percent ——> typic; (b) cation-retention capacity (from NH_4Cl) or extractable bases plus extractable aluminum > 1.5 meq/100 g clay and base saturation (by NH_4OAc) ≥ 35 percent ——> eutric; (c) cation-retention capacity (from NH_4Cl) or extractable bases plus extractable aluminum ≤ 1.5 meq/100 g clay ——> acric; (d) plinthic; (e) haplohumic; (f) sombrihumic; and (g) tropeptic. In the case of the Haplorthox subgroups a, b, and c would be the same as for Rhodorthox; (d) epiaquic; (e) plinthic; (f) quartzipsammentic; (g) tropeptic; and (h) ultic. Similar classification changes would seem appropriate in Ustox and other suborders.

This grouping of soils is more similar to that in the Brazilian classification system than the current definitions in *Soil Taxonomy*. It represents years of experience reflected in the Brazilian soil classification system.

Building Up Fertility in Oxisols: The Brazilian Experience

When dealing with parameters to be considered for adequate management of Oxisols, the following should be examined (in addition to those normally used).

Amount of Exchangeable Ca in Subsurface Layers

Taking into account this parameter, the profile should receive special attention in terms of Oxisols' management classes. Ritchey, Silva, and Costa (1982) and Ritchey, Silva, and Sousa (1983) have associated poor root development in depth with low levels of exchangeable and soil-solution Ca down the profile in these soil systems in Brazil. The Ca:Mg ratio in these subsurface layers should also receive concern.

P Fixation

In the agronomic and practical point of view an adequate estimate of P adsorption capacity of Brazilian Oxisols samples has been obtained by using indicator parameters, usually found in soil survey reports, such as: percent Fe_2O_3 from sulfuric acid digestion (Lopes 1977; Lopes and Cox 1979; Curi et al. 1986), percent Al_2O_3 from H_2SO_4 digestion (Lopes 1977; Lopes and Cox 1979), SiO_2/R_2O_3 molecular ratio (Curi and Camargo 1986), and clay content (Camargo, van Raij, and Grohmann 1974; Lopes 1977; Lopes and Cox 1979; Curi and Camargo 1986). Clay percentage has been used to define phosphate fertilizer rates in the *cerrado* region of Brazil.

Effective CEC

In Oxisol ecosystems the effective CEC ($Ca^{2+} + Mg^{2+} + K^+ + Na^+ + Al^{3+}$) is well known to be a major fertility parameter which often accounts for the crop productivity on these soils. A distinction of soil conditions related to this parameter in surface and subsurface layers should receive special attention.

Al Saturation of the Effective CEC

It seems to be more appropriate to consider this fertility parameter in top and down profile layers, remembering that this constraint is more critical in subsurface layers. Also considering the Al saturation, the base saturation of the effective CEC is a natural consequence.

Clay Percentage

When one is dealing with Oxisols in which there is a clear dominance of low activity clays, by definition the amount of the clay fraction acquires importance in terms of soil management classes.

Relief

Losses through erosion are in general more pronounced than those through leaching, mainly in relation to P; thus slope is a critical factor in soil management (Resende, Santana, and Curi 1986). For Oxisols in similar environments having topographic variations, erosion follows a relationship between slope and ramp length.

Soil Color in Association with the Nature of Parent Material

Definition of soil classes based on soil color, which can be readily determined in the field, results in separations that differentiate soils according to their genesis and, in addition, makes separations that are significant to the use and management of the soils (Curi and Fanzmeier 1984). Because the effect of parent material is still evident, influencing many covarying soil properties even in highly weathered soils that tend to have a higher degree of homogeneity (Curi and Franzmeier 1986), one should consider this parameter (which, in the Brazilian case, is well expressed by the iron oxide content of the soil material) in association with soil color for defining management classes of Oxisols.

Some practical implications of the points discussed in the previous sections of this paper can be visualized in the Brazilian experience with building up fertility of soils under *cerrado* vegetation, most of them included in the Oxisol order (Lopes 1983).

According to Lopes there are several alternatives for building up fertility of these soils, for maintaining this induced fertility, for making agriculture profitable, and increasing the probability of success in agricultural businesses in the *cerrado* region. To build up soil fertility actually means to make use of adequate rates of lime, phosphate fertilizers, and in some cases, gypsum and potassium fertilizers, all aimed at getting greater efficiency of maintenance fertilization, utilization of subsurface stored water and, consequently, lowering the detrimental effects of short drought periods on crop yields during the rainy season (*veranicos*).

Besides physical, chemical, mineralogical, climatic, and plant parameters, to achieve these goals the following aspects should be considered: (a) the program of land use for a number of years, not only for a single year; (b) number of years to reach the desired yields; and (c) money available to build up soils fertility of the area.

The success of agricultural production, including grain crops (soybeans, rice, common beans, corn, wheat), perennial crops (coffee and fruit trees), and pasture in the *cerrado* area in Brazil, is based upon technology that follows some basic principles applicable to other similar areas:

1. Acid soils, with Al and/or Mn toxicity, must receive adequate rates of lime as the first agronomical management practiced to achieve suitable yields of crops nontolerant to these constraints. Since there is no universally adequate method for recommending lime rates for Oxisols, the value of parameters such as pH, effective CEC, Al saturation, CEC and base saturation at a given pH, exchangeable Ca in subsurface layers, clay and organic carbon percentage must be stressed. Details on soil acidity and methods for lime recommendations for Oxisols are discussed in another paper of this workshop (Lopes and Curi 1986).

2. Modern fertilization technology for P deficient soils and/or those possessing high P fixation potential, as with most of the Brazilian Oxisols, requires a build up of phosphate through fertilization following maintenance fertilization. The rates of application of soluble phosphate fertilizers should be defined by the crops and soil clay content. Adequate rates of phosphate for building up fertilization must be evaluated according to quantified parameters, since phosphate fertilizers are in general the most expensive investments in the fertilization of these soil systems. Clay percentage has been used to define phosphate fertilizer rates in the *cerrado* region: 3 to 10 kg soluble P_2O_5/ha for each 1 percent clay.

3. Previous liming increases the agronomic efficiency of water-soluble phosphate fertilizers, natural rock phosphates of high reactivity and thermophosphates and reduces that of natural rock phosphates of low reactivity, as is the case with most of the Brazilian ones. In this sense, for pasture and perennial crops, species or varieties tolerant to low pH and/or Al toxicity, Brazilian natural rock phosphates are applied without liming or previous to lime application (at least 3 months earlier). Lime rates are about one-quarter of the normal rates. Natural rock phosphate rates range from 3 to 10 kg total P_2O_5/ha for each 1 percent clay.

4. The beneficial effects of high rates of simple superphosphate (around 48 percent calcium sulfate) or associations of triple superphosphate, natural rock phosphate of high reactivity, or thermophosphate with gypsum applied in building up phosphorus fertilization have been observed and confirmed as promising techniques to increase rooting depth of crops in Oxisols. This technology has been recommended for soils with low levels of exchangeable Ca (less than 0.3 meq/100 g) in subsurface layers. The rates of gypsum to overcome subsurface constraints to root development are a function of texture, organic carbon content, crop, rainfall intensity and distribution, residual effect, and so on. A first approximation of gypsum rates has been: (a) 125 kg of gypsum for each 100 kg of triple superphosphate or 50 kg of gypsum for each 100 kg of thermophosphate, or (b) 25 percent of the CaO of lime substituted by the CaO of gypsum if rates of lime are calculated to elevate base saturation up to 70 percent or add equivalent of 25 percent of CaO as gypsum if rates of lime are calculated by the Al and Ca + Mg criterion.

5. Since high rates of application of lime and phosphate fertilizers are generally required to build up fertility of most Brazilian Oxisols, and since the only real loss of these amendments is through erosion, the significance of the relief must be emphasized. Both slope and length of slope are important parameters in the decision-making process suitable to the management of Oxisols, and define classes that must receive special attention as to soil and water conservation.

6. Finally, it is commonly accepted among Brazilian soil scientists that the success of agricultural production in the *cerrado* region is a result of the integration of scientific knowledge including pedology, soil fertility, soil physics, plant pathology, seed technology, and other areas. As mentioned by Lopes (1983): "Agriculture in the 'cerrado' region should not be considered in terms of its potentiality, but by the reality of results already obtained through suitable management and integration of agronomic knowledge."

References

Camargo, O.A. de, B. van Raij, and F. Grohmann. 1974. Fixação de fósforo em solos avaliada pelo índice de Bache e Williams e sua correlação com outras propriedades. *Cienc. Cult.* 28:681-685.

Curi, N., and O.A. de Camrgo. 1986. Phosphorus adsorption characteristics of Brazilian Oxisols. *In* Proc. of the VIIIth Int. Soil Class. Work. SMSS/EMBRAPA/UPR, Brazil.

Curi, N., O.A. de Camargo, G.A.A. Guedes, and J.V. Silveira. 1986. Sorção de fósforo em materialis de Latossolos do Brasil Sudeste e Sul. Anais da III Reunião de Classificação, Correlação de Solos e Interpretação da Aptidão Agrícola. September 1984. EMBRAPA/SNCLS, Rio de Janeiro, Brazil.

Curi, N., and D.P. Franzmeier. 1984. Toposequence of Oxisols from the central plateau of Brazil. *Soil Sci. Soc. Amer. J.* 48:341-346.

———. In press. Effect of parent rocks on chemical and mineralogical properties of some Oxisols in Brazil.

Dudal, R. 1980. Soil-related constraints to agricultural development in the tropics. *In* Priorities for alleviating soil-related constraints to food production in the tropics. IRRI and Cornell Univ., NY. Pp. 23-37.

EMBRAPA. Serviço Nacional de Levantamento e Conservação de Solos. 1981. Mapa de solos do Brasil. Ministério da Agricultura. Rio de Janeiro, Brazil.

Eswaran, H. 1979. Report of the International Committee on Classification of Oxisols. *In* Proc. of the IInd Int. Soil Class. Work., Part I: Malaysia. Soil Survey Div., Land Development Dept., Bangkok, Thailand. Pp. 85-94.

Kämpf, N., and U. Schwertmann. 1983. Goethite and hematite in a climosequence in Southern Brazil and their application in classification of kaolinitic soils. *Geoderma* 29:27-39.

Kamprath, E. J. 1980. Soil acidity in well-drained soils of the tropics as a constraint to food production. *In* Priorities for alleviating soil-related constraints to food production in the tropics. IRRI and Cornell Univ., NY. Pp. 171-187.

Lopes, A.S. 1977. Available water, phosphorus fixation, and zinc levels in Brazilian cerrado soils in relation to their physical, chemical, and mineralogical properties. Ph.D. thesis. North Carolina State Univ., Raleigh, NC.

———. Solos sob "cerrado": Características, propriedades e manejo. Instituto da Potassa & Fosfato and Instituto Internacional da Potassa, Piracicaba.

Lopes, A.S., and F.R. Cox. 1979. Relação de características físicas, químicas e mineralógicas com fixação de fósforo em solos sob cerrado. *R. Bras. Ci. Solo* 3:82-88.

Lopes, A.S., and N. Curi. 1986. Oxisols acidity and fertility evaluation. *In* Proc. of the VIIIth Int. Soil Class. Work. SMSS/EMBRAPA/UPR, Brazil.

Lopes, A.S., T.J. Smyth, and N. Curi. 1986. Soil fertility methodologies for acid tropical soils: The need for a reference base and nutrient dynamics studies. Acid Trop. Soils Management Network, Brasília, Brazil.

Resende, M. 1979. Classificação de solos. Imprensa Univ., Viçosa.

———. Aplicações de conhecimentos pedológicos à conservação de solos. *Inf. Agropec.* 11:3-18.

Resende, M., D.P. Santana, and N. Curi. In press. Aplicação de conhemimentos pedológicos à fertilidade do solo. Belo Horizonte.

Resende, M., D.P. Santana, D.P. Franzmeier, and F.M.D. Coey. 1986. Magnetic properties of Brazilian Oxisols. *In* Proc. of the VIIIth Int. Soil Class. Work. SMSS/EMBRAPA/ UPR, Brazil.

Ritchey, K.D., J.E. Silva, and U.F. Costa. 1982. Calcium deficiency in clayey B horizons of savannah Oxisols. *Soil Sci.* 133:378-382.

Ritchey, K.D., J.E. Silva, and D.M.G. Sousa. 1983. Relação entre o teor de cálcio no solo e desenvolvimento de raízes avaliado por um método biológico. *R. Bras. Ci. Solo* 7:269-275.

Sanchez, P.A. 1976. Properties and management of soils in the tropics. John Wiley & Sons, New York.

Sanchez, P.A., and F.C. Salinas. 1981. Low-input technology for managing Oxiscls and Ultisols in tropical America. *Adv. in Agron.* 34:279-406.

Sidhu, P.S., R.J. Gilkes, and A.M. Posner. 1978. The synthesis and some properties of Co, Ni, Zn, Cu, Mn and Cd substituted magnetites. *J. Inorg. Nucl. Chem.* 40:429-435.

———. 1980. The behavior of Co, Ni, Zn, Cu, Mn, and Cr in magnetite during alteration to maghemite and hematite. *Soil Sci. Soc. Amer. J.* 44:135-138.

Soil Survey Staff, SCS, USDA. 1975. Soil taxonomy: A basic system of soil classification for making and interpreting soil surveys. Agric. Handb. No. 436, USDA. U.S. Gov. Printing Office, Washington, D.C.

Van Wambeke, A. 1981. Calculated soil moisture and temperature regimes of South America. SMSS Technical Monograph 2, New York.

GEOTECHNICAL CHARACTERISTICS OF OXISOL B HORIZONS

L. M. G. Motta,[1] J. Medina,[2] J. L. R. Souza,[3] and J. Olmos I. L.[4]

The opportunity to determine a few geotechnical characteristics of samples taken from B horizons of Oxisol pedons thoroughly studied by soil scientists seemed to the authors to be a valid exercise. The plan of study included the use of new testing techniques and the engineering soil classification system developed in Brazil by Nogami and Villibor called MCT (miniature compacted tropical) classification.

Materials and Methods

From the 23 pedons described and collected for the VIIIth International Soil Classification Workshop (ISCW), 9 of them were selected for the realization of this study.

Sample	Pedon	Horizon	*Soil Taxonomy*
P1	ISCW 1	Bo2	Typic Eutrorthox
P4	ISCW 4	Bo2	Typic Hapludox
P7	ISCW 7	Bo2	Typic Acrudox
P11	ISCW 11	Bo3	Rhodic Hapludox
P13	ISCW 13	Bo2	Acrudox
P18	ISCW 18	Bo	Typic Acrudox
P20	ISCW 20	Bo2	Rhodic Eutrustox
P22	ISCW 22	Bo1	Typic Acrorthox
Extra	ISCW Extra II	Bo1	Typic Acrorthox

In Table 1 are the comparative properties of soil groups obtained in miniature compacted specimens (MCT). The lateritic engineering behavior is distinguished from the nonlateritic behavior. The method was developed for soils of grain-size less than 2 mm.

The mini-CBR (California bearing ratio miniaturized) is a penetration test (piston of 1.6 cm diameter) of a sample that has been compacted with the mini-MCV rammer, at a constant compaction effort of 10 blows. Specimens were not soaked, and a surcharge weight of 490 g was placed on the top surface during the penetration.

Results

Determinations made at EMBRAPA are in Table 2. The parameters from mini-MCV tests, together with grain-size data, liquid limit and plasticity index (classes according to U.S. Highway Research Board Unified Soil Classification System) and miniature compacted specimens (MCT) are presented in Table 3. These tests were conducted at the Soil Mechanics Laboratory of COPPE/UFRJ. Test results of mini-CBR are shown in Table 4, and the graphs of compaction curves (γ_d, w) and CBR curves (mini-CBR, w) are in Figure 1. In Figure 2 were also plotted the points representative of the nine samples.

Discussion

All soil samples plot on the lateritic behavior part of the chart for classification purposes (Fig. 2). Those of high immersion loss are near the borderline of classes LG' and NG'. Soil samples P4 (Typic Hapludox) and P22 (Typic Acrorthox) have immersion losses of 10 percent and zero respectively. Sample P13, an Acrudox, is more sandy than the previous ones and has an immersion loss of 100 percent, which means lack of strong cementation when saturated.

The usual testing procedures of SNLCS laboratories were applied to determine grain-size distribution, silt to clay ratio, and CEC k_i and k_r. The mini-MCV (moisture condition value) test is described by Nogami and Villibor (1981, 1985). A sample of soil weighing about 200 g is compacted in miniaturized equipment similar to that developed by Parsons and Boden (1976). The rammer weight is 2740 g, the height of drop 305 mm, and the diameter of mold 50 mm (Fig. 3).

The difference to the traditional Proctor compaction test much used in earthworks throughout the world is that instead of applying a standardized compactive effort to the moistened mass of soil, successive blows are applied while the decreasing height of the compacted soil sample is measured. This procedure is repeated for different water contents. The MCV value is defined:

[1] Assistant Professor at COPPE/UFRJ.
[2] Professor at COPPE/UFRJ.
[3] Researcher at Serviço Nacional de Levantamento e Conservação de Solos, Empresa Brasiliera de Pesquisa Agropecuária (SNLCS,EMBRAPA),Brazil.
[4] Researcher, SNLCS, EMBRAPA, Brazil.

Table 1. Comparative Properties of Soil Groups

A = sand (Arena) A′ = sandy G = clay (Argilla) G′ = clayey S = silt S′ = silty k = kaolinitic m = micaceous q = quartzose		Class	Nonlateritic (N) behavior				Lateritic (L) behavior		
		Group	NA	NA′	NS′	NG′	LA	LA′	LG′
		Typical grain size	A S′A S(q)	S′A G′A	S(km) A′S G′S	G A′G S′G	A	G′A A′G	G A′G
h = high l = low m = medium v = very / = to	Mini-CBR*	Soaked	h/m	h/m	m/h	h	h	h/vh	h
		Decrease by soaking	m/l	l	h	h	l	l	l
		Swelling *	l	l	h	h/m	l	l	l
		Shrinkage *	l/m	l/m	m	h/m	l	l/m	m/h
		Permeability*	m/h	l	m/l	l/m	m/l	l	l
		Plasticity	l/NP	m/NP	m/h	h	NP/1	l/m	m/h

* Specimens compacted at optimum of standard compactive effort.

Table 2. Soil Parameters and Geotechnical Classification of Oxisols Studied

Sample	% Pass. 200	WL/I_P	c'	d'	P_i	e'	Classification HRB	USCS	MCT
P1	<50	58 14 64	1.5	77	0	0.64	A-7-5	SM	LA′/LG′
P4	>50	21 45	1.7	67	10	0.74	A-7-5	MH	LG′
P7	>50	12 39	2.1	27	80	1.13	A-7-5	ML	LG′
P11	>50	9 47	2.6	15	30	1.18	A-4	ML	LG′
P13	<50	11 46	0.6	10	60	1.37	A-2-7	SM	LA
P18	>50	10 32	1.8	57	100	1.11	A-5	ML	LG′
P20	>50	11 36	2.0	32	100	1.18	A-6	CL	LG′
P22	>50	NP 52	2.0	40	0	0.79	A-4	ML	LG′
Extra II	>50	28	2.2	44	20	0.87	A-7-6	CH	LG′

Note: WL = liquid limit; I_p = plasticity index; c', d', P_i, e' = parameters defined in text.

Table 3. Testing Data of Samples from EMBRAPA

Sample	CEC	k_i	k_r	Silt/Clay (%)	Grain size (%)		
					Sand	Silt	Clay
P1	2.9	1.40	1.22	15	53	6	41
P4	2.8	1.78	1.39	13	14	10	76
P7	1.3	0.71	0.41	18	10	14	76
P11	1.3	0.37	0.27	11	3	10	87
P13	1.3	1.82	1.28	39	75	7	18
P18	1.8	0.91	0.69	10	12	8	80
P20	2.4	0.71	0.55	9	13	7	80
P22	4.9	1.53	1.20	38	34	18	48
Extra II	2.8	0.43	0.25	18	11	14	75

Note: Sand 2-0.05 mm; silt 0.05-0.002 mm; clay <0.002 mm.

Table 4. Compaction Parameters (γ_d, w) and Mini-CBR Values

Sample	Specimen										
		1	2	3	4	5	6	7	8	9	10	Wo
P1	w%	16.91	17.21	19.28	22.06	22.75	12.38	14.24	16.44	17.61	19.92	18
	MCBR	25	18	7	6	3	31	26	25	17	10	16
P4	γ_d	17.51	17.64	16.91	16.52	16.10	15.23	15.87	17.32	17.84	17.07	17.8
	w%	26.06	27.88	30.65	31.49	35.35	25.64	28.44	30.39	31.80	34.13	28.5
	MCBR	20	17	9	8	3	20	16	13	9	5	16
P7	γ_d						14.24	14.73	14.37	14.07	13.59	14.7
	w%	24.71	26.14	27.80	30.51	32.23	22.90	25.05	26.66	29.38	31.29	27
	MCBR	20	16	9	5	3	22	18	11	7	4	10
P11	γ_d						15.66	16.35	16.55	15.74	15.20	16.6
	w%	27.01	31.29	32.20	33.97	36.56	23.18	26.34	29.47	29.72	34.47	30
	MCBR	21	14	10	7	4	35	27	21	19	9	20
P13	γ_d						11.99	13.14	14.16	13.98	13.71	14.3
	w%	8.87	10.91	13.36	15.05	17.60	9.00	10.95	12.39	14.34	17.35	11
	MCBR	25	20	16	7	3	33	27	14	5	2	25
P18	γ_d						18.78	18.99	18.93	18.17	17.19	19.0
	w%	28.09	28.95	30.79	33.01	34.55	20.43	21.94	23.71	25.54	26.47	28
	MCBR	14	15	8	4	3	35	35	25	21	18	16
P20	γ_d						12.26	12.28	12.81	13.77	14.42	14.7
	w%	26.84	28.94	31.25	33.73	35.33	16.61	19.92	20.11	22.49	24.71	26
	MCBR	18	15	9	6	3	38	34	33	29	21	20
P22	γ_d						12.06	11.98	12.04	12.22	13.48	14.1
	w%	15.84	17.58	20.16	21.61	24.00	14.37	16.83	18.97	18.86	22.64	19
	MCBR	23	16	14	8	4	25	21	20	19	7	20
Extra II	γ_d						15.41	16.28	16.68	16.54	16.03	16.6
	w%	26.01	28.14	30.08	32.08	34.28	20.08	22.45	23.47	25.65	27.49	28
	MCBR	10	16	9	5	2	36	20	22	20	19	16
	γ_d						13.23	13.89	14.27	15.16	15.58	15.6

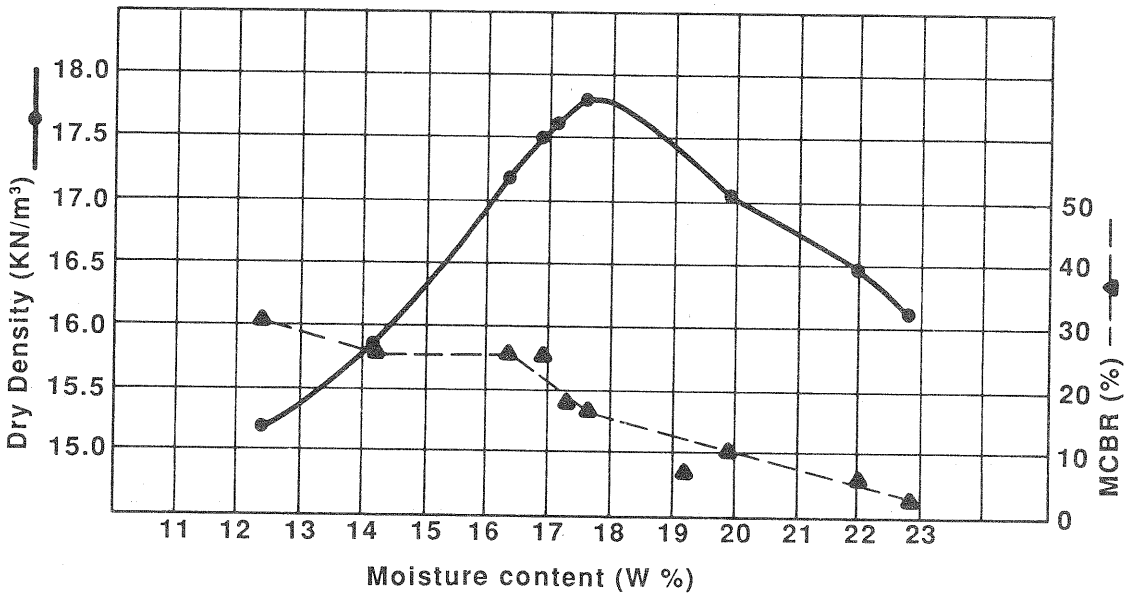


Fig. 1. Example of compaction and mini-CBR curves (sample P20).

$$\text{mini-MCV} = 10 \log_{10} (B_n). \quad (1)$$

B_n is the intersection of mini-MCV curves shown in Figure 4 with a straight line corresponding to a_n equal to 2 mm.

$$a_n = A_n - A_{4n}. \quad (2)$$

A_n is the height for n blows and A_{4n} for $4n$ blows.

The parameter c' is picked up from the mini-MCV curves.

After compaction the soil sample is partially extruded from the mold so that a part 1 cm long becomes salient. Then the mold with the extruded sample is flooded until the water level comes at least 1 cm above the mold. The loss of weight by immersion (P_i) is determined. Its plot is shown in the same figure. From the compaction curves, where dry density of compacted soil is plotted against moisture content the d' parameter (average slope of 12-blows curve in the dry side) is determined. To enter the classification chart (Fig. 2) two parameters are needed: c' and e'. The latter is defined as:

$$e' = \left(\frac{Pi}{100} + \frac{20}{d'}\right)^{1/3} \quad (3)$$

It can be observed that soils having a high value of P_i (immersion loss) are Acrox ones; they are old soils with little CEC. However, data are not enough for a tentative correlation of P_i with CEC (or with k_i or k_r).

Soil P_i is at the borderline LA/LG'. It has approximately the same amounts of sand and clay fractions.

With data from Tables 2 and 3 some correlations were tested:

1. Parameter c'

$c' = 2.6023 - 0.0475$ (silt/clay, %); $r = 0.773$ (4)
$c' = 2.3414 - 0.0203$ (sand, %); $r = 0.882$ (5)
$c' = 0.5397 + 0.0200$ (clay, %); $r = 0.836$ (6)
$c' = 2.6577 - 0.7681$ (k_i); $r = 0.779$ (7)
$c' = 2.5321 - 0.8663$ (k_r); $r = 0.720$ (8)

These correlations are reasonably good.

2. Parameter d'

$d' = -13.85 + 26.49$ (CEC); $r = 0.790$ (9)

3. Parameter e'

$e' = 0.2284 + 0.0103$ (clay, %); $r = 0.779$ (10)
$e' = 1.29 - 0.36$ (k_i); $r = 0.750$ (11)
$e' = 1.23 - 0.37$ (k_r); $r = 0.770$ (12)
$e' = 1.3713 - 0.1150$ (CEC); $r = 0.729$ (13)

The parameter P_i does not correlate with the variables considered. The d' value correlates only with the CEC. But as e' is an empirical function of P_i and d', some kind of correlation might be tried. More data are needed.

The classical soil classification systems used in Brazil for engineering purposes—HRB (now TRB) or AASHTO classification and the USCS—do not detect the so-called lateritic behavior. One soil may be classified in a weak category as subgrade material, yet may behave very well because of its structure and the cementing effect of iron oxides. CBR values are sometimes surprisingly high for what could be expected from a clayey soil, or a fine lateritic sand, according to above mentioned classifications. Therefore, the attempt to translate pedological data into engineering information cannot be accomplished by performing a few extra tests such as the Atterberg limits and the compaction tests. What should be done

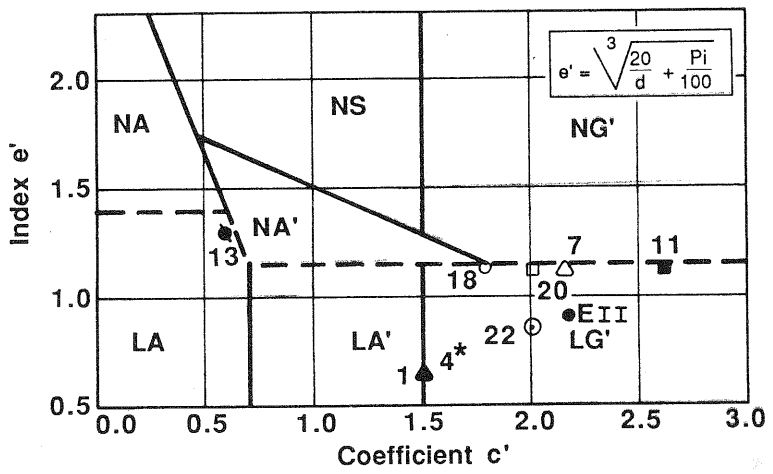


Fig. 2. Chart for classification purpose (MCT).

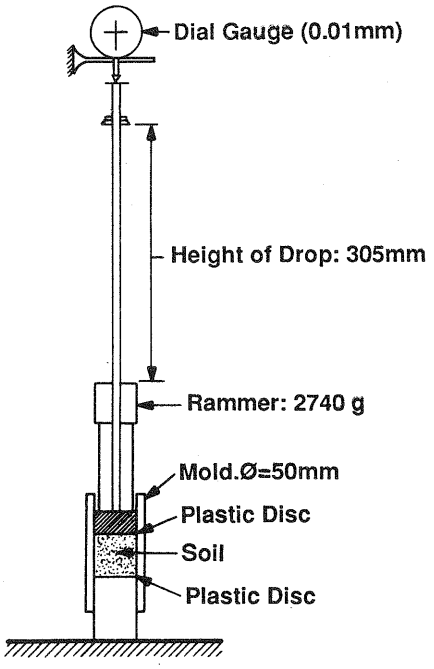


Fig. 3. Schematic Mini-MCV compaction apparatus.

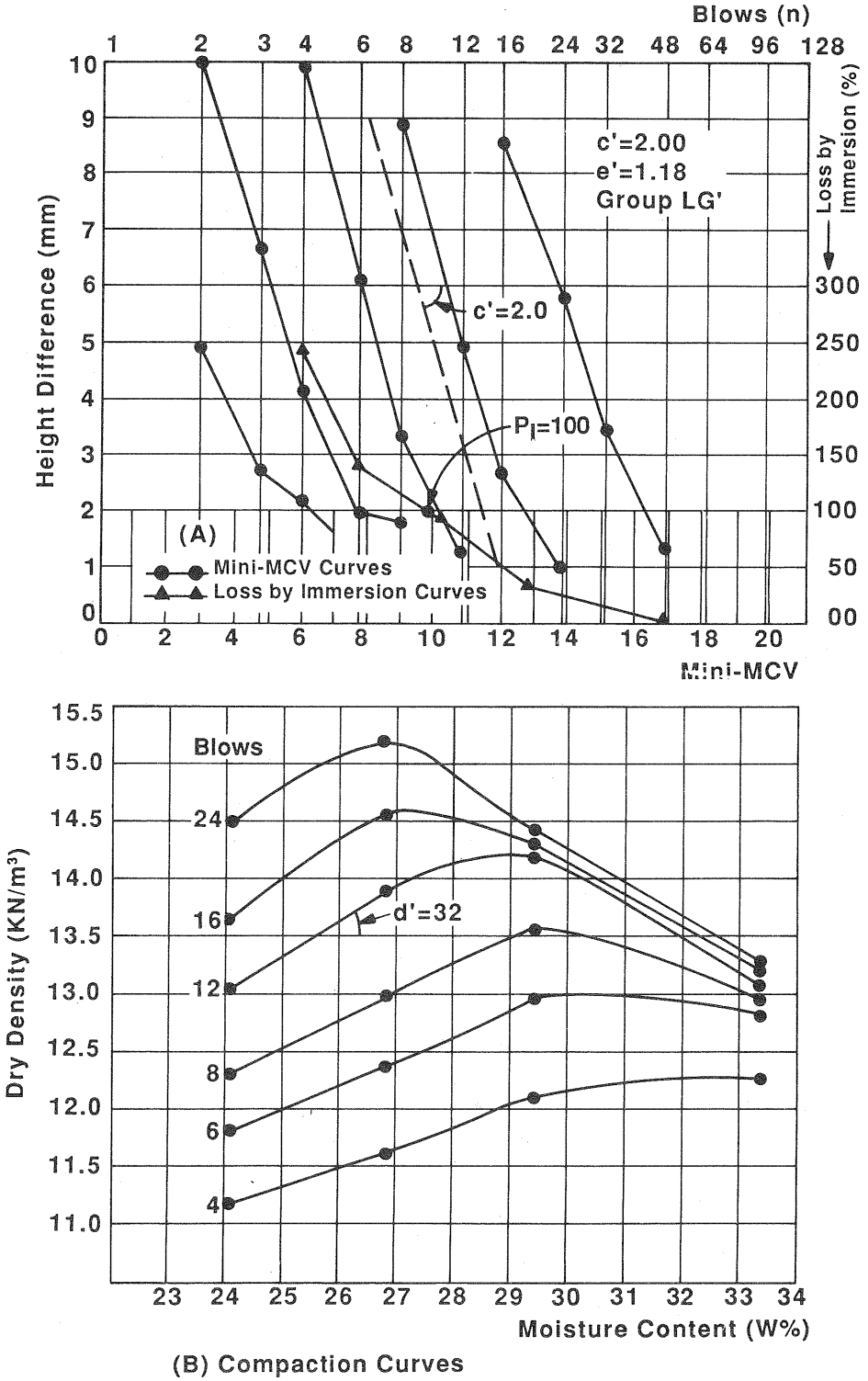


Fig. 4. Graphic representation of test results.

is either to correlate soil series with performance of engineering constructions or to perform more significant testing reflecting properties that explain engineering behavior. For pavement design of low cost roads, the MCT classification seems to be quite adequate for Brazilian soils.

Each purpose to be served best demands a different classification. The classification is a contrivance made by men to suit their purposes, not a truth that can be discovered. On the other hand taxonomy is the part of classification that is concerned primarily with relationships among soils and the factors responsible for their character. These concepts are clearly presented in the publication *Soil Taxonomy* (Soil Survey Staff 1975).

Therefore, a general soil classification system for engineering purposes developed in a country of climates and weathering and pedological processes different from those prevalent in Brazil cannot be applied blindly as if it was a taxonomic system.

Conclusion

The nine samples taken from the B horizon of Oxisols were evaluated more accurately for engineering purposes, especially for paving of low cost roads, by the MCT soil classification system than by simply determining the classes they belong to in the Unified and HRB soil classification systems.

A strong possibility exists for determining relationships between physical and chemical characteristics of Oxisols and the parameters needed for geotechnical classification.

References

Nogami, J.S., and D.F. Villibor. 1981. A new classification for highway purposes. Brazilian Symposium of Tropical Soils in Engineering, Rio de Janeiro. (In Portuguese).

———. 1985. Additional considerations about a new geotechnical classification for tropical soils. First Intern. Conf. on Geomechanics in Tropical Lateritic and Saprolitic Soils, Brasilia.

Parsons, A.W., and B. Boden. 1979. The moisture condition test and its potential applications in earthworks. SR-1522. Transport and Road Res. Lab., United Kingdom.

Soils Survey Staff, SCS, USDA. 1975. Soil taxonomy: A basic system of soil classification for making and interpreting soil surveys. Agriculture Handbook no. 436. USDA. U.S. Govt. Printing Office, Washington, D.C.

THE ASSESSMENT OF CEMENT REQUIREMENT OF OXISOLS BY A PHYSICO-CHEMICAL METHOD[1]

F.J. Casanova and J.A. Ceratti[2]

Abstract

Portland cement is one of the most effective binders that can be used for the strengthening of soils. The usual tests for the determination of its content are laborious and time-consuming. In this paper, the authors describe a simple and rapid method, based on the electrical interaction between cement and soil particles, for assessing the optimum percentage of cement required for the stabilization of Oxisols. The method was applied to 30 samples of Brazilian Oxisols and the results are shown and discussed in the light of physico-chemical principles.

Civil engineering requires different types of construction materials as well as special machinery. Its use depends on enormous expenditures of labor and money. To minimize these expenditures, one must have progressive methods of construction, high quality labor, and stability and durability of the employed materials. One way to cut down costs and speed up the work is to use locally available materials, of which soils are the most widespread. The idea of using (stabilized) soil as material for construction was put forward more than 50 years ago, and since then has been given a theoretical basis and confirmed in practice.

Soil stabilization by any method is not an end in itself, but has been one of the most rational and economic methods of building, especially in regions which do not have any stony material. The ultimate aim of the process by any method whatsoever is to produce new materials having the required strength and deformation properties, being stable and durable under alternating regimes of wetting and drying. To date, soil stabilization has long since crossed the limits of road construction. Collective experiments and the results of many investigations in this field, but for different purposes, have been generalized all over the world. At present, soils different in origin and composition are used as the starting material, and nearly all of them, except those containing high mica and organic matter (humus), respond well to stabilization with cement, resulting in the development of high-strength mixes.

The usual tests for the determination of cement content for satisfactory stabilization are laborious and time-consuming, requiring special equipment and trained people. Rapid methods have been proposed, but all of them have drawbacks, which led us to study and introduce a simple and rapid physico-chemical method originally proposed by the Central Road Research Institute of India (Chadda 1971). The method in question takes advantage of the electrical interaction of cement and clay particles, which brings about complex physico-chemical changes in the soil-cement mixtures. It would also be interesting to note how useful the test can be as a complementary approach to study the ordering of constituents in sesquioxidic soils (i.e., the clay oxides association).

Scientific Basis of Soil Strengthening

The basis of the soil stabilization method relies upon the principle of active and proper use of surface properties of soils. These depend mainly on the colloidal chemical composition and the state of their finely dispersed portions, the extent of the dispersion and dose, and the proportion of binders and other agents added to the soil. For a deep understanding of the process of soil strengthening, one must thoroughly study their composition, properties, genesis, and conditions of location. But these alone are not sufficient, and the knowledge and experience gained in the field of binders, soil physics, and chemistry, as well as of structural mechanics must also be taken into account.

Soils are very complex because their structural properties and suitability as a basic raw material may change sharply depending on the ratio and composition of their constituent phases (solid, liquid, and gaseous). The study of soil behavior under the action of loads for different proportions of binders shows that in a number of their important properties and capacity for physico-chemical reactions coherent soils must be considered as colloidal chemical systems. The extent to which these colloidal properties are expressed depends on the nature, composition, and content of clayey particles in the soil. Origin

[1] Work supported under CNPq research grant no. 30.0019/82-EC-07.

[2] Authors are Researchers at Soil Mechanics Laboratory, Department of Civil Engineering, COPPE/UFRJ, Rio de Janeiro, Brazil.

of the soil, its mineralogical and chemical composition, as well as surrounding natural conditions, are the decisive factors determining the degree of its fineness and the colloidal properties manifested by it. Mineralogical composition plays a major role in the selection and development of the most effective soil-strengthening methods.

In very fine soils, unlike concrete, the zone of direct contact of a particle surface with a binder or other material is relatively large and is proportional to the total surface of the particles. Therefore, physico-chemical and chemical interactions in soil play a decisive role and are responsible for the nature and strength of a stabilized soil structure.

Soils in the wet state are dispersed systems in which the mineral particles constitute the dispersed phase and the solution or water filling the pores among the particles form the dispersion medium. It is well known that any dispersed system possesses a definite surface energy measurable by multiplying the surface tension existing at the interface of the two phases (solid and liquid) by the total surface area of all the particles in the dispersed phase. As the surface tension of water and soil solutions have a relatively low value, the surface energy of soil is determined mainly by the total (specific) surface of its particles. Surface energy of soils of different composition is very important because it serves as the source of energy for the various processes occurring in soils and clays. The large specific surface and therefore surface energy acquires an exclusively important significance in soil stabilization and serves as an important factor in regulating the processes of interaction and desired structure formation. Change of specific surface and surface energy produces sharp change in many properties of soils, including, of course, their physico-mechanical properties.

Exchange reactions in soils and composition of absorbed cations also cause sharp changes in the structure of soils, their strength and physical properties, important from the construction point of view. Processes of coagulation and their related phenomena of physical adsorption, together with chemical adsorption, play a very important role in the process of reaction between the finely dispersed portion of soil and the stabilizing agent. A skillful application of the achievements made in the field of chemistry and physico-chemistry of soils and clays undoubtedly enable us to effectively transform the soil into valuable construction material with high strength indexes by adding small amounts of different active substances. Therefore, use of the properties inherent to these dispersed colloidal systems is the theoretical pivot of any soil stabilization method, since after taking these factors into account one can hope for radical qualitative and quantitative changes in soil properties in the desired direction.

The purpose of the work reported here is to show how the physico-chemical properties of Oxisols can be put to good use, in order to obtain not only technological but also scientific information.

Materials and Methods

Experiments were carried out in the laboratory with 30 samples of Oxisols ranging from highly plastic to moderately plastic which were collected in different parts of Brazil. Pure clay minerals were also used.

The soils were air dried, pulverized, and passed through a standard no. 10 sieve. The quantity of each soil taken for analysis was 20 g, or 10 g in the case of the clay minerals. The samples were then mixed with increasing percentages of cement and the mixtures shaken with 100 ml of distilled water in 250 ml graduated stoppered cylinders. The volumes of the soil-cement sediment at different intervals of time, were recorded after shaking the suspensions and allowing them to settle for a period of not less than 2 hours. The volumetric changes produced were calculated from the volumes of the soil-cement suspensions at time $t = tn$ and $t = to$, both read 2 hours after shaking the mixtures. This is shown graphically in Figures 1 to 7. The description of the methodology herein presented is basically that proposed by Chadda (1971), except that the volume readings are kept until no further change in volume is visible, or until it starts decreasing.

The minimum period required to complete the soil-cement interaction to form a stable suspension varies from 3 to 7 days when moderately plastic soils are used, but it can reach 15 days or even more for highly plastic soils.

The temperature must be held constant throughout the testing.

Discussion

A critical examination of the data in Tables 1 to 3 shows clearly that the addition of cement produces an increase in the volume of the sediments. This increase in volume continues up to a certain concentration of cement, and thereafter no perceivable change or sometimes a more or less pronounced reduction is observed, probably due to the aggregation of particles.

Volumetric changes produced in the soil-cement suspensions were calculated for all 30 of the Oxisol samples and are shown graphically in Figures 1 to 5. From the graphs, the minimum percentage of cement required for the stabilization can be conveniently determined. Any addition of cement beyond this point may add to the overall strength of the compacted specimen, but it may not undergo any physico-chemical reaction with soil particles (Chadda 1971). As was expected, kaolinite is the least reactive of the clay minerals (2%w of cement) followed by illite (5%w of cement) and montmorillonite (15 to 20%w of cement); this last is by far the most reactive. It is noteworthy that the montmorillonites were already calcium saturated, which discards cation exchange as the operational mechanism leading to the volumetric changes. Another important feature is related to the percentage of the volumetric changes obtained with the pure clay minerals and with the Oxisols. It is about 35 percent for a well-crystallized kaolinite, a little bit less than 50 percent for illite, and exactly 60 and 70 percent for montmorillonites. These results demonstrate the sharpness of the physico-chemical behavior of the clay minerals. On the other hand, the results for Oxisols were quite unusual, the free-swelling reaching in some cases more than 200 percent. Some of them need 12 percent of cement and sample no. 23 about 15 percent, as much as the Arizona montmorillonite.

We tried to interpret the observed behavior as due to the

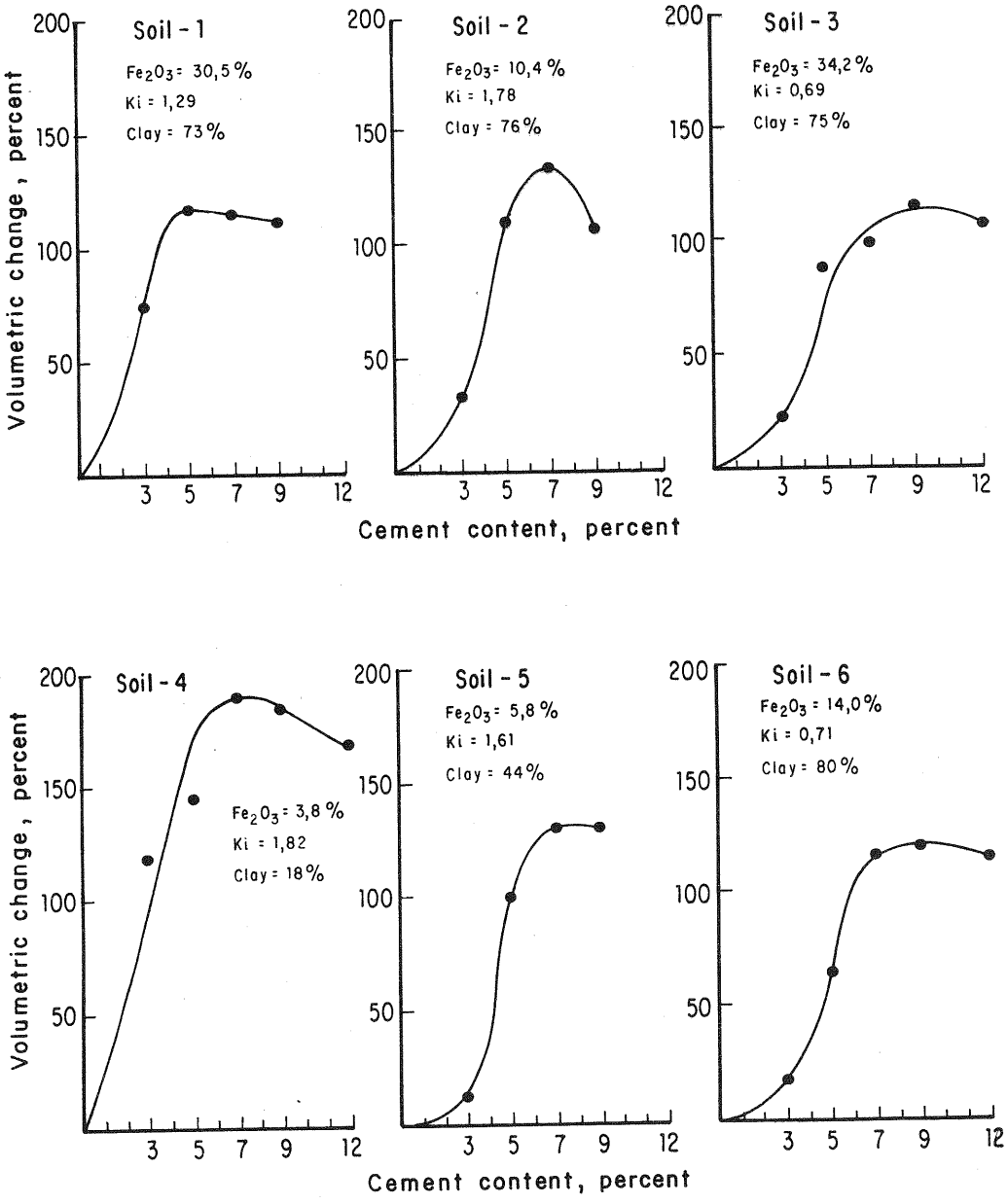


Fig. 1. Volumetric changes in soil-cement mixtures' sediments.

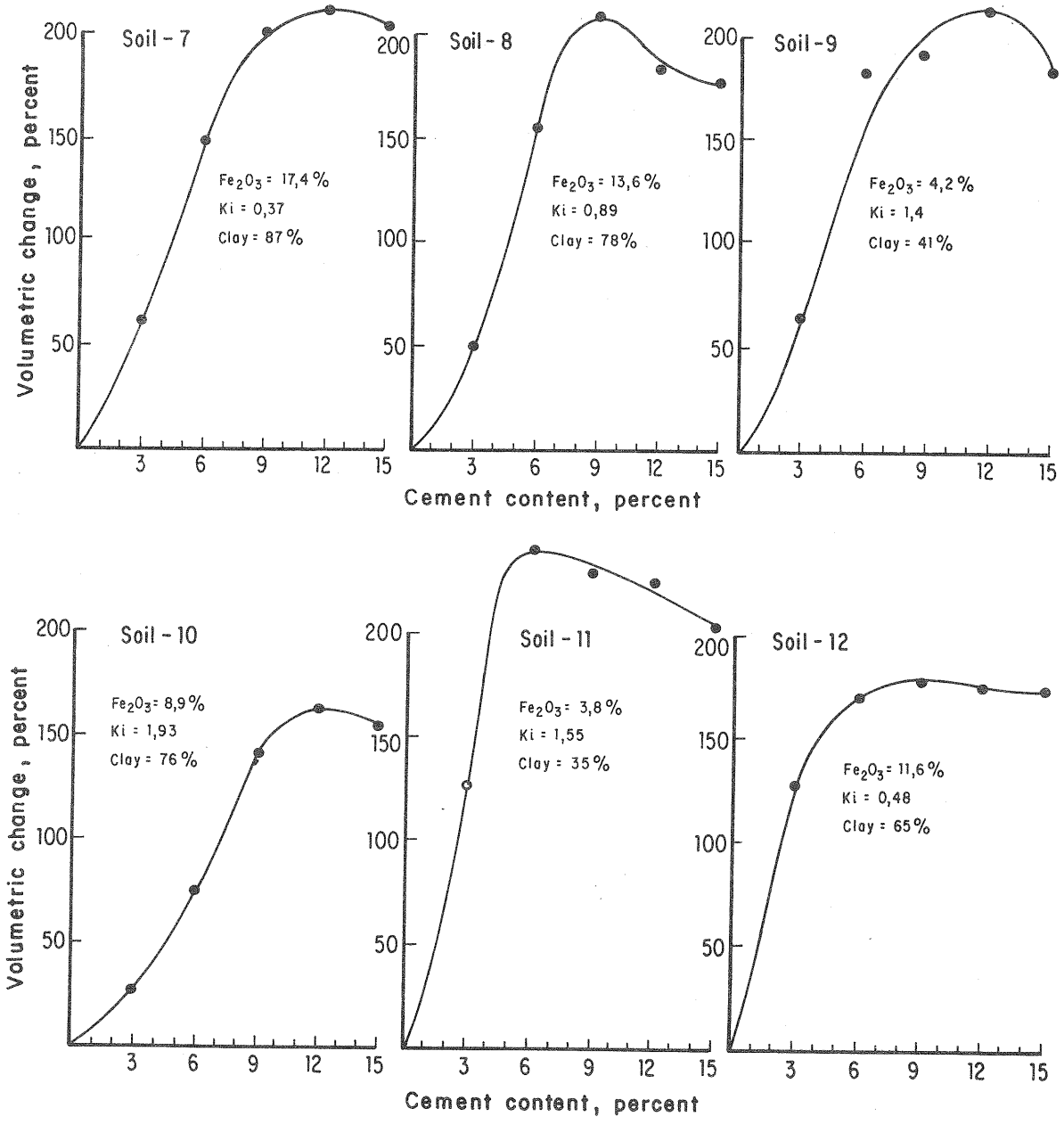


Fig. 2. Volumetric changes in soil-cement mixtures' sediments.

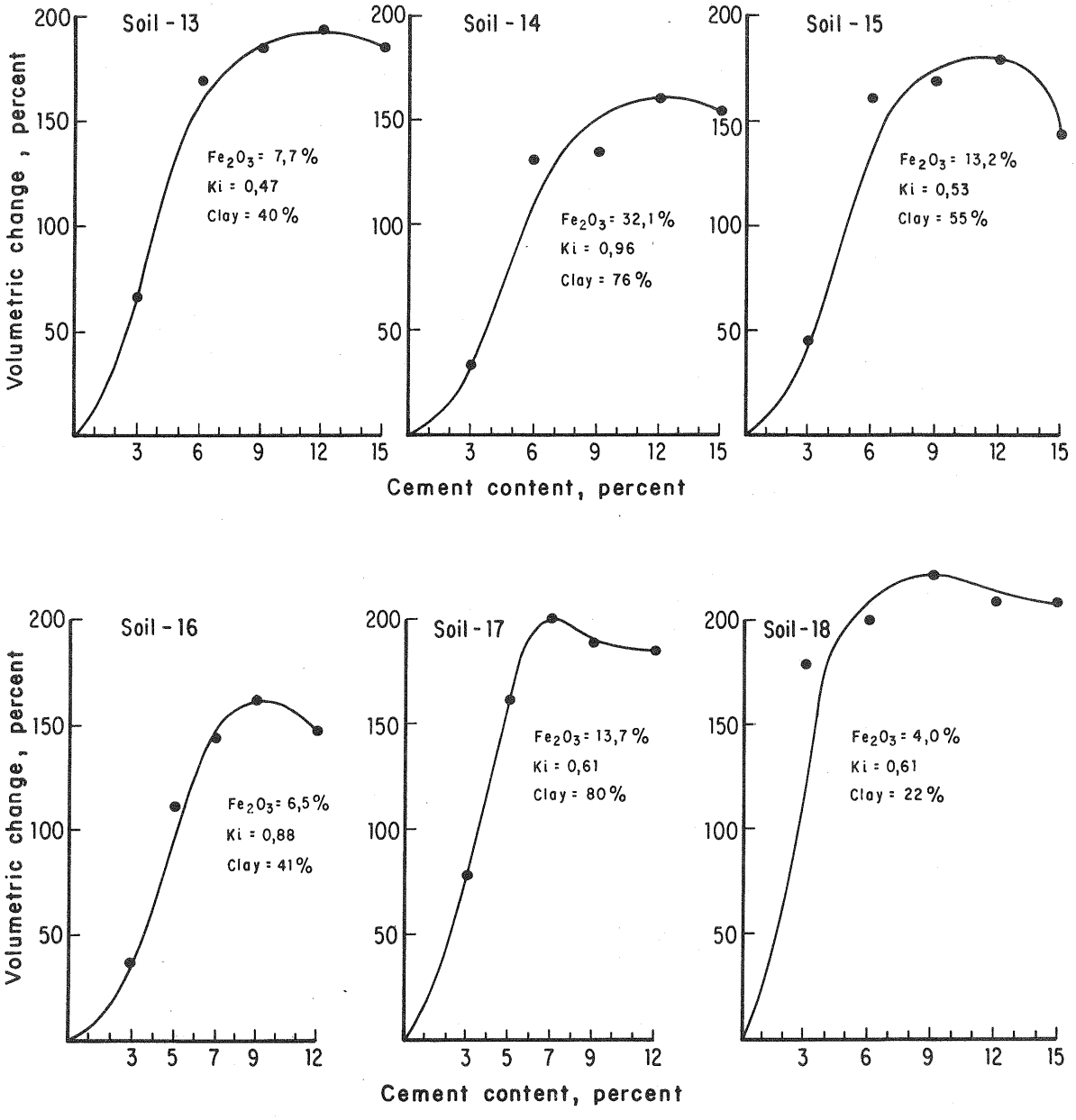


Fig. 3. Volumetric changes in soil-cement mixtures' sediments.

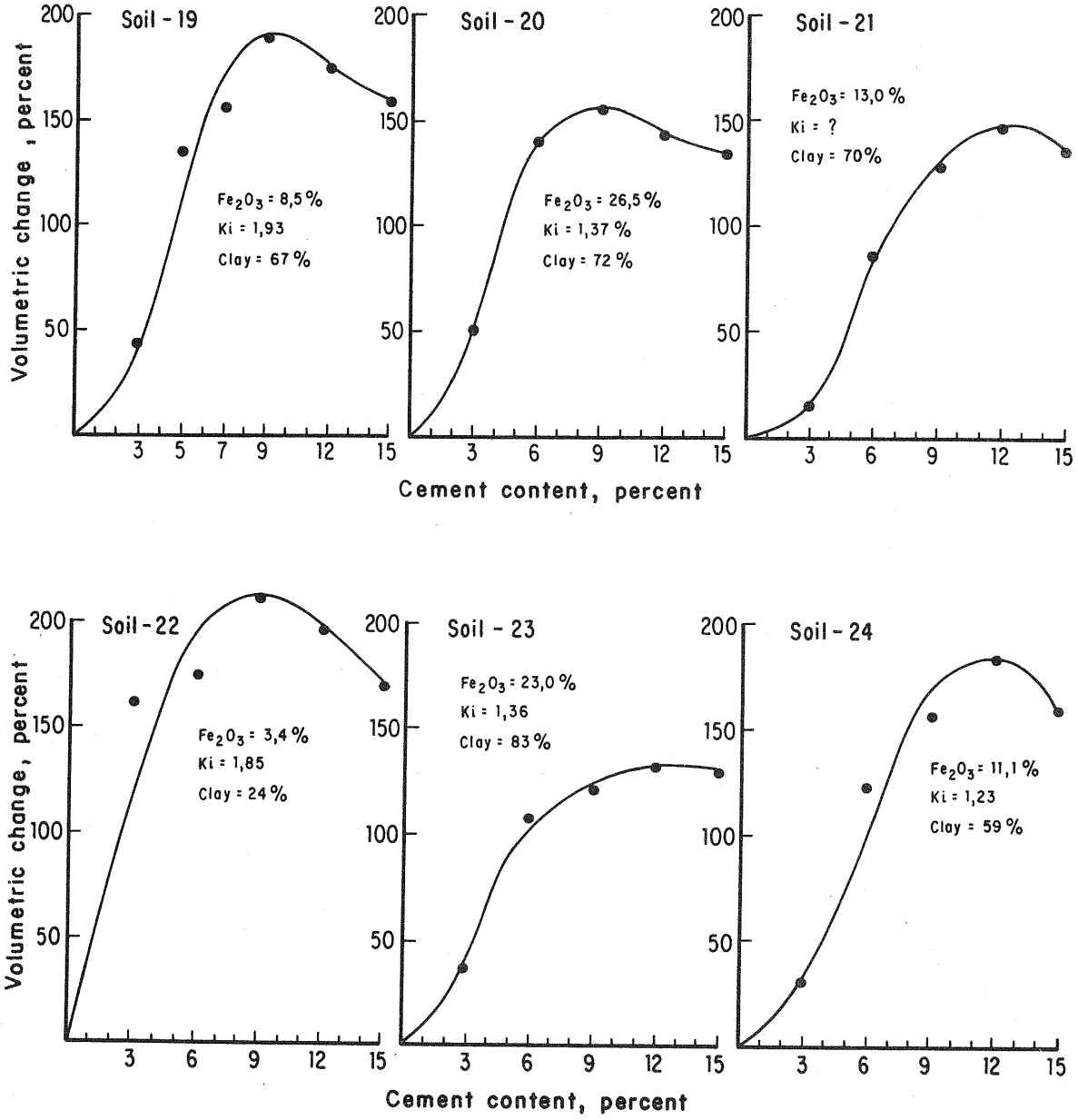


Fig. 4. Volumetric changes in soil-cement mixtures' sediments.

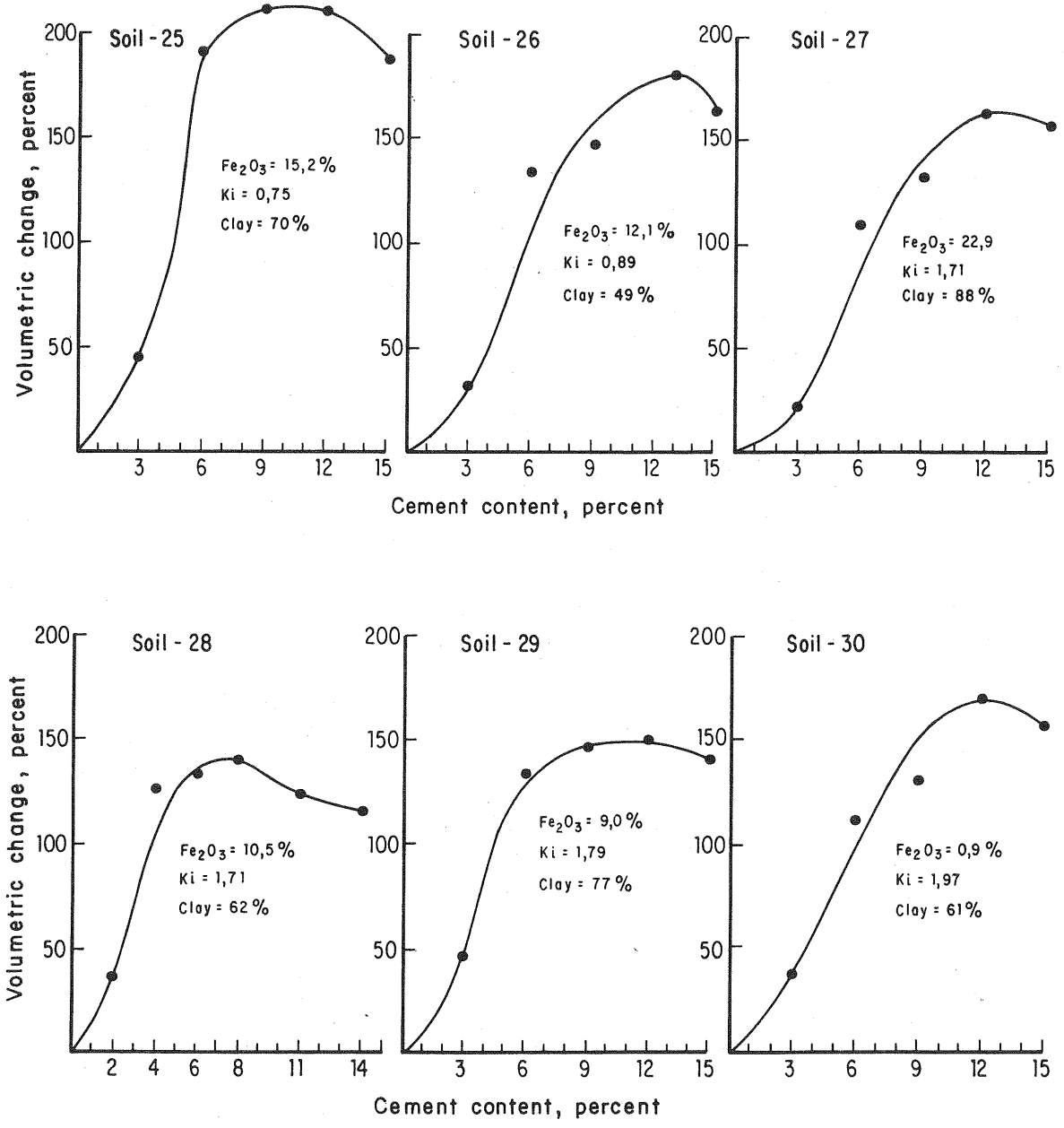


Fig. 5. Volumetric changes in soil-cement mixtures' sediments.

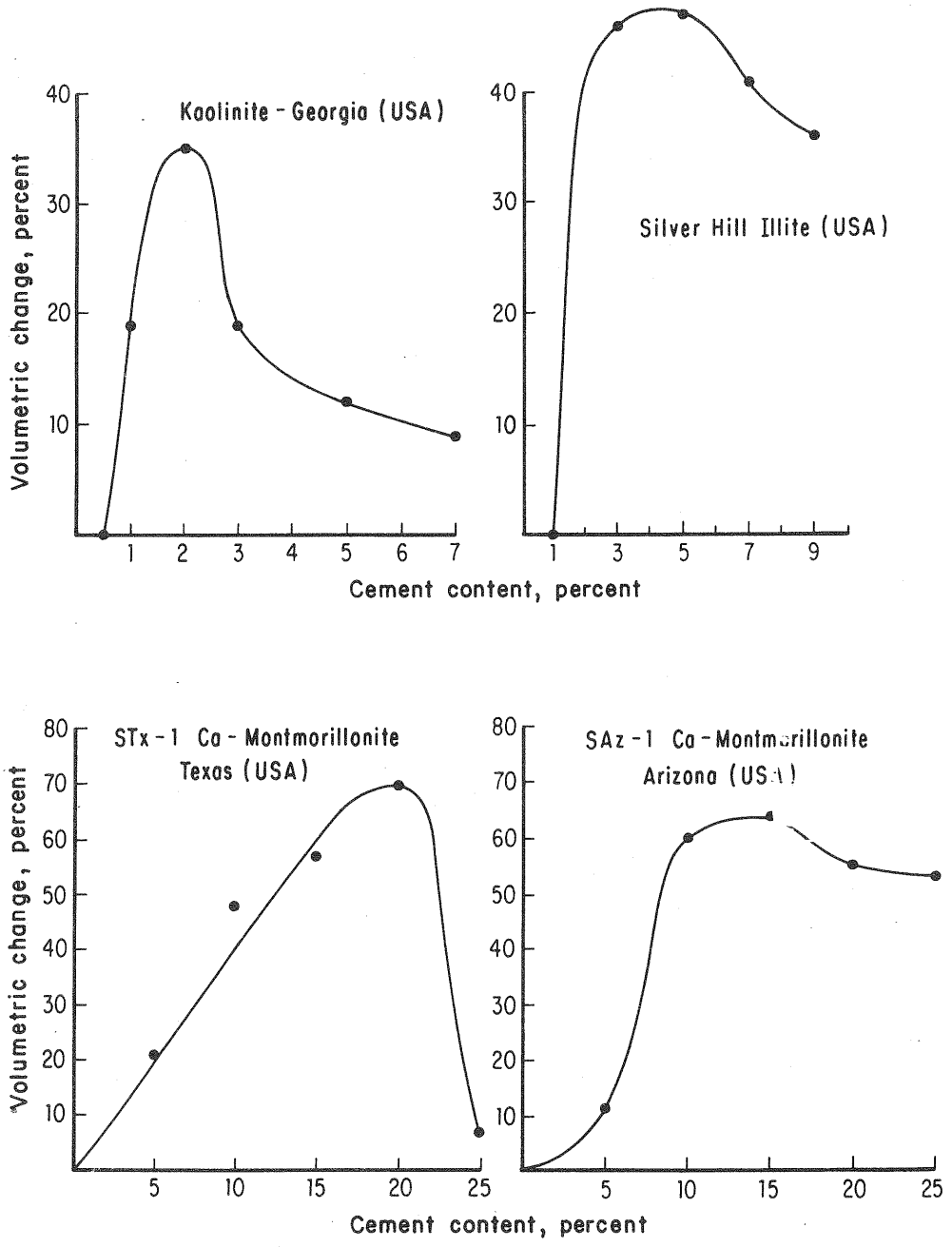
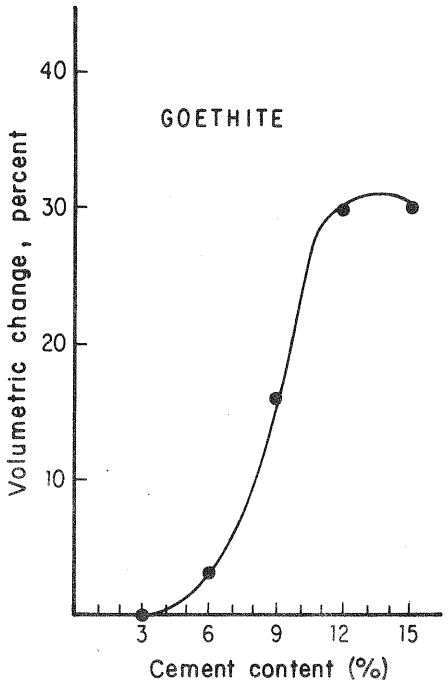
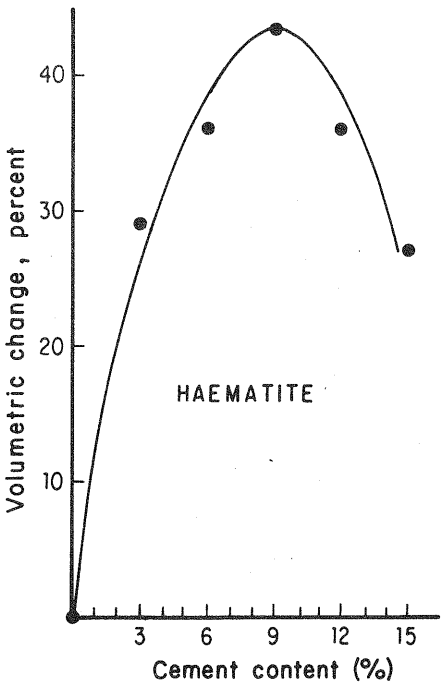


Fig. 6. Volumetric changes in clay minerals-cement mixtures' sediments.



Cement %	Time elapsed (days)				ΔV %
	0	3	6	9	
3	44	44	42	40	0
6	64	66	63	64	3
9	62	72	69	68	16
12	63	82	82	77	30
15	60	78	78	78	30



Cement %	Time elapsed (days)				ΔV %
	0	3	6	9	
3	48	61	62	62	29
6	70	93	95	95	36
9	46	66	68	66	48
12	66	90	88	–	36
15	74	92	94	–	27

Fig. 7. Volumetric changes in iron-oxides cement mixtures' sediments.

Table 1. Volumetric Readings (cm^3) and Maximal Volumetric Changes (%) of the Sedimented Soil-Cement Mixes

Soil Number	Cement (%)	Time elapsed (days) 0	1	3	7	10	Volumetric change (%)
7	3	26	36	42	42		61
(850684)	6	25	40	62	60		148
	9	26	48	78	74		200
	12	27	56	84	74		211
	15	27	62	82	75		203
8	3	20	24	30	30	30	50
(850739)	6	22	28	39	56	56	154
	9	24	42	68	74	72	208
	12	24	43	68	64		183
	15	26	51	72	65		177
9	3	22	30		36	35	64
(850610)	6	22	37		62	60	184
	9	24	45		70	64	192
	12	23	48		72	65	213
	15	24	52		68	67	183
11	3	22	30	42	50	50	127
(850626)	6	22	43	64	75	72	240
	9	24	52	75	79	74	229
	12	24	56	75	78	75	225
	15	27	56	77	82	74	203
17	3	27	35	48	48	47	78
(850747)	5	28	42	68	73	67	161
	7	26	44	74	78	71	200
	9	26	49	78	75		189
	12	29	57	83	74		186

Table 2. Volumetric Readings (cm^3) and Maximal Volumetric Changes (%) of the Sedimented Soil-Cement Mixes

Soil number	Cement (%)	Time elapsed (days) 0	1	3	7	10	Volumetric change (%)
18	3	18	40	50	50	48	178
(850676)	6	18	51	54	52	50	200
	9	19	61	60	60	56	221
	12	22	68	65	62	60	209
	15	21	68	64	63	63	208
4	3	22	26	32	48	46	118
(850699)	5	22	36	54	54	54	145
	7	20	37	56	58	55	190
	9	20	38	56	57	55	185
	12	22	37	57	59	55	168
22	3	20	30		52	52	160
(840392)	6	22	40		60	59	173
	9	20	42		62	62	210
	12	21	44		62	62	195
	15	26	50		70	68	169
25	3	24	35	34	33	32	46
(840616)	6	24	60	70	68	62	192
	9	25	78	72	70	65	212
	12	25	78	71	70	64	212
	15	26	75	72	69	65	188
KGa-1	0.5	52	51	52	48		0
Kaolinite	1	80	79	95	92		19
(Georgia)	2	62	84	84	84		35
	3	84	84	100	92		19
	5	91	90	102	98		12
	7	90	90	98	94		9

Table 3. Volumetric Readings (cm^3) and Maximal Volumetric Changes (%) of the Sedimented Soil-Cement Mixes

Soil number	Cement (%)	Time elapsed (days) 0	3	6	9	12	Volumetric change (%)
S. Hill Illite	1	34	34	32			0
	3	24	34	35	35		46
	5	25	35	37	36		48
	7	27	38	38	38		41
	9	25	34	33	33		36
STx-1 Smectite (Texas)	5	48	58	54	54		21
	10	46	68	66	66		48
	15	42	66	66	65		57
	20	46	74	78	74		70
	25	41	72	78	75		7
SAz-1 Smectite (Arizona)	5	45	46	48	50	48	11
	10	55	88	88	81		60
	15	55	87	90	82		64
	20	58	90	88	80		55
	25	59	90	90	80		53
15 (850729)	3	22	27	32	32	31	45
	6	23	32	56	60	60	161
	9	27	46	73	61		170
	12	25	46	70	65		180
	15	28	50	68	64		143
16 (850714)	3	27	37	36	35		37
	5	27	56	57	56		111
	7	28	68	66	60		143
	9	26	68	68	60		161
	12	30	74	70			147

action of the sesquioxides of iron and aluminium. As is known, iron and aluminium oxides surfaces are hydroxylated and derive their charge from the adsorption of the potential determining ions H^+ and OH^-. They can have specific surfaces in the order of 100-500 m^2/g and are net negatively charged at the high pH values encountered in the environment of the test (11.5-12.6). Anions are also able to adsorb onto oxides surfaces when the surface charge is zero, or even negative. Particularly, we share the opinion that complex hydrated calcium silicates and aluminates could be adsorbed by oxides surfaces, contributing to the observed changes. Even so, we carried out some experiments with pure and finely divided goethite and hematite and as indicated in Figure 7, these iron minerals seem not to be responsible for those elevated volumetric variations found for the Oxisols.

According to Figure 7 it is possible to conclude that they are essentially due to the interaction of clay particles with the added cement and its hydration products, including lime.

It is also very important to emphasize the apparent nonexistence in any of the analyzed Oxisols of an inequivocal association between the clay (kaolinitic) particles and those of free sesquioxides, which undoubtedly would lead to a net loss of reactive surface and consequently to lower volumetric variations.

But it seems that the high cement contents that were found are essentially due to the free sesquioxides, especially goethite and perhaps gibbsite.

Diffuse double-layer interaction cannot account for the observed behavior, because its formation is slight for kaolinite and sesquioxides. Moreover, it is clear that the combined action of cement and lime more profoundly alters the properties of the clay than can be explained by the flocculation effects of electrolytes on the DDL. Contrariwise, the removal of lime and electrolytes from pore solution after a few hours causes very low concentrations of electrolytes, and even so, the initially formed flocs persist and become, if anything, more pronounced and stable with the lapse of time (Diamond and Kinter 1966). The presence of small amounts of montmorillonite and amorphous material cannot be disregarded as another possibility, but we think this is not the case.

On the basis of the experimental results, including visual inspection, it is possible to elaborate a hypothesis. First, the whole process can be broken down into two broad phases, a primary and a secondary. The first includes hydrolysis of cement in the course of which lime is generated (*in statu nascendi*), the pH increases to about 12, and the mobility of the liquid phase is lowered. The degree of saturation of this multicomponent aqueous clay-lime suspension depends on the amount of cement and clay and type of the clay minerals, but after some minutes it is already possible to note a strong flocculation. In the second phase, the cementing substances are formed over the surfaces of clay particles or in their immediate vicinity causing the flocculating clay grains to be bonded at the contact points. Chadda (1954) has shown that in a soil-cement mixture cement particles behave as though electrically charged, their presence increasing the electrical conductivity of the mass.

Still stronger bonds may be created between the hydrating cement and clay particles coating the cement grains. It is possible, furthermore, that the particles may be integrated by epitaxy due to similar structure of the clay minerals and certain cement hydration products.

The final result of all these interactions is a sharp increase in the shear resistance at interfloc level, which results in the substantial volumetric variations when the sample is suspended in water. The effects cease as soon as the concentration of cement reaches the optimum limit required to produce a stable suspension where the shear resistance is maximum.

Conclusions

No matter what the reasons, the physico-chemical interaction between cement and soil particles in an aqueous suspension enables the simple and rapid determination of the optimum percentage of cement to stabilize soils, dispensing with trained technicians and special apparatus. Moreover, it can easily be incorporated into the routine of any laboratory and may be profitable in soil taxonomy.

Lastly, the authors would like to strongly recommend the continuance of the study, suggesting further study of the following points:

1. The role of free sesquioxides:
2. The testing of deferrated samples to appraise the role of the clay minerals kaolinite (poorly crystalline) and halloysite present in Oxisols; and
3. The types of structures that are formed before, after, and at the sharp region of the curve volumetric change (percent) versus cement content (percent).

Key for Identifying the Analyzed Soils (IInd, IIIrd RCC and VIIIth ISCW)

Lab. Number	SNLCS identification
S1	850661
S2	850632
S3	840733
S4	850699
S5	850760
S6	850753
S7	850684
S8	850739
S9	850610
S10	850639
S11	850626
S12	850692
S13	850670
S14	850655
S15	850729
S16	850714
S17	850747
S18	850676
S19	850619
S20	850706
S21	821709
S22	840392
S23	840080
S24	840446
S25	840616

Key continued...

Lab. Number	SNLCS indentification
S26	850720
S27	840073
S28	821548
S29	850646
S30	850766
S31	840089
S32	840529
S33	821489
S34	840067
S35	840099

References

Chadda, L.R. 1954. The rapid determination of cement in cement soil mixtures. *Indian Concrete Journal* 28:446-448.

—. 1971. A rapid method of assessing the cement requirement for the stabilization of soils. *Indian Concrete Journal* 45(7):298-314.

Diamond, S., and E.B. Kinter. 1966. Mechanisms of soil-lime stabilization: An interpretative review. *Public Roads* 33(12):260-265.

APPENDIX

OXISOL AMENDMENT

In 1977 the Soil Conservation Service established the International Committee on Oxisols (ICOMOX) to review the classification of Oxisols and make recommendations for changes. The work of ICOMOX was partly based on the outcome of another committee, the International Committee on Low Activity Clays (ICOMLAC). The concept of the "Kandic horizon" was developed by ICOMLAC and with this in place ICOMOX could then define the oxic horizon and the classes of the order.

The placement of soils with low activity clays (LAC) was a problem for many people working in the tropics. This relatively homogeneous group of soils was divided among several taxa in *Soil Taxonomy*. The presence of an argillic horizon was considered to be important and the definition of Oxisols excluded soils with argillic horizons. The performance of the LAC soils and many of their engineering properties, however, indicated their response was more similar to Oxisols than to Ultisols or Alfisols. After considerable testing, the concept of Oxisols was enlarged to include the LAC soils with more than 40 percent clay in the surface layers. This major conceptual change required revisions of the entire order of Oxisols. These revisions and corresponding changes in other taxa are presented in this amendment.

ICOMOX also considered other points of concern which users of *Soil Taxonomy* were encountering in the tropics. The concept of the Humox, the perudic soil moisture regime, the sombric horizon, plinthite, and the general structure of the taxa itself were tested. The data base of the National Soil Survey Laboratories proved very valuable for this purpose.

These amendments to *Soil Taxonomy* include the final proposal of ICOMOX. Those who have reviewed it, agree that the result is a major and significant improvement to *Soil Taxonomy*; but there are still a few minor areas which will need attention as more information becomes available. It is only through applying the system that its weaknesses become apparent and in turn will bring about changes in the future.

Oxic Horizon

The oxic horizon is intended to characterize a mineral subsurface horizon of sandy loam or finer particle-size with low cation exchange capacity and low weatherable mineral content. It is at least 30 cm (12 in.) thick. The clay-sized fraction is usually dominated by kaolinite with or without iron and aluminum oxyhydrates and with few or no other lattice silicate minerals except hydroxy-interlayered vermiculites. The silt and sand fraction of the oxic horizon is generally dominated by quartz with some other resistant minerals. Weatherable minerals which are potential sources of plant nutrients (K, Ca, Mg) may be present only if they do not exceed 10 percent of the 50-200 micron fraction. Rock fragments or lithorelicts may be present only if they are coated with sesquioxides or if the included weatherable minerals are completely altered.

A quantifiable cation exchange capacity limit is placed on the clay-sized fraction. Where dispersion is a problem, 3 x the percent water retained at 15 bar tension is used to estimate clay content. The apparent CEC, by the 1N NH4OAc pH7 method is equal to or less than 16 meq per 100 grams of clay and the effective CEC (ECEC) as determined by the sum of NH4OAc displaced bases plus 1N KCl extractable aluminum is equal to or less than 12 meq per 100 gram of clay. Since the determination of apparent clay CEC values involves dividing the soil CEC by the percent clay content insures that soil materials with low activity clay but with high organic matter content are excluded. The mineralogy and charge characteristics also exclude horizons containing significant quantities of short-range order minerals. The oxic horizon does not have andic soil properties.[1] Some oxic-like horizons may have high amounts of low charge illite, but they have more than 10 percent muscovite in the 50-200 micron fraction and are thus excluded from oxic horizons. This same criteria is expected to

[1] Andic soil properties are tentatively defined as soil materials meeting one or more of the following three requirements:

1. a. Acid oxalate extractable aluminum plus 1/2 acid oxalate extractable iron is 2.0 percent or more in the <2 mm fraction;
   b. Bulk density of the <2 mm fraction, measured at 1/3 bar water retention, is $\leq$0.90 g/cm^3; and
   c. Phosphate retention is more than 85 percent; or
2. a. More than 60 percent by volume of the whole soil is volcaniclastic material coarser than 2 mm; and
   b. Acid oxalate extractable aluminum plus 1/2 acid oxalate extractable iron is 0.40 percent or more in the <2 mm fraction; or
3. The 0.02 to 2.0 mm fraction is at least 30 percent of the <2 mm fraction and meets one of the following:
   a. If the <2 mm fraction has acid oxalate extractable aluminum plus

limit horizons containing much pyrophyllite, a mineral with practically no permanent charge, from oxic horizons.

The upper boundary of the oxic horizon is at 18 cm below the soil surface or the base of the Ap horizon, whichever is deeper, or at a deeper depth where the mineralogical and charge characteristics meet the requirements of the oxic horizon. Any increase in clay content at the upper boundary must be diffuse. The lower boundary is also defined by the mineralogical and charge requirements. In addition the presence of saprolite that has rock structure may define the lower boundary of an oxic horizon.

Significance to Soil Classification and Use

One important attribute of the oxic horizon is that it is almost devoid of primary weatherable minerals, thus further weathering will release few plant nutrients.[2]

Another important attribute is that in many soils with oxic horizons the clay content is relatively constant with depth indicating little or no clay mobility. This suggests a high order of stability in the clay fraction which has been attributed to cementation by sesquioxides. Oxic horizons usually have only traces of water dispersible clay, if their net charge is near zero, but this characteristic is also shared by some other horizons.

A third attribute of most oxic horizons is the stable fine and very fine granular structure and thus the friable and porous nature of the horizon. Bulk densities are generally low, often near 1 gm/cm^3 in fine and very fine particle size classes. Macrostructure may be angular or subangular blocky, but the grade of blocky structure is generally weak.

These and other attributes directly or indirectly influence the performance of soils containing oxic horizons. The very low cation exchange capacity is an important consideration in soil management. In addition, some oxic horizons have a high capacity to adsorb anions and make some, especially phosphates, unavailable to plants. Large amounts of phosphate may need to be added as an initial amendment to overcome the fixation capacity. Cations may need to be added frequently and in small amounts to compensate for leaching loss. The low CEC, where dominated by exchangeable Al, is often an advantage in that it only takes small amounts of basic cations to increase the base saturation percentage. Further, the ease with which basic cations are leached makes the chemical deepening of the root zone feasible via continued lime or gypsum applications.

Although oxic horizons often contain high amounts of clay, their tendency to form a strong grade of very fine and fine granular structure may give them characteristics similar to sands. They have low available water holding capacities because most of the pores are either very large, between the granules, and thus do not retain water against the forces of gravity; or are very small, within the granules, and retain water at too great a tension for plants to extract. Plants may show moisture stress after only a week without rain. Although the low available water holding capacity is most limiting to shallow-rooted plants, yields of deep-rooted trees such as rubber and oil-palm are also known to decline due to moisture stress.

It is considered desirable to identify soil horizons that are nearly mineralogically sterile due to being unable to supply basic cations from the continued weathering of primary minerals. As such, the oxic horizon can be considered a counterpart of the cambic horizon which has a greater content of weatherable minerals. As with the cambic horizon, the exclusion of certain coarse particle-size classes is admittedly arbitrary, but in the case of the oxic horizon it is considered necessary to preserve the uniformity of the horizon with materials that have enough clay to reflect the low CEC nature and structural tendencies.

When considered in the vertical sequence of a soil profile, an increase in clay content with depth may be associated with increased grades of blocky structure not common to the central concept of the oxic horizon. Where the clay content increase underlies coarser particle-size surface horizons, a small increase in the amount of clay appears more significant to moisture relationships than when the surface horizon is clayey in texture. This is especially true in the interpretation of soils that have been subjected to accelerated erosion. Where coarser textured surfaces erode in cultivated areas and finer textured subsoil material becomes incorporated into the plow layer, spatial heterogeneity with respect to plow layer characteristics develops. Thus, it is considered that this pattern is more closely related to soils that have argillic horizons than those that do not have rather abrupt increases in clay content with depth. Therefore, some horizons, with many oxic horizon properties such as low CEC and absences of weatherable minerals, will classify as kandic horizons and may be part of Ultisols and Alfisols rather than Oxisols if there is less than 40 percent clay in the upper 18 cm.

The identification of an oxic horizon in most soils requires that the clay content increase with depth not exceed 1.2 times the clay content in the overlying horizons within a vertical distance of 15 cm (gradual boundary limit) if the surface horizon contains 20 percent to 40 percent clay. If the surface horizon contains more than 40 percent clay an oxic horizon must have less than an 8 percent absolute clay content increase within a 15 cm depth. If the surface horizon contains less than 20 percent clay, the oxic horizon must have an absolute clay content increase less than 4 percent in a vertical distance of 15 cm. This is admittedly an arbitrary limit, but one that lends itself

---

1/2 acid oxalate extractable iron of 0.40 percent, there is at least 30 percent volcanic glass in the 0.02 to 2.0 mm fraction;

b. If the <2 mm fraction has acid oxalate extractable aluminum plus 1/2 acid oxalate extractable iron of 2.0 percent or more, there is at least 5 percent volcanic glass in the 0.02 to 2.0 mm fraction; or

c. If the <2 mm fraction has acid oxalate extractable aluminum plus 1/2 acid oxalate extractable iron of between 0.40 percent and 2.0 percent, there is a proportional content of volcanic glass in the 0.02 to 2.0 mm fraction between 5 and 30 percent.

[2] The 10 percent weatherable limit approximates a reserve of only 25 meq Na+, K+, Ca++, Mg++ in the primary minerals (Herbillon, pers. comm.).

to consistent identification in the field and rather easy verification by laboratory techniques.

Genesis

Oxic horizons are generally in soils on very old stable geomorphic surfaces. They may occur in soils on younger surfaces if the parent rock is easily weatherable, such as basalts or serpentinites, or if the material is preweathered. Oxic horizons are not common in soils on steep slopes where rejuvenation of the soil takes place through erosion, truncation, or lateral flow of base-enriched subsurface water.

Soils on old geomorphic surfaces which may date to mid- or late-Tertiary have generally been reworked. Many of the surficial deposits are preweathered, transported over short distances, and deposited, perhaps several times. After deposition and stabilization of the landscape, weathering and soil formation starts anew. Stone lines composed of quartz or petroplinthite are common in some of these soils if the original material could supply the stones. Quartz veins may be traced through the saprolite but end abruptly or taper off at the stone line, indicating that the material above the stone line has been transported. Particle-size sorting may take place during transport and deposition and lithologic discontinuities are common, although materials are very similar.

Earlier it was stated that the parent materials may be strongly preweathered. Postdepositional weathering continues, and the intensity is a function of the environmental conditions. In aridic climates, this is minimal, and it is supposed that the oxic properties were attained during previous, more humid phases of the climate, in poorly drained environments, or weathered in transport.

In more easily weatherable parent materials and when climatic conditions are favorable, oxic horizons form in soils on young surfaces and over a relatively short period. Leaching and desilicification are the most important processes, resulting in a deep sola. The weathering front moves rapidly down the soil and on many basic and ultrabasic rocks there is no real saprolitic zone as the oxic horizon rests on rock or on a thin weathering crust. Primary minerals are altered to kaolinite, and simultaneously or at a later stage, gibbsite and goethite also accumulate. Accidents of nature may occur leaving behind some partially weathered rock or mineral fragments in the oxic horizon. These are generally rare and if present are frequently coated with sesquioxides. Pseudomorphs of olivine and augite may be present in some oxic horizons, but these are not considered as indicators of lack of weathering.

On stable surfaces, time has permitted the homogenization of the soil material by pedoturbation processes. It is also possible that the active pedoturbation has disrupted and assimilated any evidence of lessivage such as clay skins. Consequently, most oxic horizons are uniform in color, texture, and other mineralogic-chemical properties to great depths in the soil. The pedoturbation processes have also disrupted any rock structure. In some saprolites, weathering results in a pseudomorphic alteration of feldspar phenocrysts to gibbsite, the aggregates of which retain the original fabric. Mineralogically-chemically, the saprolite may meet the requirements of an oxic horizon, but is not considered an oxic horizon if it retains more than 5 percent rock fabric and if the secondary minerals are pseudomorphs after the primary minerals. In this respect, booklets of kaolinite formed through the pseudomorphic alteration of biotite are considered as weatherable minerals. In an oxic horizon, these are disrupted and assimilated in the soil material.

Soils with oxic horizons frequently occupy the upper part of the landscape. The silica potential is also very low in such soils, having a net leaching environment, so that there is no possibility for synthesis of 2:1 clay minerals. Even in the wet soils with oxic horizons, the recharging water may be so low in bases and silica, that despite the high water table, the soil is continuously flushed and leached. Isohyperthermic soil temperature regimes and udic or perudic soil moisture regimes are often considered optimal for oxic horizon formation. However, soils with oxic horizons are common in areas with ustic soil moisture regimes or with isothermic soil temperature regimes but are rare in areas with aridic soil moisture regimes and isomesic soil temperature regimes. Some oxic horizons are present in non-iso soil temperature regimes and, although paleoclimatic factors have been attributed to their formation, parent material is also probably a major contributor.

Summary of Oxic Horizon Properties

In summary, the oxic horizon is a subsurface horizon that:

1. Is at least 30 cm thick;
2. Has a particle-size of sandy loam or finer in the fine earth fraction;
3. Has a fine earth fraction (<2 mm) that has an apparent ECEC (NH4OAc bases plus 1N KCl extractable Al/ percent clay) equal to or less than 12 meq per 100 g clay and has an apparent CEC pH7 (NH4OAc CEC/ percent clay) equal to or less than 16 meq/100 g clay (measured clay or 3 x 15 bar water, whichever is greater but less than 100);
4. Does not have as much as 10 percent weatherable minerals in the 50-200 micron faction;
5. Has a diffuse upper particle-size boundary (i.e., <1.2 times clay content increase within a vertical distance of 15 cm if the surface horizon contains 20-40 percent clay; less than 4 percent absolute clay content increase if the surface contains <20 percent clay; <8 percent absolute if the surface contains >40 percent clay);
6. Does not have andic soil properties[3];
7. Has less than 5 percent by volume that shows rock structure unless the lithorelicts containing weatherable minerals are coated with sesquioxides.

Oxisols

Oxisols (plate 4D) are reddish, yellowish, or grayish colored soils. They are most common on the gentle slopes of geologically old surfaces in tropical and subtropical regions. Their profiles are distinctive because of the lack of obvious horizons. Their surface horizons are usually somewhat darker

[3] See footnote 1.

in color than the subsoil, but the transition of subsoil features is gradual.

Oxisols consist mainly of quartz, kaolinite, oxides, and organic matter. Both the structure and "feel" of Oxisols are deceptive. Upon first examination they appear structureless and feel like a loamy particle-size. While some are loamy or even coarser, many are extremely clayey, but that clay is aggregated in a strong grade of fine and very fine granular structure. To obtain a true "feel" of the fine texture, a wet sample must be worked for several minutes in the hands to break down the sandy-feeling, granular structure. The strong granular structure apparently causes most Oxisols to have a much more rapid permeability than would be predicted by the particle-size distribution class. Although compaction and reduction in permeability can be caused by cultivation, they are extremely resistant to compaction and so free draining that cultivation can take place soon after rain without puddling.

Oxisols are present in every soil moisture regime from aridic to perudic and aquic. Natural vegetation ranges from tropical rain forests to desert savannas. The lack of a unifying climatic factor throughout their geographic distribution indicates that their formation is genetically controlled by parent material parameters. As part of the definition, they are limited to very low cation exchange capacities and weatherable mineral contents. They are present over many kinds of geologic bedrock but upon close examination, often to great depth, there is evidence that the material from which the soil forms has been transported. Where the material is not clearly transported, formation is most common in mafic rock.

Although many Oxisols are extremely infertile, there are some that have small but adequate supplies of nutrients and are immediately productive when cultivated. The reserves of plant nutrients even in the most fertile Oxisols are not great and to sustain high yields fertilizers and lime are needed after only a few years of cultivation. In most of the Oxisols, fertilizers are needed for the first crop unless enough fertility for one or two crops is available from the ash derived from burning the natural vegetation. Phosphorus is generally the most restrictive plant nutrient, mainly because of the tendency for the clay and oxide rich surface horizon to fix large amounts of fertilizer phosphorus in an unavailable form. However, once this capacity to fix the phosphate has been overcome by an initial application, there is no further fixation problem and annual fertilizer rates are no higher than for other soils. Because of the initial expense of fertilization, Oxisols are cultivated extensively only where modern agronomic techniques are sustainable by an infrastructure of agrobusiness. In primitive, shifting cultivation they are used only if they naturally support a large biomass to yield a large volume of ash upon burning.

Road building and other engineering practices are relatively easy in most Oxisols because of the physical stability of the clay. There is little silt in most Oxisols, thus they have an extremely low available water holding capacity. Soil organic matter contents are usually much higher than indicated by the soil color. This may be due to red staining of the associated iron oxides. Frequently this organic matter is very stable, infertile humus, and is slow to decompose.

The most extensive areas of Oxisols are on the interior plateaus of South America, the lower portion of the Amazon basin, significant portions of the central African basin and important areas in Asia, Australia, and several tropical and subtropical islands.

Definition

Oxisols are mineral soils that

1. Meet one of these two requirements:
   a. Have an oxic horizon with its upper boundary within 150 cm of the soil surface and do not have a clay content increase necessary to define the upper boundary of a kandic horizon within a depth of 150 cm; or
   b. Have 40 percent or more clay in the surface 18 cm, after mixing, and, within 150 cm of the soil surface, either an oxic horizon or a kandic horizon that meets the weatherable mineral requirements of an oxic horizon; and
2. Do not have a spodic horizon.

Key to Suborders

CA. Oxisols that are either saturated with water within 30 cm of the mineral soil surface 30 days per year in most years or artificially drained, and have one or more of the following:

1. a histic epipedon;
2. if faintly mottled or not mottled within 50 cm of the soil surface, an epipedon that has a moist color value less than 3.5 and chroma of 2 or less immediately below the epipedon; or
3. if there are distinct or prominent mottles within 50 cm of the soil surface, a chroma of 3 or less or a hue of 2.5Y or yellower in 50 percent or more of the horizon immediately below the epipedon.

Aquox, p.

CB. Other Oxisols that have an aridic soil moisture regime.

Torrox, p.

CC. Other Oxisols that have an ustic soil moisture regime.

Ustox, p.

CD. Other Oxisols that have a perudic soil moisture regime.

Perox, p,

CE. Other Oxisols.

Udox, p.

Aquox

These are wet Oxisols. They are present in shallow depressions and as seepage areas at the base of slopes. Because the water table may seasonally fluctuate within the profiles, there is a tendency to accumulate iron in the form of secondary nodules, concretions, and plinthite. Most areas are small.

Definition

Aquox are the Oxisols that are saturated with water within 30 cm of the mineral surface 30 days or more per year in most years or are artificially drained and have one or more of the following:

1. A histic epipedon;
2. If not mottled, a moist color value less than 3.5 and a dominant chroma of 2 or less immediately below the epipedon; or

3. If there are distinct or prominent mottles within a depth of 50 cm of the soil surface, a dominant chroma of 3 or less or a hue of 2.5Y or yellower in 50 percent or more of the horizon immediately below the epipedon.

Key to Great Groups

CAA. Aquox that have an apparent ECEC of less than 1.50 meq/100 g clay and a pH value (1N KCl) of 5 or more in some part of the oxic horizon within a depth of 150 cm of the soil surface.

Acraquox, p.

CAB. Other Aquox that have plinthite forming a continuous phase within a depth of 125 cm of the soil surface.

Plinthaquox, p.

CAC. Other Aquox that have more than 35 percent base saturation (NH4OAc) in all parts within a depth of 125 cm of the soil surface.

Eutraquox, p.

CAD. Other Aquox.

Haplaquox, p.

Acraquox

This great group is provided for those Aquox with extremely low cation exchange capacities. Few examples have been made available for study.

Definition

Acraquox are the Aquox that have an apparent ECEC of less than 1.50 meq/100 g clay and a pH value (1N KCl) of 5 or more in some part of the oxic horizon within a depth of 150 cm of the soil surface.

Key to Subgroups

CAAA. Acraquox that have more than 5 percent plinthite in some horizon within a depth of 125 cm of the soil surface.

Plinthic Acraquox

CAAB. Other Acraquox that have mottles with chroma of more than 2 in 50 percent or more of the horizon immediately below the epipedon.

Aeric Acraquox

CAAC. Other Acraquox.

Typic Acraquox

Eutraquox

These Aquox have base saturation of more than 35 percent at pH7 in all horizons to a depth of 125 cm.

Definition

Eutraquox are the Aquox that

1. Have more than 35 percent base saturation (NH4OAc) in all parts within a depth of 125 cm of the soil surface;
2. Do not have plinthite that forms a continuous phase within a depth of 125 cm of the soil surface; and
3. Do not have an apparent ECEC of less than 1.50 meq/100 g clay and a pH value (1N KCl) of 5 or more in some part of the oxic horizon within a depth of 150 cm of the soil surface.

Key to Subgroups

CACA. Eutraquox that have a histic epipedon.

Histic Eutraquox

CACB. Other Eutraquox that have more than 5 percent plinthite in some horizon within a depth of 125 cm of the soil surface.

Plinthic Eutraquox

CACC. Other Eutraquox that have mottles with chroma of more than 2 in 50 percent or more of the horizon immediately below the epipedon.

Aeric Eutraquox

CACD. Other Eutraquox that have 16 kg or more organic carbon per square meter to a depth of one meter, exclusive of surface litter.

Humic Eutraquox

CACE. Other Eutraquox.

Typic Eutraquox

Haplaquox

These are low base status Aquox.

Definition

Haplaquox are the Aquox that

1. Have 35 percent or less base saturation (NH4OAc) in some or all parts within a depth of 125 cm of the soil surface;
2. Do not have plinthite that forms a continuous phase within a depth of 125 cm of the soil surface; and
3. Do not have an apparent ECEC of less than 1.50 meq/100 g clay and a pH value (1N KCl) of 5 or more in some part of the oxic horizon within a depth of 150 cm of the soil surface.

Key to Subgroups

CADA. Haplaquox that have a histic epipedon.

Histic Haplaquox

CADB. Other Haplaquox that have more than 5 percent plinthite in some horizon within a depth of 125 cm of the soil surface.

Plinthic Haplaquox

CADC. Other Haplaquox that have mottles with chroma of more than 2 in 50 percent or more of the horizon immediately below the epipedon.

Aeric Haplaquox

CADD. Other Haplaquox that have 16 kg or more organic carbon per square meter to a depth of one meter, exclusive of the surface litter.

Humic Haplaquox

CADE. Other Haplaquox.

Typic Haplaquox

Plinthaquox

This great group is provided for pedons of Aquox that have continuous plinthite within 125 cm of the soil surface. Only small areas of Plinthaquox have been observed and no data has been made available for study.

Definition

Plinthaquox are the Aquox that

1. Have plinthite that forms a continuous phase within a depth of 125 cm of the soil surface; and
2. Do not have an apparent ECEC of less than 1.50 meq/100 g clay and a pH value (1N KCl) of 5 or more in some part of the oxic horizon within a depth of 150 cm of the soil surface.

Key to Subgroups

CABA. Plinthaquox that have mottles with chroma of more than 2 in 50 percent or more of the horizon immediately below the epipedon.

Aeric Plinthaquox

CABB. Other Plinthaquox.

Typic Plinthaquox

Perox

This is a new suborder. Although the perudic soil moisture regime was defined as one in which precipitation equals or exceeds potential evapotranspiration every month of the year, the criteria was not used in *Soil Taxonomy* (1975). Perox are well-drained Oxisols with a perudic soil moisture regime. Clearing and burning is difficult because of atmospheric wetness. Also, it is difficult to cure many seed crops and storage of produce is difficult. There are not large areas of perudic soil moisture regime, but they appear distinctive enough to show and identify on some small scale soil maps. If found useful, perhaps the concept should be considered in other orders.

Definition

Perox are the Oxisols that have a perudic soil moisture regime.

Key to Great Groups

CDA: Perox that have a sombric horizon within 150 cm of the soil surface.

Sombriperox, p.

CDB: Other Perox that have both an apparent ECEC of less than 1.50 meq/100 g clay and a pH value (1N KCl) of 5 or more in some part of the oxic or kandic horizon within a depth of 150 cm of the soil surface.

Acroperox, p.

CDC: Other Perox that have more than 35 percent base saturation (NH_4OAc) in all parts within a depth of 125 cm of the soil surface.

Eutroperox, p.

CDD: Other Perox that have more than 40 percent clay in the surface 18 cm, after mixing, and the upper boundary of a kandic horizon occurring within a depth of 150 cm of the soil surface.

Kandiperox, p.

CDE: Other Perox.

Haploperox, p.

Acroperox

These are well drained Oxisols in the perudic soil moisture regime that have very low cation exchange values.

Definition

Acroperox are the Perox that

1. Have an apparent ECEC of less than 1.50 meq/100 g clay and a pH value (1N KCl) of 5 or more in some part of the oxic or kandic horizon within a depth of 150 cm of the soil surface; and
2. Do not have a sombric horizon within a depth of 150 cm of the soil surface.

Key to Subgroups

CDBA. Acroperox that have mottles of 4 or more value moist and 2 or less chroma within a depth of 125 cm of the soil surface and a petroferric contact within 125 cm of the soil surface.

Aquic Petroferric Acroperox

CDBB. Other Acroperox that have a petroferric contact within 125 cm of the soil surface.

Petroferric Acroperox

CDBC. Other Acroperox that have mottles of 4 or more value moist and 2 or less chroma within a depth of 125 cm of the soil surface and a lithic contact within 125 cm of the soil surface.

Aquic Lithic Acroperox

CDBD. Other Acroperox that have a lithic contact within a depth of 125 cm of the soil surface.

Lithic Acroperox

CDBE. Other Acroperox that have a delta pH (KCl pH - 1:1 water pH) with a 0 or net positive charge in some layer 18 cm or more thick within a depth of 125 cm of the soil surface.

Anionic Acroperox

CDBF. Other Acroperox that have more than 5 percent plinthite in some horizon within a depth of 125 cm of the soil surface.

Plinthic Acroperox

CDBG. Other Acroperox that have mottles of 4 or more value moist and 2 or less chroma within a depth of 125 cm of the soil surface.

Aquic Acroperox

CDBH. Other Acroperox that have 16 kg or more organic carbon per square meter to a depth of one meter, exclusive of surface litter and a color hue of 2.5 YR or redder with moist values of less than 4 in most of the 25 to 125 cm depth from the soil surface.

Humic Rhodic Acroperox

CDBI. Other Acroperox that have 16 kg or more organic carbon per square meter to a depth of one meter, exclusive of surface litter and color hue of 7.5 YR or yellower with moist values of 6 or more in most of the 25 to 125 cm depth from the soil surface.

Humic Xanthic Acroperox

CDBJ. Other Acroperox that have 16 kg or more organic carbon per square meter to a depth of one meter, exclusive of surface litter.

Humic Acroperox

CDBK. Other Acroperox that have a color hue of 2.5 YR or redder with moist values of less than 4 in most of the 25 to 125 cm depth from the soil surface.

Rhodic Acroperox

CDBL. Other Acroperox that have a color hue of 7.5 YR or yellower with moist values of 6 or more in most of the 25 to 125 cm depth from the soil surface.

Xanthic Acroperox

CDBM. Other Acroperox.

Typic Acroperox

Eutroperox

This great group is provided for Oxisols in the perudic soil moisture regime with high base saturation. No examples have been available for testing.

Definition

Eutroperox are the Perox that

1. Have more than 35 percent base saturation (NH4OAc) in all parts within a depth of 125 cm of the soil surface;
2. Do not have a sombric horizon within a depth of 150 cm of the soil surface; and
3. Do not have an apparent ECEC of less than 1.50 meq/100 g clay and a pH value (1N KCl) of 5 or more in some part of the oxic or kandic horizon within a depth of 150 cm of the soil surface.

Key to Subgroups

CDCA. Eutroperox that have mottles of 4 or more value moist and 2 or less chroma within a depth of 125 cm of the soil surface and a petroferric contact within 125 cm of the soil surface.

Aquic Petroferric Eutroperox

CDCB. Other Eutroperox that have a petroferric contact within 125 cm of the soil surface.

Petroferric Eutroperox

CDCC. Other Eutroperox that have mottles of 4 or more value moist and 2 or less chroma within a depth of 125 cm of the soil surface and a lithic contact within 125 cm of the soil surface.

Aquic Lithic Eutroperox

CDCD. Other Eutroperox that have a lithic contact within a depth of 125 cm of the soil surface.

Lithic Eutroperox

CDCE. Other Eutroperox that have more than 5 percent plinthite in some horizon within a depth of 125 cm of the soil surface and mottles of 4 or more value moist and 2 or less chroma within a depth of 125 cm of the soil surface.

Plinthaquic Eutroperox

CDCF. Other Eutroperox that have more than 5 percent plinthite in some horizon within a depth of 125 cm of the soil surface.

Plinthic Eutroperox

CDCG. Other Eutroperox that have mottles of 4 or more value moist and 2 or less chroma within a depth of 125 cm of the soil surface.

Aquic Eutroperox

CDCH. Other Eutroperox that have more than 40 percent clay in the surface 18 cm after mixing and the upper boundary of a kandic horizon within a depth of 150 cm of the soil surface.

Kandiudalfic Eutroperox

CDCI. Other Eutroperox that have 16 kg or more organic carbon per square meter to a depth of one meter, exclusive of surface litter and have the lower boundary of the oxic horizon within a depth of 125 cm of the soil surface.

Umbreptic Eutroperox

CDCJ. Other Eutroperox that have the lower boundary of the oxic horizon within a depth of 125 cm of the soil surface.

Inceptic Eutroperox

CDCK. Other Eutroperox that have 16 kg or more organic carbon per square meter to a depth of one meter, exclusive of surface litter and a color hue of 2.5 YR or redder with moist values of less than 4 in most of the 25 to 125 cm depth from the soil surface.

Humic Rhodic Eutroperox

CDCL. Other Eutroperox that have 16 kg or more organic carbon per square meter to a depth of one meter, exclusive of surface litter and color hue of 7.5 YR or yellower with moist values of 6 or more in most of the 25 to 125 cm depth from the soil surface.

Humic Xanthic Eutroperox

CDCM. Other Eutroperox that have 16 kg or more organic carbon per square meter to a depth of one meter, exclusive of surface litter.

Humic Eutroperox

CDCN. Other Eutroperox that have a color hue of 2.5 YR or redder with moist values of less than 4 in most of the 25 to 125 cm depth from the soil surface.

Rhodic Eutroperox

CDCO. Other Eutroperox that have a color hue of 7.5 YR or yellower with moist values of 6 or more in most of the 25 to 125 cm depth from the soil surface.

Xanthic Eutroperox

CDCP. Other Eutroperox.

Typic Eutroperox

Haploperox

Only the presence of a perudic soil moisture regime distinguishes these Oxisols from the Udox. Their subsoils have granular structure and the epipedons may be either dark or light colored.

Definition

Haploperox are the Perox that

1. Have 35 percent or less base saturation (NH4OAc) in some or all parts within a depth of 125 cm of the soil surface;
2. Do not have a sombric horizon within a depth of 150 cm of the soil surface;
3. Do not have an apparent ECEC of less than 1.50 meq/100 g clay and a pH value (1N KCl) of 5 or more in some part of the oxic horizon within a depth of 150 cm of the soil surface; and
4. Do no have more than 40 percent clay in the surface 18 cm, after mixing, and an upper boundary of a kandic horizon within a depth of 150 cm of the soil surface.

Key to Subgroups

CDEA. Haploperox that have mottles of 4 or more value moist and 2 or less chroma within a depth of 125 cm of the soil surface and a petroferric contact within 125 cm of the soil surface.

Aquic Petroferric Haploperox

CDEB. Other Haploperox that have a petroferric contact within 125 cm of the soil surface.

Petroferric Haploperox

CDEC. Other Haploperox that have mottles of 4 or more value moist and 2 or less chroma within a depth of 125 cm of the soil surface and a lithic contact within 125 cm of the soil surface.

Aquic Lithic Haploperox

CDED. Other Haploperox that have a lithic contact within a depth of 125 cm of the soil surface.

Lithic Haploperox

CDEE. Other Haploperox that have more than 5 percent plinthite in some horizon within a depth of 125 cm of the soil surface and mottles of 4 or more value moist and 2 or less chroma within a depth of 125 cm of the soil surface.

Plinthaquic Haploperox

CDEF. Other Haploperox that have more than 5 percent plinthite in some horizon within a depth of 125 cm of the soil surface.

Plinthic Haploperox

CDEG. Other Haploperox that have mottles of 4 or more value moist and 2 or less chroma within a depth of 125 cm of the soil surface.

Aquic Haploperox

CDEH. Other Haploperox that have an 18 cm or thicker layer in the upper 75 cm with a bulk density less than 1 g/cc and in which all the Al plus one-half the Fe that is extractable with acid oxalate totals more than 1.0 percent.

Andic Haploperox

CDEI. Other Haploperox that have 16 kg or more organic carbon per square meter to a depth of one meter, exclusive of surface litter and a color hue of 2.5 YR or redder with moist values of less than 4 in most of the 25 to 125 cm depth from the soil surface.

Humic Rhodic Haploperox

CDEJ. Other Haploperox that have 16 kg or more organic carbon per square meter to a depth of one meter, exclusive of surface litter and color hue of 7.5 YR or yellower with moist values of 6 or more in most of the 25 to 125 cm depth from the soil surface.

Humic Xanthic Haploperox

CDEK. Other Haploperox that have 16 kg or more organic carbon per square meter to a depth of one meter, exclusive of surface litter.

Humic Haploperox

CDEL. Other Haploperox that have a color hue of 2.5 YR or redder with moist values of less than 4 in most of the 25 to 125 cm depth from the soil surface.

Rhodic Haploperox

CDEM. Other Haploperox that have a color hue of 7.5 YR or yellower with moist values of 6 or more in most of the 25 to 125 cm depth from the soil surface.

Xanthic Haploperox

CDEN. Other Haploperox.

Typic Haploperox

Kandiperox

These Oxisols with a perudic soil moisture regime have clay textured surface horizons and a kandic subsurface horizon. Prior to this amendment, they would have been Paleudults. Subsoils often have weak to moderate grades of blocky structure. No pedons have been studied.

Definition

Kandiperox are the Perox that

1. Have more than 40 percent clay in the surface 18 cm, after mixing, and an upper boundary of a kandic horizon within a depth of 150 cm of the soil surface;
2. Have 35 percent or less base saturation (NH4OAc) in some or all parts within a depth of 125 cm of the soil surface;
3. Do not have a sombric horizon within a depth of 150 cm of the soil surface; and
4. Do not have an apparent ECEC of less than 1.50 meq/100 g clay and a pH value (1N KCl) of 5 or more in some part of the oxic horizon within a depth of 150 cm of the soil surface.

Key to Subgroups

CDDA. Kandiperox that have mottles of 4 or more value moist and 2 or less chroma within a depth of 125 cm of the soil surface and a petroferric contact within 125 cm of the soil surface.

Aquic Petroferric Kandiperox

CDDB. Other Kandiperox that have a petroferric contact within 125 cm of the soil surface.

Petroferric Kandiperox

CDDC. Other Kandiperox that have mottles of 4 or more value moist and 2 or less chroma within a depth of 125 cm of the soil surface and a lithic contact within 125 cm of the soil surface.

Aquic Lithic Kandiperox

CDDD. Other Kandiperox that have a lithic contact within a depth of 125 cm of the soil surface.

Lithic Kandiperox

CDDE. Other Kandiperox that have more than 5 percent plinthite in some horizon within a depth of 125 cm of the soil surface and mottles of 4 or more value moist and 2 or less chroma within a depth of 125 cm of the soil surface.

Plinthaquic Kandiperox

CDDF. Other Kandiperox that have more than 5 percent plinthite in some horizon within a depth of 125 cm of the soil surface.

Plinthic Kandiperox

CDDG. Other Kandiperox that have mottles of 4 or more value moist and 2 or less chroma within a depth of 125 cm of the soil surface.

Aquic Kandiperox

CDDH. Other Kandiperox that have an 18 cm or thicker layer in the upper 75 cm with a bulk density less than 1 g/cc and in which all the Al plus one-half the Fe that is extractable with acid oxalate totals more than 1.0 percent.

Andic Kandiperox

CDDI. Other Kandiperox that have 16 kg or more organic carbon per square meter to a depth of one meter, exclusive of surface litter and a color hue of 2.5 YR or redder with moist values of less than 4 in most of the 25 to 125 cm depth from the soil surface.

Humic Rhodic Kandiperox

CDDJ. Other Kandiperox that have 16 kg or more organic carbon per square meter to a depth of one meter, exclusive of surface litter and color hue of 7.5 YR or yellower with moist values of 6 or more in most of the 25 to 125 cm depth from the soil surface.

Humic Xanthic Kandiperox

CDDK. Other Kandiperox that have 16 kg or more organic carbon per square meter to a depth of one meter, exclusive of surface litter.

Humic Kandiperox

CDDL. Other Kandiperox that have a color hue of 2.5 YR or redder with moist values of less than 4 in most of the 25 to 125 cm depth from the soil surface.

Rhodic Kandiperox

CDDM. Other Kandiperox that have a color hue of 7.5 YR or yellower with moist values of 6 or more in most of the 25 to 125 cm depth from the soil surface.

Xanthic Kandiperox

CDDN. Other Kandiperox.

Typic Kandiperox

Sombriperox

These Perox are not known at this time but are expected to be present.

Definition

Sombriperox are the Perox that have a sombric horizon within a depth of 150 cm of the soil surface.

Key to Subgroups

CDAA. Sombriperox that have a petroferric contact within a depth of 125 cm of the soil surface.

Petroferric Sombriperox

CDAB. Other Sombriperox that have a lithic contact within a depth of 125 cm of the soil surface.

Lithic Sombriperox

CDAC. Other Sombriperox that have 16 kg or more organic carbon per square meter to a depth of one meter, exclusive of surface litter.

Humic Sombriperox

CDAD. Other Sombriperox.

Typic Sombriperox

Torrox

These are Oxisols of the arid regions. They frequently have a higher base saturation than other Oxisols and when irrigated and fertilized are excellent soils for a variety of crops. Their known occurrence is limited to Hawaii and perhaps some areas in Australia. Pedon 107 illustrates the Torrox in Hawaii.

Definition

Torrox are the Oxisols that have a torric moisture regime.

Key to Great Groups

CBA: Torrox that have both an apparent ECEC of less than 1.50 meq/100 g clay and a pH value (1N KCl) of 5 or more in some part of the oxic horizon within a depth of 150 cm of the soil surface.

Acritorrox, p.

CBB: Other Torrox that have more than 35 percent base saturation (NH4OAc) in all parts within a depth of 125 cm of the soil surface.

Eutrotorrox, p.

CBC: Other Torrox.

Haplotorrox, p.

Acritorrox

This great group is provided for Torrox with very low cation exchange values. No examples have been available for study.

Definition

Acritorrox are the Torrox that have an apparent ECEC of less than 1.50 meq/100 g clay and a pH value (1N KCl) of 5 or more in some part of the oxic horizon within a depth of 150 cm of the soil surface.

Key to Subgroups

CBAA. Acritorrox that have a petroferric contact within a depth of 125 cm of the soil surface.

Petroferric Acritorrox

CBAB. Other Acritorrox that have a lithic contact within a depth of 125 cm of the soil surface.

Lithic Acritorrox

CBAC. Other Acritorrox.

Typic Acritorrox

Eutrotorrox

These high base saturated Torrox are best known in the Hawaiian islands where they are used for irrigated crops.

Definition

Eutrotorrox are the Torrox that

1. Have more than 35 percent base saturation (NH4OAc) in all parts within a depth of 125 cm of the soil surface; and
2. Do not have an apparent ECEC of less than 1.50 meq/100 g clay and a pH value (1N KCl) of 5 or more in some part of the oxic horizon within a depth of 150 cm of the soil surface.

Key to Subgroups

CBBA. Eutrotorrox that have a petroferric contact within a depth of 125 cm of the soil surface.

Petroferric Eutrotorrox

CBBB. Other Eutrotorrox that have a lithic contact within a depth of 125 cm of the soil surface.

Lithic Eutrotorrox

CBBC. Other Eutrotorrox.

Typic Eutrotorrox

Haplotorrox

This great group is provided for other Torrox that are low in

base saturation percentage. No examples have been available for study.

Definition

Haplotorrox are the Torrox that

1. Have 35 percent or less base saturation (NH4OAc) in some or all parts within a depth of 125 cm of the soil surface; and
2. Do not have an apparent ECEC of less than 1.50 meq/100 g clay and a pH value (1N KCl) of 5 or more in some part of the oxic horizon within 150 cm of the soil surface.

Key to Subgroups

CBCA. Haplotorrox that have a petroferric contact within a depth of 125 cm of the soil surface.

Petroferric Haplotorrox

CBCB. Other Haplotorrox that have a lithic contact within a depth of 125 cm of the soil surface.

Lithic Haplotorrox

CBCC. Other Haplotorrox.

Typic Haplotorrox

Udox

Previously these Oxisols with udic soil moisture regimes were known as Orthox. The connotation of *orth* is the "true" Oxisols, and this certainly was the concept of Oxisols as *Soil Taxonomy* was prepared. It now appears that there is as much extent, or perhaps more, of Ustox than Udox. Many of the soils in the udic soil moisture regime of the upper Amazon basin classify as Ultisols rather than Oxisols as originally thought. Therefore it appears inappropriate to refer to well-drained Oxisols with udic soil moisture regimes as "the true" Oxisols, and the name Udox is selected in keeping with usage in other orders. There are less than 90 days during which crops are not planted; however, there are one to three months in most years that are considered "dry" in local terms.

Definition

Udox are the Oxisols that have an udic moisture regime.

Key to Great Groups

CEA: Udox that have a sombric horizon within a depth of 150 cm of the soil surface.

Sombriudox, p.

CEB: Other Udox that have both an apparent ECEC of less than 1.50 meq/100 g clay and a pH value (1N KCl) of 5 or more in some part of the oxic or kandic horizon within a depth of 150 cm of the soil surface.

Acrudox, p.

CEC: Other Udox that have more than 35 percent base saturation (NH4OAc) in all parts within a depth of 125 cm of the soil surface.

Eutrudox, p.

CED: Other Udox that have more than 40 percent clay in the surface 18 cm after mixing, and the upper boundary of a kandic horizon occurring within a depth of 150 cm of the surface.

Kandiudox, p.

CEE: Other Udox.

Hapludox, p.

Acrudox

These are Udox with very low CEC values in the subsoil. Frequent but small applications of fertilizer and lime are required. Because the CEC is low, the amount of exchangeable Al in the subsoil is low and can be corrected by leaching basic cations from lime and fertilizer.

Definition

Acrudox are the Udox that

1. Have an apparent ECEC of less than 1.50 meq/100 g clay and a pH value (1N KCl) of 5 or more in some part of the oxic or kandic horizon within a depth of 150 cm of the soil surface; and
2. Do not have a sombric horizon within a depth of 150 cm of the soil surface.

Key to Subgroups

CEBA. Acrudox that have mottles of 4 or more value moist and 2 or less chroma within a depth of 125 cm of the soil surface and a petroferric contact within 125 cm of the soil surface.

Aquic Petroferric Acrudox

CEBB. Other Acrudox that have a petroferric contact within 125 cm of the soil surface.

Petroferric Acrudox

CEBC. Other Acrudox that have mottles of 4 or more value moist and 2 or less chroma within a depth of 125 cm of the soil surface and a lithic contact within 125 cm of the soil surface.

Aquic Lithic Acrudox

CEBD. Other Acrudox that have a lithic contact within a depth of 125 cm of the soil surface.

Lithic Acrudox

CEBE. Other Acrudox that have mottles of 4 or more value moist and 2 or less chroma within a depth of 125 cm of the soil surface and have a delta pH (KCl pH - 1:1 water pH) with a 0 or net positive charge in some layer 18 cm or more thick within a depth of 125 cm of the soil surface.

Aquic Anionic Acrudox

CEBF. Other Acrudox that have a delta pH (KCl pH - 1:1 water pH) with a 0 or net positive charge in some layer 18 cm or more thick within a depth of 125 cm of the soil surface.

Anionic Acrudox

CEBG. Other Acrudox that have more than 5 percent plinthite in some horizon within a depth of 125 cm of the soil surface.

Plinthic Acrudox

CEBH. Other Acrudox that have mottles of 4 or more value moist and 2 or less chroma within a depth of 125 cm of the soil surface.

Aquic Acrudox

CEBI. Other Acrudox that have more than 35 percent base saturation (NH4OAc) in all parts within a depth of 125 cm of the soil surface.

Eutric Acrudox

CEBJ. Other Acrudox that have 16 kg or more organic carbon per square meter to a depth of one meter, exclusive of suface

litter and a color hue of 2.5 YR or redder with moist values of less than 4 in most of the 25 to 125 cm depth from the soil surface.

Humic Rhodic Acrudox

CEBK. Other Acrudox that have 16 kg or more organic carbon per square meter to a depth of one meter, exclusive of surface litter and color hue of 7.5 YR or yellower with moist values of 6 or more in most of the 25 to 125 cm depth from the soil surface.

Humic Xanthic Acrudox

CEBL. Other Acrudox that have 16 kg or more organic carbon per square meter to a depth of one meter, exclusive of surface litter.

Humic Acrudox

CEBM. Other Acrudox that have a color hue of 2.5 YR or redder with moist values of less than 4 in most of the 25 to 125 cm depth from the soil surface.

Rhodic Acrudox

CEBN. Other Acrudox that have a color hue of 7.5 YR or yellower with moist values of 6 or more in most of the 25 to 125 cm depth from the soil surface.

Xanthic Acrudox

CEBO. Other Acrudox.

Typic Acrudox

Eutrudox

These are Udox with high base saturation throughout the profile. These are highly valued by shifting cultivators and are most common in areas near basic geologic rock.

Definition

Eutrudox are the Udox that

1. Have more than 35 percent base saturation (NH4OAc) in all parts within a depth of 125 cm of the soil surface;
2. Do not have a sombric horizon within a depth of 150 cm of the soil surface; and
3. Do not have an apparent ECEC of less than 1.50 meq/100 g clay and a pH value (1N KCl) of 5 or more in some part of the oxic or kandic horizon within a depth of 150 cm of the soil surface.

Key to Subgroups

CECA. Eutrudox that have mottles of 4 or more value moist and 2 or less chroma within a depth of 125 cm of the soil surface and a petroferric contact within 125 cm of the soil surface.

Aquic Petroferric Eutrudox

CECB. Other Eutrudox that have a petroferric contact within 125 cm of the soil surface.

Petroferric Eutrudox

CECC. Other Eutrudox that have mottles of 4 or more value moist and 2 or less chroma within a depth of 125 cm of the soil surface and a lithic contact within 125 cm of the soil surface.

Aquic Lithic Eutrudox

CECD. Other Eutrudox that have a lithic contact within a depth of 125 cm of the soil surface.

Lithic Eutrudox

CECE. Other Eutrudox that have more than 5 percent plinthite in some horizon within a depth of 125 cm of the soil surface and mottles of 4 or more value moist and 2 or less chroma within a depth of 125 cm of the soil surface.

Plinthaquic Eutrudox

CECF. Other Eutrudox that have more than 5 percent plinthite in some horizon within a depth of 125 cm of the soil surface.

Plinthic Eutrudox

CECG. Other Eutrudox that have mottles of 4 or more value moist and 2 or less chroma within a depth of 125 cm of the soil surface.

Aquic Eutrudox

CECH. Other Eutrudox that have more than 40 percent clay in the surface 18 cm after mixing and the upper boundary of a kandic horizon within a depth or 150 cm of the soil surface.

Kandiudalfic Eutrudox

CECI. Other Eutrudox that have 16 kg or more organic carbon per square meter to a depth of one meter, exclusive of surface litter and have the lower boundary of the oxic horizon within a depth of 125 cm of the soil surface.

Umbreptic Eutrudox

CECJ. Other Eutrudox that have the lower boundary of the oxic horizon within a depth of 125 cm of the soil surface.

Inceptic Eutrudox

CECK. Other Eutrudox that have 16 kg or more organic carbon per square meter to a depth of one meter, exclusive of surface litter and a color hue of 2.5 YR or redder with moist values of less than 4 in most of the 25 to 125 cm depth from the soil surface.

Humic Rhodic Eutrudox

CECL. Other Eutrudox that have 16 kg or more organic carbon per square meter to a depth of one meter, exclusive of surface litter and color hue of 7.5 YR or yellower with moist values of 6 or more in most of the 25 to 125 cm depth from the soil surface.

Humic Xanthic Eutrudox

CECM. Other Eutrudox that have 16 kg or more organic carbon per square meter to a depth of one meter, exclusive of surface litter.

Humic Eutrudox

CECN. Other Eutrudox that have a color hue of 2.5 YR or redder with moist values of less than 4 in most of the 25 to 125 cm depth from the soil surface.

Rhodic Eutrudox

CECO. Other Eutrudox that have a color hue of 7.5 YR or yellower with moist values of 6 or more in most of the 25 to 125 cm depth from the soil surface.

Xanthic Eutrudox

CECP. Other Eutrudox.

Typic Eutrudox

Hapludox

These Udox are acid and range in color from dark red to pale yellow. They are common in the uplands of Africa, the central part of Indonesia, and many other areas.

Definition

Hapludox are the Udox that

1. Have 35 percent or less base saturation (NH4OAc) in

some or all parts within a depth of 125 cm of the soil surface;
2. Do not have a sombric horizon within a depth of 150 cm of the soil surface;
3. Do not have an apparent ECEC of less than 1.50 meq/100 g clay and a pH value (1N KCl) of 5 or more in some part of the oxic horizon within a depth of 150 cm of the soil surface; and
4. Do not have more than 40 percent clay in the surface 18 cm, after mixing, and an upper boundary of a kandic horizon within a depth of 150 cm of the soil surface.

Key to Subgroups

CEEA. Hapludox that have mottles of 4 or more value moist and 2 or less chroma within a depth of 125 cm of the soil surface and a petroferric contact within 125 cm of the soil surface.

Aquic Petroferric Hapludox

CEEB. Other Hapludox that have a petroferric contact within 125 cm of the soil surface.

Petroferric Hapludox

CEEC. Other Hapludox that have mottles of 4 or more value moist and 2 or less chroma within a depth of 125 cm of the soil surface and a lithic contact within 125 cm of the soil surface.

Aquic Lithic Hapludox

CEED. Other Hapludox that have a lithic contact within a depth of 125 cm of the soil surface.

Lithic Hapludox

CEEE. Other Hapludox that have more than 5 percent plinthite in some horizon within a depth of 125 cm of the soil surface and mottles of 4 or more value moist and 2 or less chroma within a depth of 125 cm of the soil surface.

Plinthaquic Hapludox

CEEF. Other Hapludox that have more than 5 percent plinthite in some horizon within a depth of 125 cm of the soil surface.

Plinthic Hapludox

CEEG. Other Hapludox that have mottles of 4 or more value moist and 2 or less chroma within a depth of 125 cm of the soil surface.

Aquic Hapludox

CEEH. Other Hapludox that have the lower boundary of the oxic horizon within a depth of 125 cm of the soil surface.

Inceptic Hapludox

CEEI. Other Hapludox that have an 18 cm or thicker layer in the upper 75 cm with a bulk density less than 1 g/cc and in which all the Al plus one-half the Fe that is extractable with acid oxalate totals more than 1.0 percent.

Andic Hapludox

CEEJ. Other Hapludox that have 16 kg or more organic carbon per square meter to a depth of one meter, exclusive of surface litter and a color hue of 2.5 YR or redder with moist values of less than 4 in most of the 125 to 125 cm depth from the soil surface.

Humic Rhodic Hapludox

CEEK. Other Hapludox that have 16 kg or more organic carbon per square meter to a depth of one meter, exclusive of surface litter and color hue of 7.5 YR or yellower with moist values of 6 or more in most of the 25 to 125 cm depth from the soil surface.

Humic Xanthic Hapludox

CEEL. Other Hapludox that have 16 kg or more organic carbon per square meter to a depth of one meter, exclusive of surface litter.

Humic Hapludox

CEEM. Other Hapludox that have a color hue of 2.5 YR or redder with moist values of less than 4 in most of the 25 to 125 cm depth from the soil surface.

Rhodic Hapludox

CEEN. Other Hapludox that have a color hue of 7.5 YR or yellower with moist values of 6 or more in most of the 25 to 125 cm depth from the soil surface.

Xanthic Hapludox

CEEO. Other Hapludox.

Typic Hapludox

Kandiudox

These Udox have more than 40 percent clay in the surface and an increase in clay content with depth. They have previously been classified as Paleudults and Tropudalfs. The subsoil frequently has a moderate grade of blocky structure.

Definition

Kandiudox are the Udox that

1. Have more than 40 percent clay in the surface 18 cm, after mixing, and an upper boundary of a kandic horizon within a depth of 150 cm of the soil surface;
2. Have 35 percent or less base saturation (NH4OAc) in some or all parts within a depth of 125 cm of the soil surface;
3. Do not have a sombric horizon within a depth of 150 cm of the soil surface; and
4. Do not have an apparent ECEC of less than 1.50 meq/100 g clay and a pH value (1N KCl) of 5 or more in some part of the oxic horizon within a depth of 150 cm of the soil surface.

Key to Subgroups

CEDA. Kandiudox that have mottles of 4 or more value moist and 2 or less chroma within a depth of 125 cm of the soil surface and a petroferric contact within 125 cm of the soil surface.

Aquic Petroferric Kandiudox

CEDB. Other Kandiudox that have a petroferric contact within 125 cm of the soil surface.

Petroferric Kandiudox

CEDC. Other Kandiudox that have mottles of 4 or more value moist and 2 or less chroma within a depth of 125 cm of the soil surface and a lithic contact within 125 cm of the soil surface.

Aquic Lithic Kandiudox

CEDD. Other Kandiudox that have a lithic contact within a depth of 125 cm of the soil surface.

Lithic Kandiudox

CEDE. Other Kandiudox that have more than 5 percent plinthite in some horizon within a depth of 125 cm of the soil surface and mottles of 4 or more value moist and 2 or less chroma within a depth of 125 cm of the soil surface.

Plinthaquic Kandiudox

CEDF. Other Kandiudox that have more than 5 percent plinthite in some horizon within a depth of 125 cm of the soil surface.

Plinthic Kandiudox

CEDG. Other Kandiudox that have mottles of 4 or more value moist and 2 or less chroma within a depth of 125 cm of the soil surface.

Aquic Kandiudox

CEDH. Other Kandiudox that have an 18 cm or thicker layer in the upper 75 cm with a bulk density less than 1 g/cc and in which all the Al plus one-half the Fe that is extractable with acid oxalate totals more than 1.0 percent.

Andic Kandiudox

CEDI. Other Kandiudox that have 16 kg or more organic carbon per square meter to a depth of one meter, exclusive of surface litter and a color hue of 2.5 YR or redder with moist values of less than 4 in most of the 25 to 125 cm depth from the soil surface.

Humic Rhodic Kandiudox

CEDJ. Other Kandiudox that have 16 kg or more organic carbon per square meter to a depth of one meter, exclusive of surface litter and color hue of 7.5 YR or yellower with moist values of 6 or more in most of the 25 to 125 cm depth from the soil surface.

Humic Xanthic Kandiudox

CEDK. Other Kandiudox that have 16 kg or more organic carbon per square meter to a depth of one meter, exclusive of surface litter.

Humic Kandiudox

CEDL. Other Kandiudox that have a color hue of 2.5 YR or redder with moist values of less than 4 in most of the 25 to 125 cm depth from the soil surface.

Rhodic Kandiudox

CEDM. Other Kandiudox that have a color hue of 7.5 YR or yellower with moist values of 6 or more in most of the 25 to 125 cm depth from the soil surface.

Xanthic Kandiudox

CEDN. Other Kandiudox.

Typic Kandiudox

Sombriudox

These are poorly understood Udox that have an increase in organic carbon content in the subsoil. The only known pedons are near the Rift Valley in Africa.

Definition

Sombriudox are the Udox that have a sombric horizon within a depth of 150 cm of the soil surface.

Key to Subgroups

CEAA. Sombriudox that have a petroferric contact within a depth of 125 cm of the soil surface.

Petroferric Sombriudox

CEAB. Other Sombriudox that have a lithic contact within a depth of 125 cm of the soil surface.

Lithic Sombriudox

CEAC. Other Sombriudox that have 16 kg or more organic carbon per square meter to a depth of one meter, exclusive of surface litter.

Humic Sombriudox

CEAD. Other Sombriudox.

Typic Sombriudox

Ustox

The Ustox are those Oxisols that are moist from natural rainfall in most years for at least 90 days which is usually long enough for one rainfed crop, but not more than 270 days. Thus, crops are not grown continuously because there is inadequate moisture for at least 90 days in most years. Ustox may be the most extensive suborder occurring over a large portion of the interior of South America and in extensive areas of Africa. A few Ustox are in areas of xeric soil moisture regime, for example, in Australia. The range of natural rainfall within the Ustox provides that two crops can be grown on some Ustox while others are limited to only one crop unless supplemental irrigation is available.

Definition

Ustox are the Oxisols that have an ustic moisture regime.

Key to Great Groups

CCA: Ustox that have a sombric horizon within 150 cm of the soil surface.

Sombriustox, p.

CCB: Other Ustox that have both an apparent ECEC of less than 1.50 meq/100 g clay and a pH value (1N KCl) of 5 or more in some part of the oxic or kandic horizon within a depth of 150 cm of the soil surface.

Acrustox, p.

CCC: Other Ustox that have more than 35 percent base saturation (NH4OAc) in all parts within a depth of 125 cm of the soil surface.

Eutrustox, p.

CCD: Other Ustox that have more than 40 percent clay in the surface 18 cm after mixing, and the upper boundary of a kandic horizon occurring within a depth of 150 cm of the soil surface.

Kandiustox, p.

CCE: Other Ustox.

Haplustox, p.

Acrustox

These are Ustox with extremely low cation exchange values. They can easily have their chemical environment altered by fertilizer and lime applications. Because of their low buffering capacity, it is desirable to use small but frequent applications of fertilizer and lime. Low content of exchangeable Al in the subsoil can be corrected by leaching basic cations from lime and fertilizer.

Definition

Acrustox are the Ustox that

1. Have an apparent ECEC of less than 1.50 meq/100 g clay and a pH value (1N KCl) of 5 or more in some part of the oxic or kandic horizon within a depth of 150 cm of the soil surface; and
2. Do not have a sombric horizon within a depth of 150 cm of the soil surface.

Key to subgroups

CCBA. Acrustox that have mottles of 4 or more value moist and 2 or less chroma within a depth of 125 cm of the soil surface and a petroferric contact within 125 cm of the soil surface.

Aquic Petroferric Acrustox

CCBB. Other Acrustox that have a petroferric contact within 125 cm of the soil surface.

Petroferric Acrustox

CCBC. Other Acrustox that have mottles of 4 or more value moist and 2 or less chroma within a depth of 125 cm of the soil surface and a lithic contact within 125 cm of the soil surface.

Aquic Lithic Acrustox

CCBD. Other Acrustox that have a lithic contact within a depth of 125 cm of the soil surface.

Lithic Acrustox

CCBE. Other Acrustox that have mottles of 4 or more value moist and 2 or less chroma within a depth of 125 cm of the soil surface and have a delta pH (KCl pH - 1:1 water pH) with a 0 or net positive charge in some layer 18 cm or more thick within a depth of 125 cm of the soil surface.

Aquic Anionic Acrustox

CCBF. Other Acrustox that have a delta pH (KCl pH - 1:1 water pH) with a 0 or net positive charge in some layer 18 cm or more thick within a depth of 125 cm of the soil surface.

Anionic Acrustox

CCBG. Other Acrustox that have more than 5 percent plinthite in some horizon within a depth of 125 cm of the soil surface.

Plinthic Acrustox

CCBH. Other Acrustox that have mottles of 4 or more value moist and 2 or less chroma within a depth of 125 cm of the soil surface.

Aquic Acrustox

CCBI. Other Acrustox that have more than 35 percent base saturation (NH4OAc) in all parts within a depth of 125 cm of the soil surface.

Eutric Acrustox

CCBJ. Other Acrustox that have 16 kg or more organic carbon per square meter to a depth of one meter, exclusive of surface litter and a color hue of 2.5 YR or redder with moist values of less than 4 in most of the 25 to 125 cm depth from the soil surface.

Humic Rhodic Acrustox

CCBK. Other Acrustox that have 16 kg or more organic carbon per square meter to a depth of one meter, exclusive of surface litter and color hue of 7.5 YR or yellower with moist values of 6 or more in most of the 25 to 125 cm depth from the soil surface.

Humic Xanthic Acrustox

CCBL. Other Acrustox that have 16 kg or more organic carbon per square meter to a depth of one meter, exclusive of surface litter.

Humic Acrustox

CCBM. Other Acrustox that have a color hue of 2.5 YR or redder with moist values of less than 4 in most of the 25 to 125 cm depth from the soil surface.

Rhodic Acrustox

CCBN. Other Acrustox that have a color hue of 7.5 YR or yellower with moist values of 6 or more in most of the 25 to 125 cm depth from the soil surface.

Xanthic Acrustox

CCBO. Other Acrustox.

Typic Acrustox

Eutrustox

These high base status Ustox are well known by local farmers because of their relatively high native fertility. Often they supported natural forests while surrounding areas of like rainfall but low base status supported savannas. It is rare to see forest vegetation today because the forests have been completely cut by native farmers. Why these Ustox have high saturation throughout their profile is not known, but they tend to occur over or near basic rocks such as limestone or basalt.

Definition

Eutrustox are the Ustox that

1. Have more than 35 percent base saturation (NH4OAc) in all parts within a depth of 125 cm of the soil surface;
2. Do not have a sombric horizon within a depth of 150 cm of the soil surface; and
3. Do not have an apparent ECEC of less than 1.50 meq/100 g clay and a pH value (1N KCl) of 5 or more in some part of the oxic or kandic horizon within a depth of 150 cm of the soil surface.

Key to Subgroups

CCCA. Eutrustox that have mottles of 4 or more value moist and 2 or less chroma within a depth of 125 cm of the soil surface and a petroferric contact within 125 cm of the soil surface.

Aquic Petroferric Eutrustox

CCCB. Other Eutrustox that have a petroferric contact within 125 cm of the soil surface.

Petroferric Eutrustox

CCCC. Other Eutrustox that have mottles of 4 or more value moist and 2 or less chroma within a depth of 125 cm of the soil surface and a lithic contact within 125 cm of the soil surface.

Aquic Lithic Eutrustox

CCCD. Other Eutrustox that have a lithic contact within a depth of 125 cm of the soil surface.

Lithic Eutrustox

CCCE. Other Eutrustox that have more than 5 percent plinthite in some horizon within a depth of 125 cm of the soil surface and mottles of 4 or more value moist and 2 or less chroma within a depth of 125 cm of the soil surface.

Plinthaquic Eutrustox

CCCF. Other Eutrustox that have more than 5 percent plinthite in some horizon within a depth of 125 cm of the soil surface.

Plinthic Eutrustox

CCCG. Other Eutrustox that have mottles of 4 or more value moist and 2 or less chroma within a depth of 125 cm of the soil surface.

Aquic Eutrustox

CCCH. Other Eutrustox that have more than 40 percent clay in the surface 18 cm after mixing and the upper boundary of a kandic horizon within a depth of 150 cm of the soil surface.

Kandiustalfic Eutrustox

CCCI. Other Eutrustox that have 16 kg or more organic carbon per square meter to a depth of one meter, exclusive of surface litter and have the lower boundary of the oxic horizon within a depth of 125 cm of the soil surface.

Umbreptic Eutrustox

CCCJ. Other Eutrustox that have the lower boundary of the oxic horizon within a depth of 125 cm of the soil surface.

Inceptic Eutrustox

CCCK. Other Eutrustox that have 16 kg or more organic carbon per square meter to a depth of one meter, exclusive of surface litter and a color hue of 2.5 YR or redder with moist values of less than 4 in most of the 25 to 125 cm depth from the soil surface.

Humic Rhodic Eutrustox

CCCL. Other Eutrustox that have 16 kg or more organic carbon per square meter to a depth of one meter, exclusive of surface litter and color hue of 7.5 YR or yellower with moist values of 6 or more in most of the 25 to 125 cm depth from the soil surface.

Humic Xanthic Eutrustox

CCCM. Other Eutrustox that have 16 kg or more organic carbon per square meter to a depth of one meter, exclusive of surface litter.

Humic Eutrustox

CCCN. Other Eutrustox that have a color hue of 2.5 YR or redder with moist values of less than 4 in most of the 25 to 125 cm depth from the soil surface.

Rhodic Eutrustox

CCCO. Other Eutrustox that have a color hue of 7.5 YR or yellower with moist values of 6 or more in most of the 25 to 125 cm depth from the soil surface.

Xanthic Eutrustox

CCCP. Other Eutrustox.

Typic Eutrustox

Haplustox

These Ustox are present in dark red to yellow and all intervening colors. They represent vast areas in central South America and Africa.

Definition

Haplustox are the Ustox that

1. Have 35 percent or less base saturation (NH4OAc) in some or all parts within a depth of 125 cm of the soil surface;
2. Do not have a sombric horizon within a depth of 150 cm of the soil surface;
3. Do not have an apparent ECEC of less than 1.50 meq/100 g clay and a pH value (1N KCl) of 5 or more in some part of the oxic horizon within a depth of 150 cm of the soil surface; and
4. Do not have more than 40 percent clay in the surface 18 cm, after mixing, and an upper boundary of a kandic horizon within a depth of 150 cm of the soil surface.

Key to Subgroups

CCEA. Haplustox that have mottles of 4 or more value moist and 2 or less chroma within a depth of 125 cm of the soil surface and a petroferric contact within 125 cm of the soil surface.

Aquic Petroferric Haplustox

CCEB. Other Haplustox that have a petroferric contact within 125 cm of the soil surface.

Petroferric Haplustox

CCEC. Other Haplustox that have mottles of 4 or more value moist and 2 or less chroma within a depth of 125 cm of the soil surface and a lithic contact within 125 cm of the soil surface.

Aquic Lithic Haplustox

CCED. Other Haplustox that have a lithic contact within a depth of 125 cm of the soil surface.

Lithic Haplustox

CCEE. Other Haplustox that have more than 5 percent plinthite in some horizon within a depth of 125 cm of the soil surface and mottles of 4 or more value moist and 2 or less chroma within a depth of 125 cm of the soil surface.

Plinthaquic Haplustox

CCEF. Other Haplustox that have more than 5 percent plinthite in some horizon within a depth of 125 cm of the soil surface.

Plinthic Haplustox

CCEG. Other Haplustox that have mottles of 4 or more value moist and 2 or less chroma within a depth of 125 cm of the soil surface and have the lower boundary of the oxic horizon within a depth or 125 cm of the soil surface.

Aqueptic Haplustox

CCEH. Other Haplustox that have mottles of 4 or more value moist and 2 or less chroma within a depth of 125 cm of the soil surface.

Aquic Haplustox

CCEI. Other Haplustox that have the lower boundary of the oxic horizon within a depth of 125 cm of the soil surface.

Inceptic Haplustox

CCEJ. Other Haplustox that have 16 kg or more organic carbon per square meter to a depth of one meter, exclusive of surface litter and a color hue of 2.5 YR or redder with moist values of less than 4 in most of the 25 to 125 cm depth from the soil surface.

Humic Rhodic Haplustox

CCEK. Other Haplustox that have 16 kg or more organic carbon per square meter to a depth of one meter, exclusive of surface litter and color hue of 7.5 YR or yellower with moist values of 6 or more in most of the 25 to 125 cm depth from the soil surface.

Humic Xanthic Haplustox

CCEL. Other Haplustox that have 16 kg or more organic carbon per square meter to a depth of one meter, exclusive of surface litter.

Humic Haplustox

CCEM. Other Haplustox that have a color hue of 2.5 YR or redder with moist values of less than 4 in most of the 25 to 125 cm depth from the soil surface.

Rhodic Haplustox

CCEN. Other Haplustox that have a color hue of 7.5 YR or yellower with moist values of 6 or more in most of the 25 to 125 cm depth from the soil surface.

Xanthic Haplustox

CCEO. Other Haplustox.

Typic Haplustox

Kandiustox

These Ustox have more than 40 percent clay in the surface 18 cm and an increase in clay content sufficient to meet the kandic horizon criteria below that depth. Most of these soils have been previously classified as Ultisols or Alfisols. The subsoil seldom contains evidence of translocated clay, but in some pedons they tend to have a weak to moderate grade of blocky structure in the subsoil, although there is usually a strong secondary structure that is fine granular.

Definition

Kandiustox are the Ustox that

1. Have more than 40 percent clay in the surface 18 cm, after mixing, and an upper boundary of a kandic horizon within a depth of 150 cm of the soil surface;
2. Have 35 percent or less base saturation (NH4OAc) in some or all parts within a depth of 125 cm of the soil surface;
3. Do not have a sombric horizon within a depth of 150 cm of the soil surface; and
4. Do not have an apparent ECEC of less than 1.50 meq/100 g clay and a pH value (1N KCl) of 5 or more in some part of the oxic horizon within a depth of 150 cm of the soil surface.

Key to subgroups

CCDA. Kandiustox that have mottles of 4 or more value moist and 2 or less chroma within a depth of 125 cm of the soil surface and a petroferric contact within 125 cm of the soil surface.

Aquic Petroferric Kandiustox

CCDB. Other Kandiustox that have a petroferric contact within 125 cm of the soil surface.

Petroferric Kandiustox

CCDC. Other Kandiustox that have mottles of 4 or more value moist and 2 or less chroma within a depth of 125 cm of the soil surface and a lithic contact within 125 cm of the soil surface.

Aquic Lithic Kandiustox

CCDD. Other Kandiustox that have a lithic contact within a depth of 125 cm of the soil surface.

Lithic Kandiustox

CCDE. Other Kandiustox that have more than 5 percent plinthite in some horizon within a depth of 125 cm of the soil surface and mottles of 4 or more value moist and 2 or less chroma within a depth of 125 cm of the soil surface.

Plinthaquic Kandiustox

CCDF. Other Kandiustox that have more than 5 percent plinthite in some horizon within a depth of 125 cm of the soil surface.

Plinthic Kandiustox

CCDG. Other Kandiustox that have mottles of 4 or more value moist and 2 or less chroma within a depth of 125 cm of the soil surface.

Aquic Kandiustox

CCDH. Other Kandiustox that have 16 kg or more organic carbon per square meter to a depth of one meter, exclusive of surface litter and a color hue of 2.5 YR or redder with moist values of less than 4 in most of the 25 to 125 cm depth from the soil surface.

Humic Rhodic Kandiustox

CCDI. Other Kandiustox that have 16 kg or more organic carbon per square meter to a depth of one meter, exclusive of surface litter and color hue of 7.5 YR or yellower with moist values of 6 or more in most of the 25 to 125 cm depth from the soil surface.

Humic Xanthic Kandiustox

CCDJ. Other Kandiustox that have 16 kg or more organic carbon per square meter to a depth of one meter, exclusive of surface litter.

Humic Kandiustox

CCDK. Other Kandiustox that have a color hue of 2.5 YR or redder with moist values of less than 4 in most of the 25 to 125 cm depth from the soil surface.

Rhodic Kandiustox

CCDL. Other Kandiustox that have a color hue of 7.5 YR or yellower with moist values of 6 or more in most of the 25 to 125 cm depth from the soil surface.

Xanthic Kandiustox

CCDM. Other Kandiustox.

Typic Kandiustox

Sombriustox

These are poorly understood Ustox. Often this layer has andic properties and spodic properties. The only known pedons are near the Rift Valley in Africa.

Definition

Sombriustox are the Ustox that have a sombric horizon within a depth of 150 cm of the soil surface.

Key to Subgroups

CCAA. Sombriustox that have a petroferric contact within a depth of 125 cm of the soil surface.

Petroferric Sombriustox

CCAB. Other Sombriustox that have a lithic contact within a depth of 125 cm of the soil surface.

Lithic Sombriustox

CCAC. Other Sombriustox that have 16 kg or more organic carbon per square meter to a depth of one meter, exclusive of surface litter.

Humic Sombriustox

CCAD. Other Sombriustox.

Typic Sombriustox

WORKSHOP PROGRAM

Sunday, 11 May 1986

	Participants arrive in Rio de Janeiro
	Check-in Copacabana Palace Hotel
	Excelsior Copacabana Hotel
0900 to 1200	Registration, Copacabana Palace Hotel
1400 to 1800	Night in Rio de Janeiro, Copacabana
	Palace Hotel Excelsior Copacabana Hotel

Monday, 12 May 1986

0800	Registration
	OPENING CEREMONY
	Chairman: G. Ranzani
	Venue: Copacabana Palace Hotel
0900	Words of welcome: Chief, EMBRAPA/ SNLCS
	F.H. Beinroth, UPR
	R.W. Arnold, USDA/SCS/SMSS
	G. Ranzani, Representing Presidence of EMBRAPA
0930	Refreshments
	Technicals Session I: PERSPECTIVES AND BACKGROUND
	Chairman: W.G. Sombroek
	Venue: Copacabana Palace Hotel
1000	R. Travernier: Historical development of the concepts and classification of Oxisols
1030	R.W. Arnold: Rationale and activities for refining Soil Taxonomy
1100	S.W. Buol: The ICOMOX proposal
1200	Discussion
1230	Lunch
	Technical Session II: IMPLICATIONS OF THE ICOMOX PROPOSAL
	Chairman: R.W. Arnold
	Venue: Copacabana Palace Hotel
1400	F.R. Moormann: The Kandi concept in relation to the ICOMOX proposal
1445	A.E. Hewitt AND M.L. Leamy: Implications of the ICOMOX relative to the classification of Andisols
1530	Refreshments
1600	J. Bouma: Implications of the ICOMOX proposal to the mandate of ICOMAQ
1645	Discussion
1800	Adjourn
	Night in Rio de Janeiro, Copacabana Palace Hotel/Excelsior Copacabana Hotel

Tuesday, 13 May 1986

	Technical Session III: PROPERTIES OF OXISOLS
	Chairman: R. Schargel
	Venue: Copacabana Palace Hotel
0900	G. Uehara: Acric properties and their significance to soil classification
0930	C.S. Holzhey and H.M. Kimble: Problems of analytical characterization of Oxisols
1000	Discussion
1030	Refreshments
1100	B.F. Hajak and R.L. Guthrie: Soil families in Oxisols
1130	A. Herbillon and L.L. Antonello: Estimation of weatherable minerals in LAC soils
1200	Discussion
1230	Lunch
	Technical Session IV: OXISOLS OF DIFFERENT REGIONS
	Chairman: M.R. Ribeiro
	Venue: Copacabana Palace
1400	P. Klinger, M. Camargo, J. Olmos I.L., and A.P. Carvalho: The Brazilian classification of Latosols
1445	J.E. Witty, F.H. Beinroth and H.Ikawa: The impact of the ICOMOX proposal

	on the classification of soils in the United States and Puerto Rico
1515	Discussion
1530	Refreshments
1600	R. Schargel and J.A. Comerma: Evaluation of the ICOMOX proposal in the Venezuelan context
1630	S. Paramananthan, L. Moncharoen and M. Recel: Evaluation of the ICOMOX proposal in the Asian context
1700	O. Spaargaren and C. Kalima: Oxisols of Zambia
1730	Discussion
1800	Adjourn
	Night in Rio de Janeiro, Copacabana Palace Hotel/Excelsior Copacabana Hotel

Wednesday, 14 May 1986

FIELD TRIP I:	Rio de Janeiro to Campinas
0630	Dep. hotel
0715	Arr. Rio de Janeiro airport (GIG)
0800	Dep. Rio, Transbrasil flight TR 545
0900	Arr. São Paulo
0930	Dep. São Paulo airport, 80 km route
1030	Arr. Pedon B-1
1200	Dep. Pedon B-1, 30 km route
1230	Arr. restaurant for lunch
1345	Dep. restaurant, 66 km route
1500	Arr. Pedon B-2
1700	Dep. Pedon B-2, 77 km route
1830	Arr. Campinas, Hotel Novotel Campinas Norte

Thursday, 15 May 1986

0730	Dep. Campinas, 87 km route
0900	Arr. Pedon B-3
1100	Dep. Pedon B-3, 38 km route
1130	Arr. restaurant for lunch
1230	Dep. restaurant, 44 km route
1300	Arr. Pedon B-4
1430	Dep. Pedon B-4, 2 km route
1440	Arr. Pedon B-6
1530	Dep. Pedon b-6, 300 m walking
1540	Arr. Pedon B-5
1740	Dep. Pedon b-5, 123 km route
1850	Arr. Araraquara
	Night in Araraquara, Hotel Eldorado Morada do Sol

Friday, 16 May 1986

FIELD TRIP III:	Araraquara to Araxá
0700	Dep. Araraquara, 52 km route
0800	Arr. Pedon B-7
0930	Dep. Pedon B-7, 20 km route
0950	Arr. Pedon B-8
1110	Dep. Pedon B-8, 16 km route
1130	Arr. Ribeirão Preto for lunch
1230	Dep. Ribeirão Preto, 83 km route
1400	Arr. Pedon B-9
1445	Dep. Pedon B-9, 28 km route
1515	Arr. Pedon-10
1630	Dep. Pedon B-10, 167 km route
1900	Arr. Araxá
	Night in Araxá, Grande Hotel Balneário de Araxá

Saturday, 17 May 1986

FIELD TRIP IV:	Araxá to Uberlândia
0700	Dep. Araxá, 139 km route
0900	Arr. Pedon B-11
1040	Dep. Pedon B-11, 90 km route
1200	Arr. restaurant for lunch
1300	Dep. Restaurant, 106 km route
1430	Arr. Pedon B-12
1630	Dep. Pedon B-12, 105 km route
1800	Arr. Uberlândia
	Night in Uberlândia, Hotel Presidente

Sunday, 18 May 1986

	Free morning and early afternoon
	Technical Session V: FIELD TRIP REVIEW
	Chairman: S.W. Buol
	Venue: Hotel Presidente
1530	Review and discussion of pedons B-1 through B-12
1730	Adjourn
	Night in Uberlândia, Hotel Presidente

Monday, 19 May 1986

FIELD TRIP V:	Uberlândia to Goiânia
0700	Dep. Uberlandia, 105 km route
0830	Arr. Pedon B-13
1000	Dep. Pedon B-13, 41 km route
1040	Arr. Pedon B-14
1200	Dep. Pedon B-14, 30 km route
1230	Arr. restaurant for lunch
1330	Dep. restarurant, 135 km route
1510	Arr. Pedon B-15
1630	Dep. Pedon B-15, 98 km route
1800	Arr. Goiânia
1930	Dep. for dinner
2130	Return to hotel
	Night in Goiânia, Augustus Hotel

Tuesday, 20 May 1986

Free morning
FIELD TRIP VI: Vicinity of Goiânia
1230 Dep. Goiânia, 25 km route
1300 Arr. Pedon B-16
1430 Dep. Pedon B-16, 10 km route
1500 Arr. Pedon B-17
1700 Dep. Pedon B-17, 35 km route
1730 Arr. Goiânia
Night in Goiânia, Augustus Hotel

Wednesday, 21 May 1986

FIELD TRIP VIII: Goiânia to Brasília
0700 Dep. Goiânia, 45 km route
0800 Arr. Pedon B-18
0920 Dep. Pedon B-18, 160 km route
1120 Arr. Pedon B-19
1230 Dep. Pedon B-19, 5 km route
1240 Arr. CNPH cafeteria for lunch
1340 Dep. CNPH cafeteria, 30 km route
1410 Arr. Pedon B-20
1540 Dep. Pedon B-20, 20 km route
1610 Arr. Pedon B-21
1730 Dep. Pedon B-21, 10 km route
1750 Arr. Brasília
Night in Brasília, Hotel Carlton

Thursday, 22 May 1986

FIELD TRIP VIII: Brasília-Planaltina (CPAC) - Brasília
0730 Dep. Brasília, 35 km route
0830 Arr. Pedon B-22
1030 Dep. Pedon B-22, 800 m route
1040 Arr. Pedon B-23
1240 Dep. Pedon B-23, 1 km route
1300 Arr. CPAC cafeteria for lunch
Technical Session VI: REVIEW OF FIELD TRIP AND AGRONOMIC ASPECTS OF OXISOLS
Chairman: E. Schlichting
Venue: CPAC Auditorium
1415 Review and discussion of pedons B-13 to B-23 and the field trips in general
Discussion leader: S.W. Buol
1545 Refreshments
1600 W. Goedert and E. Lobato: Agroeconomic considerations of modern agriculture on Oxisols
1645 N. Curi and A.S. Lopes: Differentiation of Oxisols: a need for building up soil fertility and suitable management
1715 Discussion
1800 Dep. CPAC, 35 km route
1900 Arr. Brasília
Night in Brasília, Hotel Carlton

Friday, 23 May 1986

Technical Session VII: REVIEW OF THE ICOMOX PROPOSAL
Chairman: H. Eswaran
Venue: Hotel Carlton
0900 Review and discussion of the ICOMOX proposal in the light of the Brazil experience
Discussion leader: S.W. Buol
1030 Refreshments
1100 Continuation of discussion
1230 Lunch
Free afternoon
Closing dinner
Night in Brasília, Hotel Carlton

Saturday, 24 May 1986

Participants depart Brasília

LIST OF NON-BRAZILIAN PARTICIPANTS

R.W. Arnold
Director
Soil Survey Division
USDA Soil Conservation Service
P.O. Box 2890
Washington, DC 20013, USA

F.H. Beinroth
Professor
Dept. of Agronomy and Soils
University of Puerto Rico
Mayaguez, PR 00708, USA

J. Bouma
Deputy Director
Soil Survey Institute
Box 98
6700 AB Wageningen, THE NETHERLANDS

S.W. Buol
Professor
Dept. of Soil Science
North Carolina State University
P.O. Box 7619
Raleigh, NC 27695-7619, USA

H. Eswaran
Program Leader
Soil Management Support Services
USDA Soil Conservation Service
P.O Box 2890
Washington, DC 20013, USA

B.F. Hajek
Professor
Agronomy and Soils Dept.
Auburn University
Funchess Hall, Room 201
Auburn, AL 36949, USA

A.J. Herbillon
Professor
Centre de Pédologie Biologique
Centre National de la Recherche Scientifique
17, rue Notre Dames des Pauvres
B.P. 5
54501 Vandoeuvre-les-Nancy, FRANCE

A.E. Hewitt
NZ Soil Bureau
Private Bag
Lower Hutt, NEW ZEALAND

C.S. Holzhey
Head
National Soil Survey Laboratory
USDA Soil Conservation Service
Federal Building, Room 345
100 Centennial Mall North
Lincoln, NE 68508-3866, USA

C. Kalima
Soil Survey Unit
Mount Makulu Central Research Station
Private Bag 7
Chilanga, ZAMBIA

L. Moncharoen
Soil Correlator
Soil Survey and Classification Division
Department of Land Development
Bangkok 10900, THAILAND

F.R. Moormann
Professor
Institute of Earth Sciences
State University of Utrecht
P.O. Box 80.021
3508 TA Utrecht, THE NETHERLANDS

R. Schargel
Professor
UNELLEZ
Mesa de Cavacas
Guanare, Edo. Protuguesa, VENEZUELA

† E. Schlichting
Professor
Institut für Bodenkunde und Standortslehre
Universitaet Hohenheim
P.O. Box 700562
7000 Stuttgart 70, WEST GERMANY

W.G. Sombroek
Director
International Soil Reference and Information Centre
P.O. Box 353
6700 AJ Wageningen, THE NETHERLANDS

O. Spaargaren
Soil Correlator
Soil Survey Unit
Mount Makulu Central Research Station
Private Bag 7
Chilanga, ZAMBIA

R. Travernier
Professor Emeritus
Geological Institute
University of Ghent
Krijgslaan 281
9000 Ghent, BELGIUM

G. Uehara
Professor
Dept. of Agronomy and Soil Science
University of Hawaii
1910 East-West Road
Honolulu, HI 96822, USA

T. Varghese
Professor
Soil Science and Agricultural Chemistry
College of Agriculture
Kerala State University
Vellayani - 695 522
Kearala State, S. INDIA

J.E. Witty
National Leader
Soil Classification
USDA Soil Conservation Service
P.O. Box 2890
Washington, DC 20013, USA

A.R. Mermut
Professor
University of Saskatchewan
Department of Soil Science
Saskatoon - SASK
S7N - OWO, CANADA

LIST OF BRAZILIAN PARTICIPANTS

I. Andreoli
Dept. Solos e Adubos
Fac. Ciências Agrárias e Veterinárias - UNESP
Rod. Carlos Tonanni Km 5 s/n
14870 - Jaboticabal, SP, Brasil

L.H.C. dos Anjos
Dept. Solos
Universidade Federal Rural do Rio de Janeiro
Km 47 da Rodovia Rio-São Paulo
Seropédica
23460 - Itaguaí, RJ, Brasil

F.S. Antunes
Prog. Eng. Civil - COPPE
Universidade Federal do Rio de Janeiro
Cx. Postal, 68506
21945 - Rio de Janeiro, RJ
Brasil

A.M. Baruqui
EPAMIG
Rua da Bahia, 360 - 8º andar
30000 - Belo Horizonte, MG
Brasil

W.A. Carvalho
Dept. de Ciências do Solo
Fac. de Ciências Agronômicas - UNESP
Cx. Postal, 237
18600 - Botucatu, SP, Brasil

F.J. Casanova
Prog. Eng. Civil - COPPE
Universidade Federal do Rio de Janeiro
Cx. Postal, 68506
21945 - Rio de Janeiro, RJ
Brasil

A.D. Cavedon
Proj. Nacional de Irrigação
Min. Extraordinário Para Assuntos de Irrigação
SQAN Lote 1 Q 601
70830 - Brasília, DF, Brasil

J.C. Cordeiro
Centro de Ciências Agrárias
Universidade Federal do Piauí
64000 - Teresina, PI, Brasil

A.M.R. da Costa
DERNA Fundação IBGE
Rua Paulo Fernandes, 24
20271 - Rio de Janeiro, RJ, Brasil

N. Curi
Dept. Ciência do Solo
Escola Superior de Agricultura de Lavras
Cx. Postal, 37
37200 - Lavras, MG, Brasil

G. Sparovek
Dept. Solos e Adubos
Fac. Ciências Agrárias e Veterinárias
UNESP
Rod. Carlos Tonanni Km 5 s/n
14870 - Jaboticabal, SP, Brasil

W.J. Goedert
CPAC - EMBRAPA
Cx. Postal, 70.0023
73300 - Planaltina, DF, Brasil

N. Kämpf
Dept. de Solos
Universidade Federal do Rio Grando do Sul
Av. Bento Gonçalves, 7712
Cx. Postal, 776
90000 - Porto Alegre, RS, Brasil

E. Klamt
Dept. Solos
Universidade Federal do
Rio Grande do Sul
Av. Bento Gonçalves, 7712
Cx. Postal, 776
90000 - Porto Alegre, RS, Brasil

R.C. de Lemos
CETEC
Av. José Cândido da Silveira,2000
31170 - Belo Horizonte, MG
Brasil

I.F. Lepsch
Seção de Pedologia
Instituto Agronômico
Cx. Postal, 28
13100 - Campinas, SP, Brasil

A.S. Lopes
Dept. Ciência do Solo
Escola Superior de Agricultura
de Lavras
Cx. Postal, 37
37200 - Lavras, MG, Brasil

J. da S. Madeira Neto
CPAC - EMBRAPA
Cx. Postal, 70.0023
73300 - Planaltina, DF, Brasil

L.E. Mantovani
CPATSA - EMBRAPA
Cx. Postal, 23
56300 - Petrolina, PE, Brasil

A.F.S.M. Marques
CETEC
Av. José Cândido da Silveira, 2000
31170 - Belo Horizonte, MG, Brasil

J. Medina
Prog. Eng. Civil - COPPE
Universidade Federal do Rio de Janeiro
Cx. Postal, 68506
21945 - Rio de Janeiro, RJ, Brasil

A.C. Moniz
Seção de Pedologia
Instituto Agronômico
Cx. Postal, 28
13100 - Campinas, SP, Brasil

L.M.G. da Motta
Prog. Eng. Civil - COPPE
Universidade Federal do Rio de Janeiro
Cx. Postal, 68506
21945 - Rio de Janeiro, RJ, Brasil

R.A.M. Nascimento
Dept. Solos
Universidade Federal Rural do Rio de
Janeiro
Km 47 da Rodovia Rio-São Paulo
Seropédica
23460 - Itaguaí, RJ, Brasil

J.B. de Oliveira
Seção de Pedologia
Instituto Agronômico
Cx. Postal, 28
13100 - Campinas, SP, Brasil

V. de Oliveira
DERNA - Fundação IBGE
Rua Paulo Fernandes, 24
20271 - Rio de Janeiro, RJ, Brasil

H. do Prado
Seção de Pedologia
Instituto Agronômico
Cx. Postal, 28
13100 - Campinas, SP, Brasil

R.A. Quintino
DERNA - EMBRAPA
Rua Paulo Fernandes, 24
20271 - Rio de Janeiro, RJ, Brasil

B. van Raij
Seção de Fertilidade do Solo e
Nutrição de Plantas
Instituto Agronômico
Cx. Postal, 28
13100 - Campinas, SP, Brasil

G. Ranzani
Dept. Técnico Científico - EMBRAPA
SAIN W3 Norte Final
70770 - Brasília, DF, Brasil

S.B. de Rezende
Dept. de Solos
Universidade Federal de Viçosa
36570 - Viçosa, MG, Brasil

L.P. Ribeiro
Dept. de Geoquímica
Universidade Federal da Bahia
Rua Caetano Moura, 123
40000 - Salvador, BA, Brasil

M.R. Ribeiro
Dept. de Solos
Universidade Federal Rural
de Pernambuco
Rua Dom Manuel de Medeiros s/n
50000 - Recife, PE, Brasil

D.P. Santana
CNPMS - EMBRAPA
Rod. MG 424 Km 45
35700 - Sete Lagoas, MG, Brasil

A. Santos Filho
Dept. de Solos
Universidade Federal do Paraná
Rua dos Funcionários s/n
Cx. Postal, 672
80000 - Curitiba, PR, Brasil

G.A. Santos
Dept. de Solos
Universidade Federal Rural do
Rio de Janeiro
Km 47 da Rodovia Rio-São Paulo
Seropédica
23460 - Itaguaí, RJ, Brasil

M.C. dos Santos
Dept. de Solos
Universidade Federal Rural de
Pernambuco
Av. Dom Manuel de Medeiros s/n
50000 - Recife, PE, Brasil

C.G. Souza
DERNA - Fundação IBGE
Rua Paulo Fernandes, 24
20271 - Rio de Janeiro, RJ, Brasil

J.M.A.S. Valadares
Seção de Pedologia
Instituto Agronômico
Cx. Postal, 28
13100 - Campinas, SP, Brasil

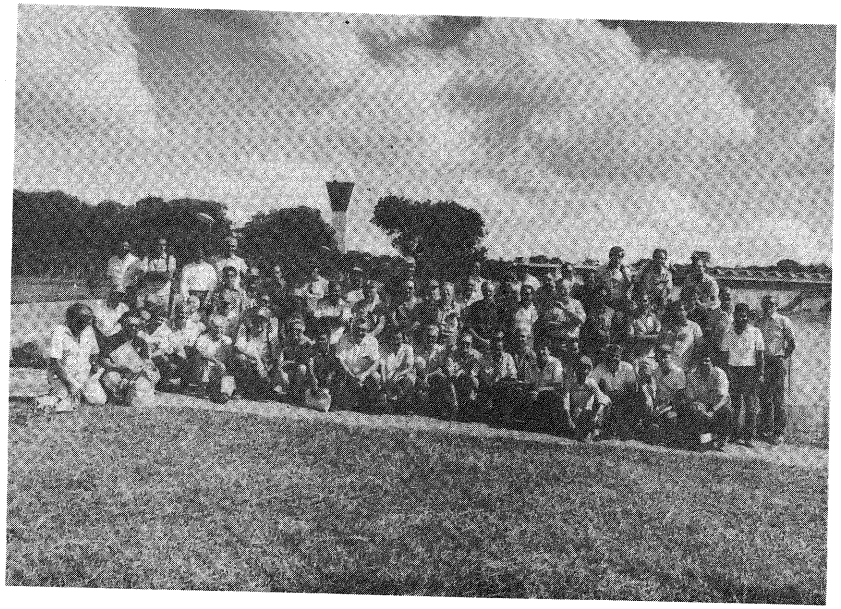
P. Vidal T.
Dept. de Solos e Adubos
Fac. Ciências Agrárias e Veterinárias -
UNESP
Rod. Carlos Tonanni Km 5 s/n
14870 - Jaboticabal, SP, Brasil

SNLCS PARTICIPANTS

J.A.M. do Amaral
W.S. de Araujo
D.S. Assis
M.N. Camargo
A.P. Carvalho
M.A. de M. Duriez
P.J. Fasolo
O.O.M. da Fonseca
J.R.N.F. Gama
I.A. Gomes
P.K.T. Jacomine
R.A.L. Johas
P.C. de Lima
T. da C. Lima
O.F. Lopes
L.A.R. Medeiros
M.E.C.C. de M. Melo
H.F.R. de Melo Filho

E.P. Mothci
L.B. de Oliveira
J. Olmos I.L.
F. Palmieri
L.A. Panoso
J.L. de Paula
A.M. Pires Filho
R.O. Pötter
A. Ramalho Filho
M. de J. Rauen
R.S. Rêgo
T.E. Rodrigues
F.B. Rodrigues e Silva
H.G. dos Santos
J.M.L. da Silva
J.L.R. de Souza
K.P. Wittern

Serviço Nacional de Levantamento e Conservação de Solos - EMBRAPA
Rua Jardim Botânico, 1024
22460 - Rio de Janeiro, RJ
Brasil



Field tour participants of the Eighth International Soil Classification Workshop.

Impressão e Acabamento
GRAPHOS
Rua Santo Cristo, 70/78 — Tel.: 223-1272