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FERRALSOLS AND RELATED SOILS: CHARACTERISTICS AND CLASSIFICATION

Edited by

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International Soil Reference and Information Centre
Wageningen - The Netherlands

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FERRALSOLS AND RELATED SOILS: CHARACTERISTICS AND CLASSIFICATION

Edited by

E. Klamt[1] and L.P. van Reeuwijk[2]

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1. EVALUATION OF CHARACTERISTICS OF FERRALSOLS AND RELATED SOILS

E. Klamt, L.P. van Reeuwijk and W.G. Sombroek

1.1 Introduction

Ferralsols are strongly weathered soils found on old geomorphic surfaces, covering extensive areas in the tropical region of South America and Africa and minor ones in Asia, Australia and Central America. These regions are sparsely populated because of natural soil infertility, inhospitable environment for men life (e.g., tropical diseases), distance from developed centres and other reasons. But they represent possibilities for the expansion of agricultural areas, mainly due to their suitable climatic and topographic conditions for crop production. At the same time it is recognized that many of these soils are under pristine tropical rain forest, a most valuable natural resource on its own.

Because of their occurrence in tropical regions, where generally the development of scientific investigation has not reached the level of temperate regions, detailed studies of their characteristics are scarce. To strengthen the state of knowledge on Ferralsols, the International Soil Reference and Information Centre (ISRIC) has described in the field and sampled a considerable number of profiles of this group and related soils and analyzed their most important physical, chemical and mineralogical properties.

The purpose of this monograph is to present the data obtained; to analyze their consistence and/or variability; to search for possible charactesitics better describing and differentiating Ferralsols and related soils, such as Cambisols, Acrisols, Lixisols and Nitisols with low activity clays.

1.2 Literature Review

1.2.1 Concept of Ferralsols and Related Soils

As defined in the Revised Legend of the Soil Map of the World (FAO, 1988), Ferralsols are soils having a Ferralic B horizon, lacking an Argic or Natric B horizon above the Ferralic B horizon. The Ferralic B horizon is a subsurface horizon that:

a) is at least 30 cm thick,
b) has cation-exchange capacity (CEC) $\leq$ 16 $cmol_c$/kg clay or an effective cation-exchange capacity (ECEC) $\leq$ 12 $cmol_c$/kg clay (sum of NH_4OAc-exchangeable bases plus 1 M KCl-exchangeable acidity),
c) has < 10% weatherable minerals in the 50-200 μm fraction,
d) has texture that is sandy loam or finer and has at least 8% clay in the fine-earth fraction,
e) has < 10% water-dispersable clay,
f) has < 5% by volume showing rock structure,
g) has a silt/clay ratio $\leq$ 0.2 and,
h) does not have andic properties.

Not considering minor differences, this soil class corresponds to the *Oxisols* of Soil Taxonomy (SCS/USDA, 1975); *Latosols* of the soil classification as used in the Brazilian soil surveys (Camargo et al., 1987); *Krasnozems* of the Australian soil classification system (Isbell, 1977) and *Ferralitic* soils (Duchaufour, 1963) or *Fermonosialsols* and *Oxydisols* (Segalen et al., 1974) in the French systems.

At the second categorical level, Ferralsols have been subdivided into the following units: *Plinthic* - having plinthite within 125 cm of the soil surface; *Geric* - having $\leq$ 1.5 $cmol_c$/kg exchangeable bases plus unbuffered 1 *M* KCl-extractable Al and a pH (1 *M* KCl) $\geq$ 5; or a ΔpH (pH-KCl minus pH-H2O) $\geq$ +0.1; *Umbric* - having an umbric A or mollic A horizon; *Rhodic* - having a red to dusky red B horizon; *Xanthic* - having a yellow to pale yellow B horizon; and *Haplic* - other Ferralsols (FAO, 1988). "Related soils", as conceived in this paper, are low-activity clay Cambisols, Acrisols, Lixisols and Nitisols.

After completion of part of this study the 1988 revised version of the Legend of the Soil Map of the World came ahead. This implies that the concepts of the 1985 version have been used as basis for data analysis, but a specific chapter has been devoted to describe the changes introduced by the 1988 revision, its merits and influence on the classification of Ferralsols.

1.2.2 Soil Morphology and Particle-Size Distribution

Ferralsols have very deep sola, diffuse boundaries between horizons and are well drained, while the Cambisols, Acrisols, Lixisols and Nitisols have somewhat shallower sola, with clear to gradual horizonation.

The most prominent and observable morphological property of Ferralsols is their colour, iron being the main painter, followed by organic matter. Studies by Kämpf and Schwertmann (1983), Torrent et al. (1984), Schwertmann (1985) and other authors have shown that the red and yellow hues are related respectively to the proportion of hematite and goethite in the soil material.

Ferralsols have a sandy loam or finer texture and little textural differentiation within the profile. With respect to textural differentiation, Cambisols are related to Ferralsols, while Acrisols, Lixisols and Nitisols show a pronounced textural increase from the topsoil to the subsurface horizons. In many soils it is difficult to define the presence of Ferralic B horizon, due to the presence of a weak textural gradient and/or a gradient which satisfies the requirement for Argic B horizon, but with absence of indications of clay translocation (clay skins) and weak structural development.

As a rule these soils have a low silt content, because primary minerals in this fraction are unstable and secondary minerals are found mainly in the clay fraction. Due to strong aggregation of some clayey soils they feel like loam or sand, when estimating field texture. The silt/clay ratio is also low and is used as weathering index and classification parameter. Soils with a silt/clay ratio < 0.5 are regarded as highly weathered; a ratio < 0.7 is used in the Brazilian system as a parameter to define Latosolic B horizon (Camargo, Klamt and Kauffman, 1987); and a ratio ≤ 0.2 to define the Ferralic B horizon (FAO, 1988).

Clay cutans or clay skins, developed by eluviation/illuviation of clay particles is a diagnostic feature used to define Argillic and Argic B horizons (SCS/USDA, 1975 and FAO, 1988). This feature is very difficult to determine in these soils and constitutes the most severe classification problem to separate Ferralsols (Ferralic horizon) and Cambisols (Cambic horizon) without or with weak skins, from Acrisols, Lixisols and Nitisols, which have and Argic horizon with clay skins (Moormann and Buol, 1981).

Ferralsols in general have a massive to weak subangular blocky structure, while in Cambisols, Acrisols, Lixisols and particularly Nitisols, up to moderate and strong subangular blocky structures are found. The strong granular or crumb-like structure of some Ferralsols, known as "coffee powder", is related to aggregation of particles by amorphous and/or crystalline forms of iron and/or aluminum oxihydroxides, although some authors (Verheye and Stoops, 1975) have related these to biological activity (termites).

The soils under investigation are in general very friable to friable when moist as well as slightly sticky to sticky and slightly plastic to plastic when wet, depending mainly on texture. But even the clayey types do not become as sticky, plastic and hard as most soils of temperate or colder climates, in which mainly 2:1 type clay minerals are found.

Nodules, concretions of iron and other heavy metal compounds, petric and petroferric phases are common features of these soils. They are usually very porous, most of the pores being of microscopic diameter ($< 75\ \mu m$). Since they are difficult to be determined in the field, indirect measurements such as the velocity and amount of water intake by soil peds, are ways to estimate pore abundance.

1.2.3 Exchange Properties of Ferralsols and Related Soils

Highly weathered Ferralsols, Acrisols, Lixisols, Cambisols and Nitisols have a very low CEC and base saturation and often a high aluminum saturation. These properties are related to the mineralogical composition and organic matter content of the soil mass. This is expressed in the concept of Ferralsols, which have a Ferralic horizon, with a fine-earth fraction (< 2 mm) having a CEC (by NH_4OAc) ≤ 16 $cmol_c/kg$ clay (FAO, 1988).

Klamt and Sombroek (1988) have shown that the mean CEC of 1 g of carbon is 3.36 $cmol_c/kg$ (range: 1.4 to 9.4 $cmol_c/kg$) and that the contribution of organic matter to soil CEC is high (average: 51%) in surface horizons of Oxisols (Ferralsols). In the B horizon this contribution is lower (average: 18%). They state that this contribution should be considered in determining the CEC of the clay fraction, a parameter used in classification of Ferralsols.

1.2.4 Mineralogical Composition

The characteristics and properties of Ferralsols and related soils, as in other soil groups are mainly related to the nature and composition of their mineral soil mass, which consists mainly of kaolinite, hematite and/or goethite, gibbsite, "amorphous" materials and quartz. Aluminous interlayered chlorites and mica may occur in minor proportions (Moniz & Jackson, 1967; Moura Filho & Buol, 1972; Rodrigues & Klamt, 1978; Weaver, 1974; Le Roux, 1973). A leaching environment, with high temperature and high continuous rainfall, occurrence on old and stable surface and the presence of highly weatherable parent materials are determinants for Ferralsol formation (Eswaran & Tavernier, 1980). Some Ferralsols occurring in different climatic conditions (drier and/or colder) indicate that they reflect changes of climate in areas of their occurrence (King, 1965; Lücken et al., 1982). The leaching environment associated with high precipitation causes strong, desilication and residual concentration of Al, Fe and Mn oxides/hydroxides in these soils (Eswaran & Tavernier, 1980), although these features have not been much investigated.

1.3 Material and Methods

1.3.1 Soil Description and Collection

In all, 58 soil profiles, representing Ferralsols (41) and low-activity clay Cambisols, Lixisols, Acrisols and Nitisols (17) of the International Soil Reference and Information Centre (ISRIC) collection, described and sampled in nineteen different countries of tropical and subtropical regions were selected for the present study. The profiles related to Ferralsols were included to increase the variability of properties for statistical analysis and also to test usefulness of parameters presently in use and to be proposed to characterize and differentiate these soils. The classification of the selected monoliths according to FAO World Soil Map Legend (FAO/UNESCO, 1974) and corresponding Great Groups in Soil Taxonomy (SCS/USDA, 1975), is described in Chapter 2 where the classification of the profiles according to the FAO revised legend (1988) and the revised Soil Taxonomy (SMSS, USDA, 1990) is analyzed.

The selection of the sites for soil description and the actual collection was carried out by both soil scientists from ISRIC and from local institutions, acquainted with the characteristics and distribution of the soils in each country, in order to obtain a good representativeness of the sites. Figure 1 illustrates the location of sites where the profiles were collected and Table 1 gives details of the geographical information.

The soil profile descriptions were based on the guidelines of Food and Agricultural Organization of the United Nations (FAO, 1977). For the collection, preparation and preservation of representative monoliths the procedures described by Van Baren and Bomer (1979) were followed. For most profiles, in addition to the monolith and bulk samples of each horizon, core samples for water retention curves (pF) and special samples for the preparation of thin sections for micromorphological investigation, were collected also.

Table 1. Geographical location of soil profiles used in this study

N° on MAP	PROFILE CODE	LOCATION	LATITUDE	LONGITUDE	ALTITUDE (m.a.s.l.)	CLASSIFICATION (FAO, 1988)
1	BR 3	Brazil, RJ, Itaperuna-Raposo	S 21° 08'	W 42° 05'	210	Rhodic Ferralsol
2	BR 4	Brazil, SP, INDERP	S 21° 14'	W 47° 47'	650	Rhodic Ferralsol
3	BR 5	Brazil, SP, Gravinhos	S 21° 21'	W 47° 44'	760	Geric Ferralsol
4	BR 6	Brazil, SP, Marilia/Assis	S 22° 33'	W 50° 19'	562	Rhodic Ferralsol
5	BR 7	Brazil, PR, Londrina/Ponta Grossa	S 23° 40'	W 51° 10'	480	Rhodic Nitisol
6	BR 8	Brazil, PR, Ivaipora/Pitanga	S 24° 18'	W 51° 43'	760	Humic Ferralsol
7	BR 9	Brazil, PR, Pitanga/Guarapuava	S 25° 06'	W 51° 32'	1100	Humic Ferralsol
8	BR 10	Brazil, PR, Curitiba/Joinville	S 25° 40'	W 49° 11'	910	Humic Ferralsol
9	BR 11	Brazil, PA, Castanhal	S 01° 22'	W 47° 11'	70	Xanthic Ferralsol
10	BR 13	Brazil, PA, Santarem/Cuiaba	S 02° 54'	W 54° 56'	75	Xanthic Ferralsol
11	BR 14	Brazil, DF, Planaltina	S 15° 30'	W 47° 40'	950	Rhodic Ferralsol
12	BR 15	Brazil, DF, Planaltina	S 15° 35'	W 47° 40'	1030	Geric Ferralsol
13	BR S1	Brazil, RJ, Resende	S 22° 28'	W 44° 31'	480	Xanthic Ferralsol
14	BR S2	Brazil, RS, Girua	S 28° 05'	W 54° 25'	350	Rhodic Ferralsol
15	CM 1	Cameroon, Barombi-Kang Exp. Sta.	-	-	180	Haplic Nitisol
16	CN 4	China, Changsha, Hunan	N 28° 12'	E 113° 05'	40	Haplic Nitisol
17	CN 7	China, Guangzhow, Logang	N 23° 13'	E 113° 28'	45	Haplic Acrisol
18	C0 2	Colombia, Gaitan/Porto Lopes	N 04° 10'	W 72° 55'	225	Ferralic Cambisol
19	CO 15	Colombia, San Jose del Guaviare	N 02° 30'	W 72° 38'	250	Plinthic Acrisol
20	CO 18	Colombia, El Granha	N 02° 25'	W 72° 40'	220	Rhodic Ferralsol
21	GA 1	Gabon, Makokou, Layon	N 00° 31'	E 12° 48'	530	Xanthic Ferralsol
22	GA 4	Gabon, Poungan/Lebamba	S 02° 13'	E 11° 33'	215	Xanthic Ferralsol
23	GA 5	Gabon, Ndende bridge	S 02° 21'	E 11° 23'	150	Xanthic Ferralsol
24	IN 9	India, Hoskote/Devanahalli, Bangalore	N 13° 08'	E 77° 50'	350	Ferric Lixisol
25	ID 1	Indonesia, Parung, Java	S 06° 23'	E 106° 32'	140	Rhodic Ferralsol
26	ID 2	Indonesia, Ranoamaya, Java	S 06° 39'	E 106° 49'	450	Ferralic Cambisol
27	ID 15	Indonesia, Central Kalimantan	S 00° 32'	E 112° 36'	150	Xanthic Ferralsol
28	CI 1	Ivory Coast, Tai Forest	N 05° 53'	W 07° 20'	177	Ferric Acrisol
29	CI 4	Ivori Coast, Tai Forest	N 05° 53'	W 07° 20'	166	Xanthic Ferralsol
30	JM 3	Jamaica, Manchester	N 18° 04'	W 77° 27'	390	Geric Ferralsol
31	KE 6	Kenya, Embu district	S 00° 32'	E 37° 28'	1260	Rhodic Ferralsol
32	KE 7	Kenya, Embu district	S 00° 32'	E 37° 28'	1325	Ferralic Cambisol
33	KE 11	Kenya, Sokoko, Kilifi district	S 03° 27'	E 39° 50'	160	Rhodic Ferralsol
34	KE 29	Kenya, Cambini, Kilifi district	S 03° 37'	E 39° 50'	96	Rhodic Ferralsol

N° on MAP	PROFILE CODE	LOCATION	LATITUDE	LONGITUDE	ALTI-TUDE (m.a.s.l.)	CLASSIFICATION (FAO, 1988)
35	MY 1	Malaysia, Serdang	N 05° 16'	E 100° 34'	-	Rhodic Ferralsol
36	MY 3	Malaysia, Kuantan, Pahang	N 03° 40'	E 103° 30'	-	Geric Ferralsol
37	MY 5	Malaysia, Temerloh/Kuantan, Pahang	N 03° 20'	E 102° 30'	-	Rhodic Ferralsol
38	MY 6	Malaysia, Puchong, Selangor	N 03° 02'	E 101° 37'	-	Ferric Acrisol
39	MY 7	Malaysia, Kuala Pilah/Tampin	N 02° 44'	E 102° 15'	-	Geric Ferralsol
40	MY 56	Malaysia, Kuching, Sarawak	N 01° 32'	E 110° 20'	50	Geric Ferralsol
41	MY 57	Malaysia, Lundu Sekambal, Sarawak	N 01° 40'	E 109° 52'	90	Xanthic Ferralsol
42	MZ 2	Mozambique, Niassa, Lichinga	S 13° 08'	E 35° 16'	1325	Rhodic Ferralsol
43	MZ 3	Mozambique, Niassa, Sanga, Unango	S 12° 57'	E 35° 23'	1075	Rhodic Nitisol
44	PE 1	Peru, Yurimaguas	S 05° 45'	W 76° 05'	182	Ferric Acrisol
45	WS 1	Savai'i Island, West Samoa	S 13° 27'	W 172° 22'	63	Geric Ferralsol
46	SU 254	CIS, Chakva, Georgia, (GLINKA MEMORIAL COLLECTION)	N 41° 45'	E 41° 45'	_	Humic Alisol
47	SU 256	CIS, Makahradze, Georgia, (GLINKA MEMORIAL COLLECTION)	N 41° 55'	E 42° 02'	-	Ferric Alisol
48	ZA 2	South Africa, Hermansburg, Natal	S 29° 04'	E 30° 47'	1135	Rhodic Ferralsol
49	ZA 20	South Africa, Highover, Richmond	S 29° 55'	E 30° 04'	3800	Ferralic Cambisol
50	US 3	United States, Lexington, North Carolina	N 35° 50'	W 80° 27'	-	Rhodic Nitisol
51	US 8	United States, Dahu Isl., Kunia, Hawaii	N 21° 24'	W 158° 02'	136	Haplic Acrisol
52	US 9	United States, Dahu Isl., Waipio, Hawaii	N 21° 26'	W 158° 00'	150	Rhodic Ferralsol
53	US 10	United States, Kauai Isl., Wailua, Hawaii	N 22° 04'	W 159° 24'	180	Geric Ferralsol
54	ZM 2	Zambia, Kasama District, N. Prov.	S 10° 13'	E 31° 08'	1385	Rhodic Ferralsol
55	ZM 4	Zambia, Mbala/Kasama, N. Prov.	S 08° 50'	E 31° 24'	1673	Rhodic Ferralsol
56	ZM 5	Zambia, Kasama District, N. Prov.	S 10° 13'	E 31° 08'	1384	Xanthic Ferralsol
57	ZM 8	Zambia, Kasama District, N. Prov.	S 10° 10'	E 31° 08'	1400	Ferric Acrisol
58	ZM 9	Zambia, Kasama District, N. Prov.	S 10° 10'	E 31° 11'	1370	Xanthic Ferralsol

1.3.2 Environmental Conditions of Sampling Sites

Ferralsols and related soils are found in tropical and subtropical humid and sub-humid regions. The occurrence of these soils in semi-arid and arid climates suggest that they represent relics of former wetter climates (CSC/USDA, 1975; Lepsch et al., 1982; Lücken et al., 1982). According to the concepts defined in Soil taxonomy (SCS/USDA, 1975), most of the profiles occur in regions with udic (50%) and ustic (43%) soil moisture regimes. Only 5% of them present perudic conditions and 2% torric. The predominant soil temperature regimes are isohyperthermic (45%) and thermic (34%); while 17% is hyperthermic and 2% isothermic and isomesic respectively.

These soils occur mainly on old and stable landscapes (SCS/USDA, 1975). As for the regional type of physiography, 57% of the profiles were samples on broad gently undulating to undulating plateaus (pediplains and peneplains), 15% on broad hills with depressions, 12% on erosional plains, 5% on alluvial terraces and 4% respectively on low hills and gently sloping fluvio-lacustrine terraces, one profile came from a karst depression (ISRIC, 1985). In terms of slope gradients, 30 profiles were sampled on flat surfaces (< 2% slope), 20 profiles on gently sloping to sloping surfaces (2-8%), 5 profiles on strongly sloping (8-16%), and one profile on moderately steep (16-30%) and one on steep sloping (30-55%) surface respectively.

The parent material from which Ferralsols and related soils have developed is in most cases difficult to determine with certainty, because weathering commonly has proceeded to great depths and produced a thick regolith. Erosional and depositional processes have reworked the parent material in most tropical and subtropical environments (Schwertmann et al., 1983) and most of these materials, and soils derived from them, were subject to several cycles of climatic and thus biological changes (Bigarella, 1964).

The sediments and soils originating from erosional and depositional processes show a great variety of characteristics due to variation in the original parent material and subsequent forms of alteration they have undergone. The

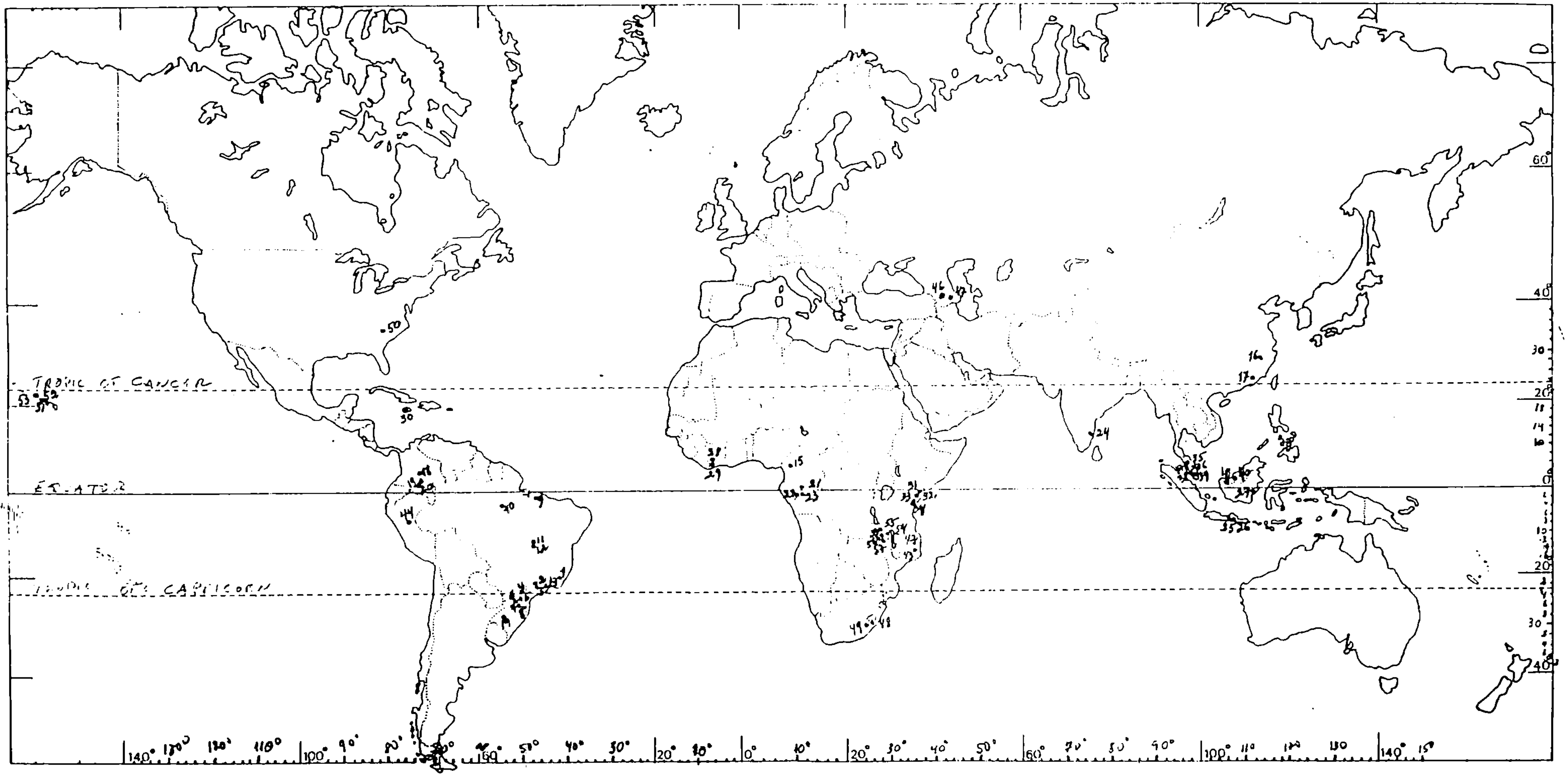


FIG. 1. Location of sites of monoliths used in this study.

wide variation in parent material of the profiles is expressed in Table 2.

TABLE 2. Distribution of the profiles according to parent material

Type of parent material	Number of profiles
Sedimentary: sandstone, limestone, unspecified	8
Volcanic extrusive: ejecta ash (andesitic) and tuff	4
Volcanic intrusive:	
a) coarse-grained, intermediate and acidic (diorite, granodiorite, granite)	6
b) fine-grained, intermediate and basic (diabase, basalt, andesite, spillite, dolerite, phonolite)	15
Metamorphic rocks:	
a) Acidic (migmatite, gneiss, schist)	5
b) Basic (charnokites, serpentinites, calcaric schist)	3
Unconsolidated material:	
a) Sandy clay texture	7
b) Clayey texture	8
Unknown	2

The vegetation at the soil collection sites varies widely and is related mainly to the present climatic conditions. A listing of the original vegetation found on the sampling sites is given on Table 3. Evergreen to semi-deciduous forest occurs on 60% of the sites which correlates well with 55% of the sites occurring in udic or perudic soil moisture regimes. The natural vegetation on two third of the sites has been substituted by cultivated crops or grassland. Forest remains on about one fifth of the soil collection sites, of which only a small proportion was due to reforestation or afforestation. Grassland occurs on one third of the sites, industrial crops such as coffee, cocoa and sugar cane on 14% and fruit crops on 4%.

TABLE 3. Type of original vegetation on the soil sites

Type of vegetation	Percentage of profiles	Number of profiles
Evergreen to semi-deciduous closed forest	45	26
Evergreen to semi-deciduous open woodland	15	9
Evergreen to semi-deciduous shrubs	13	8
Herbaceous vegetation	14	8
Unknown	13	7

The hydrology on 85% of the description sites is well drained, on 12% somewhat poorly drained and on 3% somewhat excessively drained. Erosion, when indicated, is predominantly of slight sheet erosion, but on 15% of the sites moderate sheet and/or gully erosion has been reported.

1.3.3. Laboratory Procedures

Samples of the 58 profiles collected were air-dried and gently crushed to pass through a 2 mm sieve. This *fine earth* was used to perform physical, chemical and mineralogical analyses. Methods used were described in detail by Van Reeuwijk (1986, 1993). An outline of the principles is given here.

Particle-size analysis. After removal of organic matter withH_2O_2, particle-size distribution was determined by pipetting the silt and clay fraction using sodium pyrophosphate as dispersing agent. Water-dispersable clay was also determined by the pipette method. Particle-size distribution of selected samples was also carried out including a deferration pretreatment with sodium dithionite.

Soil pH was determined using a 1:2.5 soil-water and soil-1 *M* KCl ratio.

Organic matter by the Walkley/Black wet combustion method.

CEC and exchangeable bases by the NH_4OAc method. Exchangeable cations by leaching with NH_4OAc 1 *M* pH 7 and measurement of Ca and Mg by atomic absorption and K and Na by flame emission spectrophotometry respectively; cation exchange capacity (CEC_{soil}) by replacing the NH_4 of the former determination by Na using 1 *M* NaOAc pH 7, washing the excess Na with 48% ethanol and replacing of absorbed Na by leaching with 1 *M* NH_4OAc pH 7 and determination of Na by *FES.*

Exchangeable acidity and aluminium were extracted with 1 *M* KCl, Al determined by *AAS* and exchangeable acidity by back-titration with 0.025 *M* NaOH.

Calculated were:
sum of bases (exch. Ca + Mg + K + Na),
CEC_{clay} per kg of clay (CEC_{soil} × 100/%clay),
base saturation (BS: sum of bases × 100/CEC_{soil}),
effective cation exchange capacity of the soil ($ECEC_{soil}$ = sum of bases + exch. Al),
ECEC of the clay ($ECEC_{clay}$ = $ECEC_{soil}$ x 100/%clay),
aluminum saturation (AlS: KCl-Al × 100/CEC_{soil}).

As the CEC_{soil} is composed of two main contributions: the CEC_{clay} and $CEC_{organic\ matter}$, for a correct calculation of the CEC_{clay} the CEC_{soil} has to be corrected for the organic matter contribution. This was done by regression analysis using the equation proposed by Bennema (1966), Bennema and Camargo (1979) and Klamt and Sombroek (1989) (see also Chapter 4):

$$Y = a + bX$$

where:

Y = CEC_{soil} × 100/%clay
X = %C × 100/%clay)
a = CEC of carbon (in $cmol_c$ per %C)
b = CEC of clay (in $cmol_c$/kg)

Note: The CEC of soil and other materials is nowadays commonly expressed in *$cmol_c$/kg* as this facilitates direct comparison with older data which were expressed in *meq/100 g* (expression in *$mmol_c$/kg* implies multiplication by a factor 10). In above cited publications the CEC was still expressed in meq/100 g and, therefore, the parameter *a* was originally designated *CEC of 1 g of carbon in meq.* For direct comparison and use the unit of *a* needed to be transformed to *$cmol_c$/%C* (= $mmol_c$/1 g of C = $cmol_c$/10 g of C).
In calculations *% carbon* is used rather than *% organic matter* as the former is actually determined.

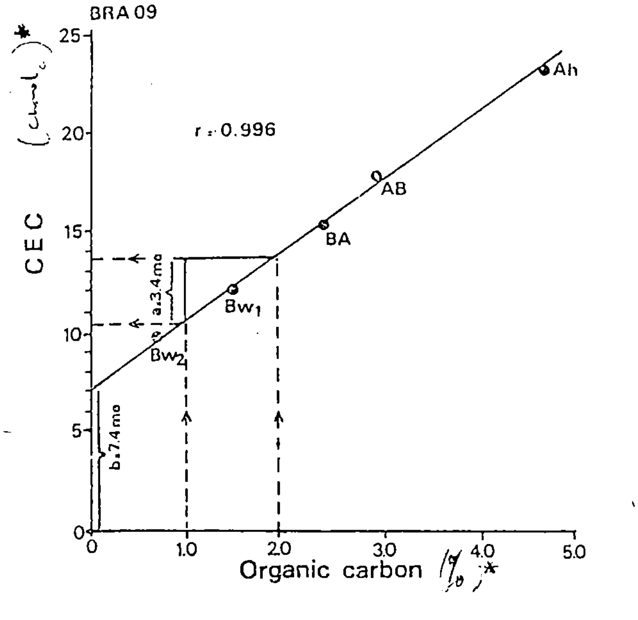


FIG. 2. Relation between CEC of the soil and its contribuants clay and organic carbon of Profile BR 09 (based on equation of Bennema, 1966; and Bennema and Camargo, 1979).
*** Units on both abcissa and ordinate are converted to 100% clay basis (i.e. for each horizon direct results of %C and CEC_{soil} multiplied by 100/%clay).**

Graphically, this equation (Fig. 2) results in a straight line, in which the intercept *b* represents the corrected CEC_{clay} (in $cmol_c/kg$) and the slope *a* the CEC resulting from 1% of carbon. (Note that this value × 100 gives the CEC of organic matter expressed as $cmol_c/kg$ C).
This procedure is valid only if: (1) the CEC originates only from organic matter and clay and (2) the CEC of organic matter and of clay is constant in the solum, which seems to be the case in the Ferralsols studied, considering the straight lines obtained.

Note: Problems related to analytical procedures such as incomplete dispersion in particle-size analysis, combustion of organic matter, and replacement of adsorbed ions in CEC determination, may adversely affect the calculated contributions of clay and organic carbon to the CEC.

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

$$\frac{CEC_{1\%\,carbon} \times \%C}{CEC_{soil}} \times 100$$

Bulk density, moisture retention and *specific surface area* were determined only on samples of the A, AB or BA and B horizons of thirty soil profiles distributed as follows:
Ferralsols: Brazil (8), Colombia (1), Ivory Coast (1), Kenya (4), Gabon (2), Indonesia (1), Malaysia (2), Mozambique (1) and Zambia (2);
Nitisols: Brazil (1) and Malaysia (1); and
Cambisols: Indonesia (1).

Soil moisture retention was determined with core samples collected in 100 ml steel rings with a 5 cm diameter, using a silt/kaolin bath for pF < 3.0 (1.0, 1.5, 2.0, 2.3, and 2.7) and pressure plates for pF > 3.0 (3.5 and 4.2). *Bulk density* was determined with the same cores.

Specific surface area was determined by the ethylene glycol monoethyl ether (*EGME*) retention method (Heilman, Carter and Gonzales, 1965).

Iron and *aluminium* were *extracted by acid ammonium oxalate* (Fe_o and Al_o) and *sodium dithionite* (Fe_d and Al_d) and determined by AAS. The ratios Fe_o/Fe_d and Al_o/Al_d were calculated.
The *elemental composition of the clay fraction* was determined by X-ray fluorescence spectroscopy and the *mineralogical composition* of oriented clay samples, mounted on porous plates with suction, by X-ray diffractometry. The clay specimens were examined after saturation with K at room temperature and heated to 550 °C and after Mg saturation and glycerol solvation.

Weatherable minerals in the fine sand fraction (50-500 μm) were estimated by counting method, using a petrographic microscope.

1.3.4. Statistical treatment of data

Statistical treatment of the data sets was performed using the SPSS Statistical Package (Nie, 1975).

1.4 Results and Discussion

1.4.1. Morphological Characteristics of the Soils

A very deep solum (> 200 cm), diffuse boundaries between horizons and good internal drainage are morphological features common to most Ferralsols, in contrast to the somewhat shallower sola with clear to gradual horizonation of Cambisols, Acrisols, Lixisols and Nitisols.

Colour is the most prominent morphological feature of these soils, with hues varying from 10R to 10YR, values from 3 to 7 and chromas from 2 to 8. Clustering these soils on basis of hues, values and chromas of the diagnostic subsurface horizons, yielded seven clusters (1 to 7, see Table 4) of soils with different colours. This number can be reduced to four (I to IV) by considering the narrow range of hues of Clusters 1 and 2, 3 and 4, and 5 and 6, respectively. Examples of the colour clusters are given in Plate 1.

Cluster I is formed by soils with Rhodic properties (FAO/UNESCO, 1974; FAO, 1988), with the exception of some profiles with too high values and/or chromas; Cluster II by those with Orthic properties; Cluster III with Xanthic properties, with the exception of one profile with too low colour values; and Cluster IV comprising dark grayish brown to dark brown soils, which do not fit in the other soil units based on soil colour. Their low colour values and chromas are related to a high organic matter content, which in turn is related to specific environmental conditions, since these soils are found in udic and perudic soil moisture regimes (SCS/USDA, 1985). Studies of Kämpf and Schwertmann (1985), Torrent et al. (1984), Curi and Franzmeier (1984), Adams and Kassis (1984), Kämpf and Klamt (1984), Schwertmann (1985), and Fabris et al. (1985) have shown that red and yellow hues are related to

Table 4. Clusters of Ferralsols and Related soils based on their hues, values and chromas.

Number of Clusters		Number of Profiles	Hues	Colour Values	Chromas	Soil Colour
I	1	16	10R - 1.5YR	3	3 - 4	Dark red
	2	28	1YR - 2.5YR	3 - 5	4 - 8	Dark red to red
II	3	5	5YR	3 - 4.5	3 - 4	Dark reddish brown to reddish brown
	4	16	5YR - 6YR	3.5 - 5	5 - 8	Yellow red
III	5	13	6.5YR - 7.5YR	4 - 7	6 - 8	Dark yellowish
	6	19	9YR - 10YR	3.5 - 6	6 - 8	brown to yellow
IV	7	5	7.5YR - 10YR	3 - 4	2 - 4	Dark grayish brown to dark brown

the proportion of hematite and goethite in the soil material.

Kämpf and Klamt (1984) proposed to divide Brazilian Latosols into three units based on Hm/(Hm+Gt) ratios and soil colour:

(1) mainly goethitic soils, with Hm/(Hm+Gt) < 0.2 and hues yellower than 6 YR;

(2) goethitic-hematitic soils, with Hm/(Hm+Gt) = 0.2-0.6 and hues between 6YR and 3YR; and

(3) mainly hematic soil, with Hm/(Hm+Gt) > 0.6 and hues 2.5YR or redder.

There is a good relationship between these three units and the clusters obtained since Cluster I fits into unit (3); Cluster II in unit (2) and Clusters III and IV into unit (1). Colour as used in the FAO (1988) Revised Legend of the Soil Map of the World is consistent with these data, but it is proposed that the hues of Rhodic Ferralsols should be set at 3YR or redder and of the Xanthic units at 6YR or yellower.

Mottles were described in a few profiles, occurring as lithorelics (BR 7, BR 10 and US 10) or related to iron segregation (CH 4) and iron concretions and stones (GA 5, CI 4), due to temporary high water tables. Couto and Sanzonowiez (1984) and Couto et al. (1985), have reported the presence of a high water table in Ferralsols without affecting soil colour. This was ascribed to a lack of energy to reduce iron oxides as a result of a low content and/or of inactive forms of organic matter.

More than half of the soils (56%) have a clayey texture, followed by sandy clay loam (18%), sandy clay (15%), clay loam (5%), and silty clay types (5%) while one profile consists of sandy loam and one of silt loam. A low silt content is a dominant characteristic of all soils studied, but particularly of Ferralsols. Clay increase and textural change with depth is by definition negligible in typical Ferralsols (BR 5 and ID 15) and Cambisols (ID 2), but slight in intergrades between Ferralsols and Nitisols (MZ 2) and Acrisols (MY 6, PE 1) and gradual/clear in typical Acrisols (CI 1, ZM 8) and Nitisols (BR 7) (see Fig. 3). Three profiles are very gravelly, the gravel consisting mainly of iron concretions. One Ferralsol (CI 4) and one Acrisol (CI 1) have ironstone (petroferric layer) in the lower part of the B horizon.

Three Ferralsol profiles show patchy clay skins (argillans) while four have broken thin clay skins; all the Nitisols show continuous moderately thick to thick argillans; most Acrisols broken thin to moderately thick, and one of the three Cambisols broken thin clay skins.

In the past, the presence of clay skins, next to other properties, has been a diagnostic feature used to separate soils with Argic from soils with Ferralic B horizons, and thus Ferralsols from Nitisols and Acrisols. According to Moormann and Buol (1981), the classification of soils with low-activity clay, having a textural gradient fulfilling the requirements for Argic B horizons, but with the absence of clay skins, is one of the most severe problems. The present study, however, indicates that clay skins seem to constitute a consistent accessory characteristic to differentiate soils with an Argic and with an Ferralic B horizon.

The Ferralsols have predominantly a weak very fine, medium and coarse subangular blocky and porous massive structure, while in the other soil groups structure is moderate to strong, fine to coarse, angular and subangular blocky. According to Sanchez (1976) many Oxisols in constantly humid climates (udic and perudic) belong to the Tropeptic subgroup because the structure tends toward the blocky type. From the five profiles classified in the Tropeptic subgroup, two occur in udic/isohyperthermic and three in ustic thermic and isohyperthermic environments.

Very strong, very fine to fine, granular or crumb structure, referred to as "coffee powder"-like structure, has its maximum development in subsurface horizons of a gibbsitic-hematitic clayey Ferralsol (BR 5), decreasing in degree of development toward gibbsitic/kaolinitic-hematitic (KE 6 and 11 and MZ 2) and kaolinitic-hematitic (BR 5) soils (see Plate 1). Nitisols with this type of structure in the lower part of the B horizon (BR 7), which indicates the presence of a Ferralic diagnostic horizon below an Argic, are classified as Latosolic Structured Red Earths (Terra

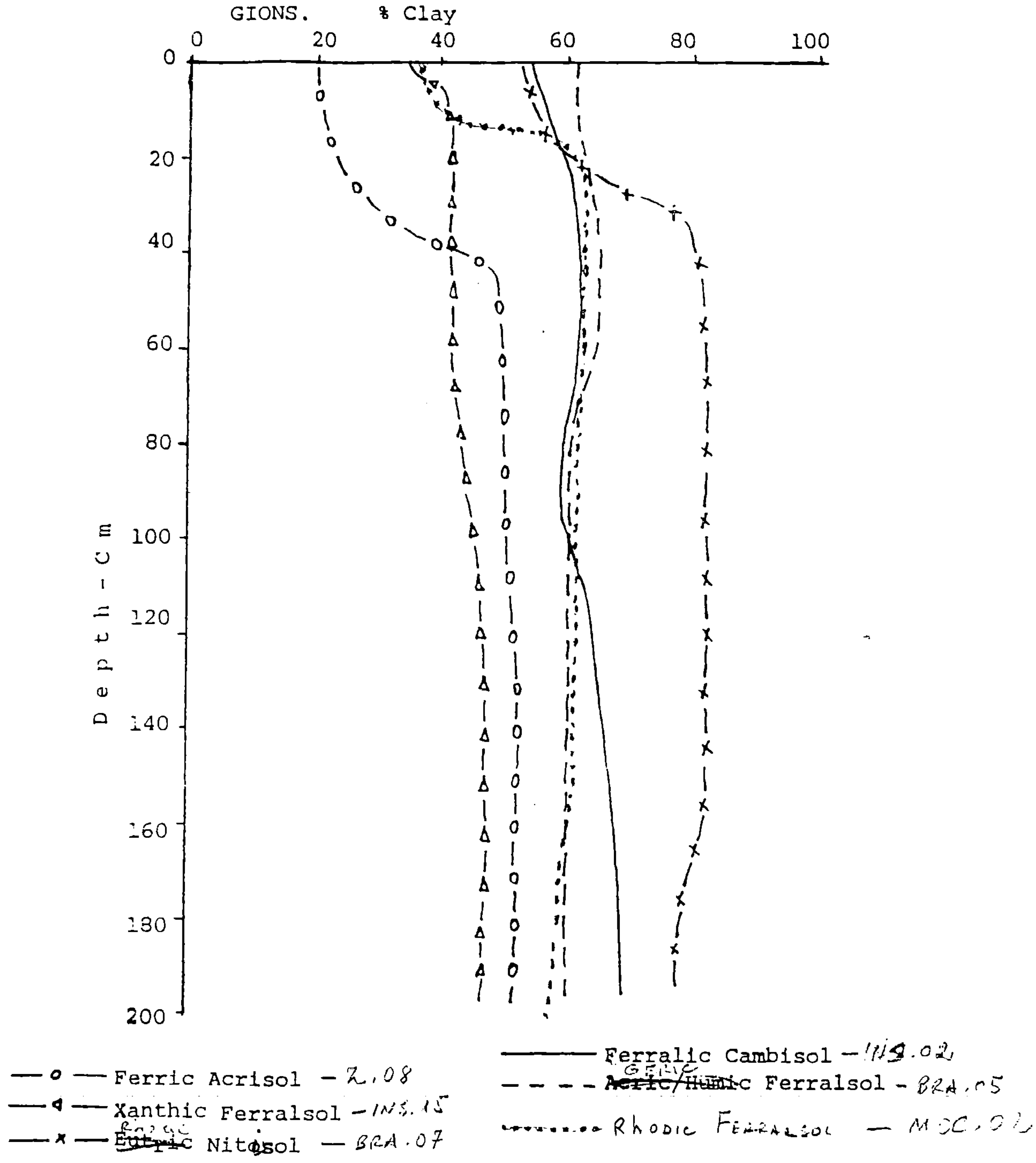


FIG. 3. Clay distribution in profiles of representative upland soils of humid and subhumid tropical regions

Roxa Estruturada Latossolica) in the Brazilian System of Soil Classification (Camargo et al, 1985). Very strong, very small aggregates occur also in the gibbsitic-goethitic soils (JM 3, WS 1, US 10), but their macrostructure has been described as weak to moderate fine to large subangular and angular blocky and massive porous. The structure of most yellow red to red, predominantly kaolinitic-goethitic Ferralsols is weak to moderate fine to coarse subangular blocky. The stronger development of structure at the surface horizons is probably related to a higher content of organic matter.

The strong, very fine to fine granular or crumb structure has been attributed to the influence of biological activity (mainly termites; Verheye and Stoops, 1975). The influence of sesquioxides (Al and/or Fe oxides/hydroxides, mainly gibbsite and hematite) on the aggregation of primary particles has been described by Baver et al. (1973) and is also evident from the present study. The combined effect of biological activity and mineralogical composition on the formation and preservation of this type of soil structure deserves to be further investigated.

In spite of the clayey texture, most Ferralsols have a slightly hard, very friable to friable, slightly sticky to sticky and slightly plastic to plastic consistence. Kaolinite

Table 5. Consistence of clayey Ferralsols, Nitisols and Acrisols, compared to a Vertisol.

Soil	ISRIC CODE	Horizon	Depth (cm)	C %	Clay %	Consistence			Mineralogical Composition
						Dry	Moist	Wet	
Humic Ferralsol	BR 5	Ap	0-26	2.47	61	hard	very friable	sticky, slightly plastic	x=Kaolinite x=Gibbsite
		Bwl	75-215	0.80	65	slightly hard	very friable	slightly sticky, slightly plastic	x=Hematite tr= Goethite
Xanthic Ferralsol	GA 1	Ah	0-7	3.27	56	slightly hard	very friable	sticky, plastic	xxx=Kaolinite x=Goethite
		Bxs2	120-135	0.36	57	hard	friable	sticky, plastic	tr=Gibbsite
Dystric Nitisol	CM 1	Ah	0-15	3.0	54	slightly hard	friable	sticky, slightly plastic	xx=Kaolinite xx=Goethite
		Bt2	83-137	0.4	82	hard	friable	sticky, plastic	tr=Mixed layer
Ferric Acrisol	SU 256	Ah	0-12	4.77	58	slightly hard	very friable	non-sticky non-Plastic	xx=Kaolonite xx=Chloritized vermiculite
		Bt3	74-103	0.64	71	hard	firm	sticky, plastic	x=Goethite
Vertisol*		A/C	43-50	0.76	64	extremely hard	very firm	very plastic, very sticky	xxx=Montmoril-lonite

* Data from Brasil, 1973, ACEGUÁ Mapping Unit.

and sesquioxides are responsible for these properties. The other soil groups have a hard, very friable to firm, slightly sticky to very sticky and slightly plastic to very plastic consistence. Table 5 illustrates the difference between the consistence of soils under investigation as compared to that of a Vertisol. Yellow and clayey kaolinitic Ferralsols (BR 13 and BR S1), in natural conditions have a somewhat dense layer in the upper part of the B horizon, the origin of which is unknown.

Most of the soils have many, very fine to medium tubular and interstitial pores, which renders them very porous. Roots are many fine to medium in the surface horizon, decreasing in quantity and size with depth. Pedofeatures such as clay balls and pedotubules are common in these soils, as well as the reworking of soil material by termites, ants, worms, etc.

Spherical iron and/or manganese concretions are found in one out of five of the Ferralsols under investigation and are few to frequent and small to medium hard. They may also occur in Nitisols and Acrisols. Rock and primary mineral fragments do not frequently occur in these deeply weathered soils, but were described in some profiles (BR 7, US 10).

1.4.2 Particle-Size Distribution and Specific Surface Area

Particle size distribution

The weight percentages of the sand (> 50 μm), silt (50-2 μm) and clay (< 2μm) fractions of the soil profiles under study were plotted in frequency diagrams (Fig. 4). The sand and silt fractions of all soils (Fig. 4*a,b*) show an asymmetrical, positively skewed and leptokurtic frequency distribution. The clay fraction of all soils (Fig. 4*c*) shows an almost normal distribution, whereas that of the Ferralsols is skewed (Fig. 4*f*). In all cases a tendency to bimodal distribution can be discerned. A concentration of samples on the sand-clay side of the textural triangle is obtained when the data of only the diagnostic subsurface horizon of Ferralsols are plotted (Figure 5*b*), if compared to the plot of all samples (Figure 5*a*).

A low silt content is a common characteristic of these deeply weathered soils, because primary minerals are unstable in this fraction and secondary minerals are found mainly in the clay fraction. The silt/clay ratio has been used as weathering index and soil classification parameter. Soils with a silt/clay ratio of 0.15 are regarded as highly weathered (Young, 1976), a ratio < 0.7 is one of the requirements used to define the Latosolic B horizon in the Brazilian system of soil classification (Camargo, Klamt and Kauffman, 1985), and of < 0.2 in the revised legend of the FAO/UNESCO Soil map of the World (FAO, 1988).

The high silt content found in some oxidic profiles (JM 3, WS 1, US 8, US 10) is related to strong aggregation of particles and the failing of properly dispersing them by the method used. Microscopic inspection showed that the silt fraction indeed consisted of pseudo-silt. Special dispersing agents and conditions (Uehara, 1979) or deferration is required to achieve adequate dispersion. This is illustrated in Table 6 which gives the particle-size distribution of profile JM 3 obtained with and without deferration pretreatment. Deferration appears substantially to increase the clay yield in all horizons.

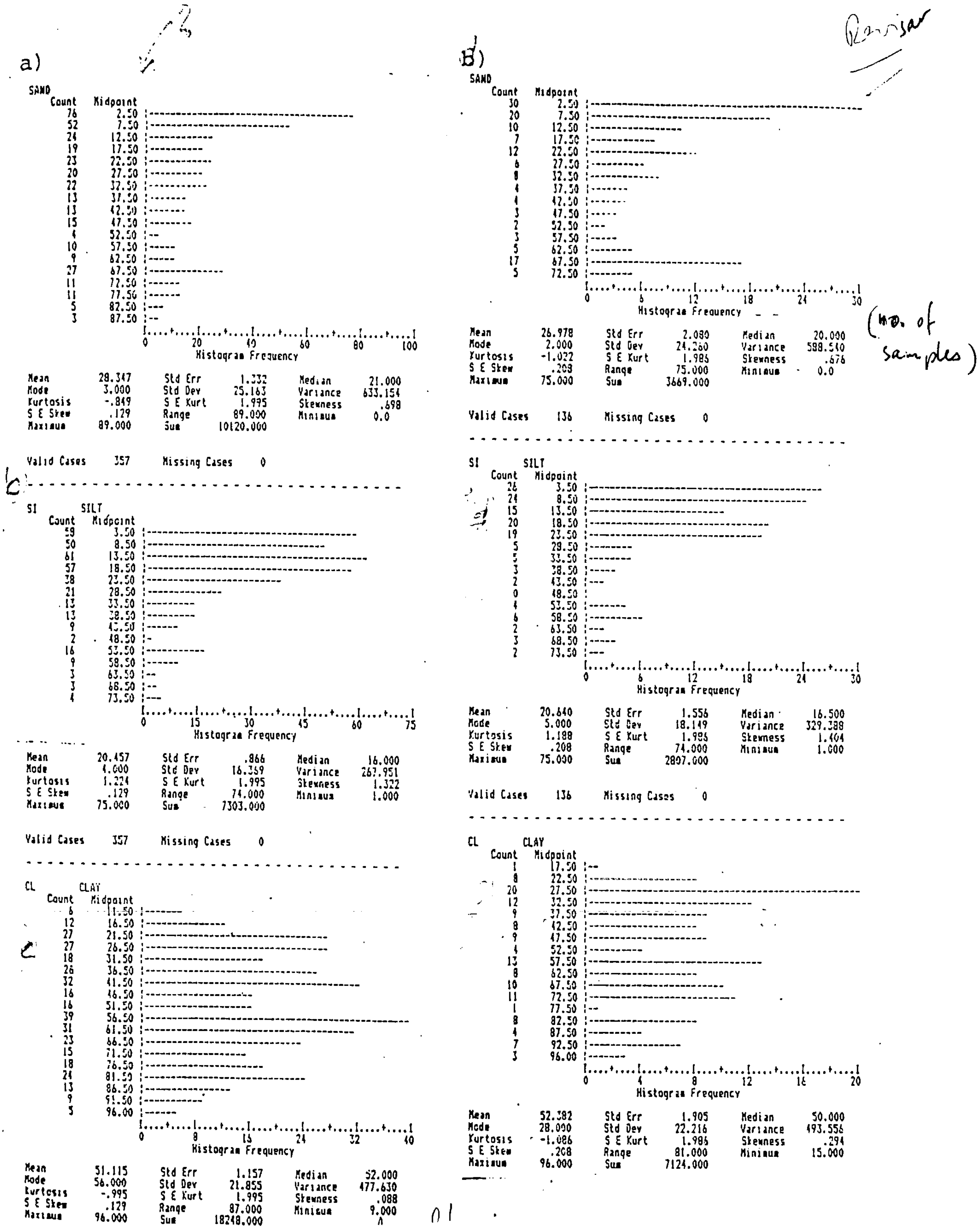
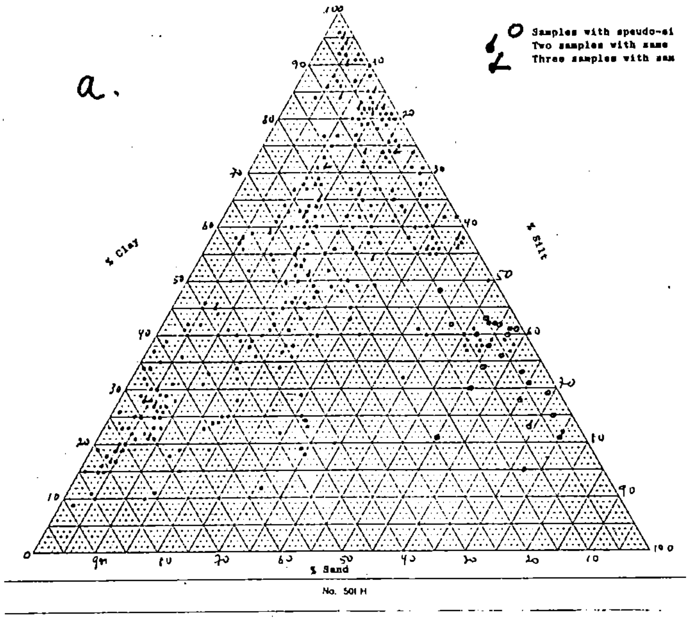


FIG. 4. Frequency distribution of sand, silt and clay content of all soil horizons (*a, b, c*), and of Ferralsol B horizons (*d, e, f*).

a.



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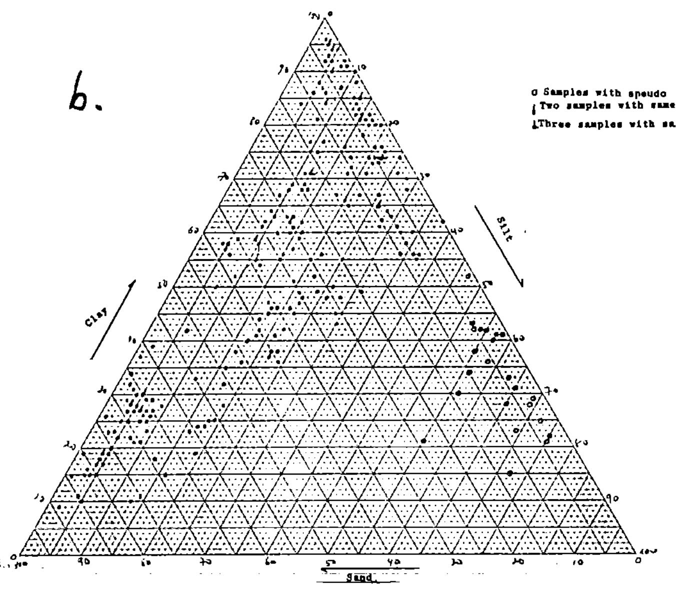

FIG. 5. The soils plotted by their texture.
***a.* All samples. *b.* Samples of Ferralsol A and B horizons.**

Most soils have a low sand content. However soils developed from sandstone (BR 6, KE 11 and 29, MY 6, ZM 2 and 5), coarse acidic igneous rocks (MY 57) and unconsolidated sandy clay sediments (BR 11, ZM 9) have high contents of sand and thus caused the bimodality of the sand content distribution curve when all soils are considered (Fig. 4).

Cluster analysis applied to sand, silt and clay data or only to sand and silt data of the diagnostic B horizons of Ferralsols, yielded five well defined clusters (Figure 5b), as schematically represented in Table 7.

Cluster 1 with 66% sand and 28% clay fits into the fine loamy particle-size class established for differentiation at family level in Soil Taxonomy (SCS/USDA 1987) and into the medium textured class of FAO (1988). Cluster 2 is fine

TABLE 6. Particle-size analysis of profile JM 3 with and without deferration.

Hor-izon	Depth (cm)	Non-deferrated			Deferrated		
		Sand >50	Silt 50-2	Clay <2μ m	Sand >50	Silt 50-2	Clay <2μm
		-------	-------	------- %	-------	-------	-------
Aps1	0-10	4	49	47	4	28	68
Aps2	10-27	4	50	46	5	19	76
Bs1	27-88	3	53	44	2	11	87
Bs2	88-153	1	49	50	1	32	67
Bs3	153-180	1	59	40	1	30	69

silty and medium respectively; Clusters 3 and 4 fit into fine textured class of FAO (1988) and clayey of Soil Taxonomy respectively. Cluster 5 is fine and very fine clayey according to FAO (1988) and Soil Taxonomy (SCS/USDA, 1987) respectively.

All soils developed from sandstone, unconsolidated sandy clay materials and coarse acidic and intermediate igneous rocks fall into the fine loamy Cluster 1. The fine silty Cluster 2 is composed of samples with strong aggregates, which were not properly dispersed (pseudo-silt) but which disappeared with the use of stronger dispersing agents and/or by deferration of the samples. The silty clay (no. 3), sandy clay (no. 4) and clayey (no. 5) clusters are made up of samples belonging to soils weathered from volcanic extrusive, fine intermediate and basic igneous rocks as well as from clayey sediments. This relation of parent material to texture of the soils is unexpected since all of these soils have undergone very strong weathering and primary minerals should have been totally altered to secondary minerals. Quartz seems to be very stable, even in tropical and subtropical environments, and can be held responsible for the coarser textures.

Specific Surface Area

As in the case of particle-size distribution, the frequency distribution of specific surface area is also asymmetrical, positively skewed but mesokurtic (see Fig. 6), underscoring a relationship between this two parameters. The absolute values (see Table 8) range from 14 (BR 6) to 165 m^2/g of soil (ID 2), the former having a low (20%) and the latter a high clay content (82%).

Specific surface area is closely related to particle-size distribution and soil parent material, but seems not to be related to soil groups as presently defined in FAO/Unesco and Soil Taxonomy. Soils with a sandy texture, weathered from sandstone, sandy clay sediments and coarse intermediate and acidic igneous rocks, show low values of specific surface area (< 50 m^2/g), with the exception of profiles MZ 3 and ZM 4 developed from diorite, with values of 70 and 75 m^2/g respectively. Soils with silty clay and sandy clay texture, developed from clayey sediments (55 to 62 m^2/g with exception of BR 10) and metamorphic rocks (65-95 m^2/g) show intermediate values. Clayey soils weathered from extrusive volcanic material (ID 1 and 2:

TABLE 7. Clusters of textural classes obtained by clustering sand, silt and clay fraction of Ferralsols diagnostic B horizons.

No. of clusters		No. of samples	Particle-size fraction (wt%)*					Particle-size Classes**
			Sand		Total Sand	Silt	Clay	
			Coarse	Fine				
1	1	29	28.6 (0-51)	37.0 (15-55)	65.6 (49-75)	6.7 (1-23)	27.9 (20-38)	fine loamy
2	2	17	3.7 (0-13)	3.5 (1-11)	7.2 (1-24)	61.4 (51-57)	31.4 (51-42)	fine silty
3	3	10	2.6 (0-8)	4.8 (0-9)	7.4 (0-17)	37.3 (32-43)	54.9 (41-62)	clayey
	4	26	10.8 (1-27)	18.9 (8-28)	29.7 (20-41)	16.8 (5-28)	53.2 (36-68)	
4	5	42	2.5 (0-6)	3.9 (0-11)	6.4 (1-16)	14.0 (2-25)	79.2 (60-96)	very fine clayey

* Mean values and range. ** According to SCS/USDA, 1987.

TABLE 8. Frequency distribution of specific surface area.

Samples	Specific Surface Area (m^2/g)					Standard deviation	Variance	Standard error	Skewness	Kurtosis
	Min.	Max.	Mean	Mode	Median					
All B horizons	14.0	165	75	60	72	36.5	1335	3.8	0.5	-0.3
Ferralic B hor.	14.0	153	73	14	72	34.3	1180	4.2	0.3	-0.3

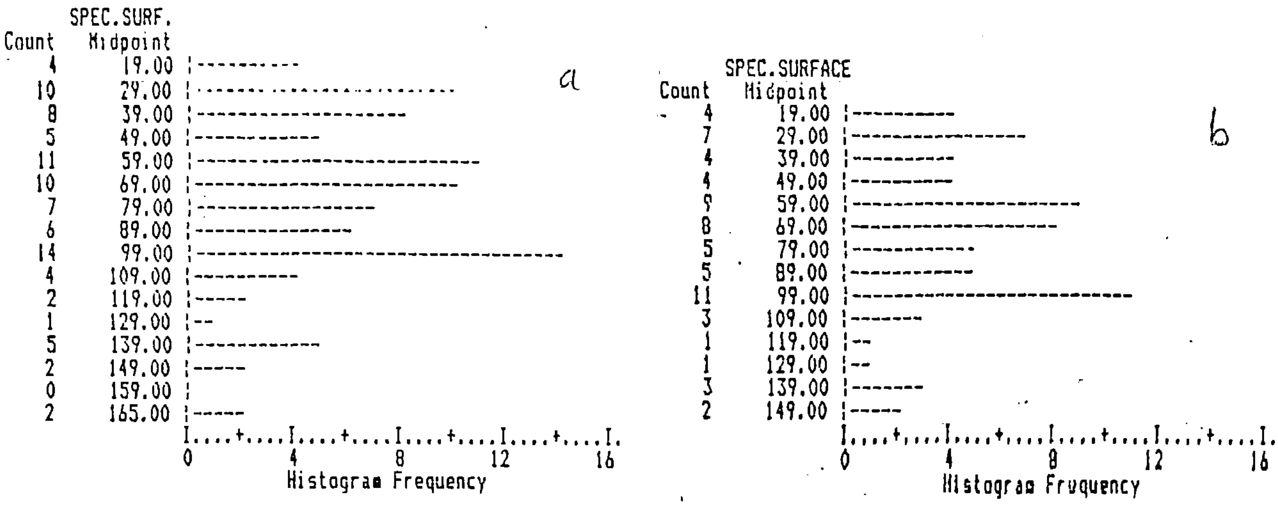

FIG. 6. Frequency distribution of specific surface area of *a*) all B horizons, and *b*) Ferralsol B horizons.

145 m^2/g) and fine basic igneous rocks (BR 7, BR9, BR-SP2, MY 3 and US 9: 105-135 m^2/g) and from Georgia (CIS) (135-145 m^2/g) with unknown parent material present high values of specific surface. The Indonesian soils contain halloysite and metahalloysite and probably allophane as main clay minerals; the Brazilian soils with large specific surface contain chloritized vermiculite and probably halloysite and amorphous material whereas the Russian profiles have mixed layer clay minerals, which may explain the high values obtained for specific surface area. Soils weathered from fine basic igneous rocks and clayey sediments with very strong fine aggregates, such as BR 5 and JM 3, have specific surface areas of 60 and 62 m^2/g respectively, which is low considering their clayey texture. Apparently aggregation causes clay particles to be shielded off to some extent.

1.4.3 Cation Exchange Properties and other Chemical Characteristics

pH

Only the data of soil pH show a normal distribution, data of other chemical properties show asymmetric, positively skewed and leptokurtic frequency distributions, regardless if data of all samples, only of B horizons or of Ferralic B horizons are considered (see Fig. 7).

Most of the soils are acid. Although the values range from 3.3 - 7.0, more than 80% of the samples analysed have pH values below 5.7. The Eutric Nitisol (BR 7 and US 3), eutrophic Rhodic Ferralsols (BR 5, KE 6, ID 6, US 9) and one Acric Ferralsol (MY 7) have pH values above 6. With the exception of subsurface horizons of eight Ferralsols, the pH in water is higher than in 1 M KCl (negative ΔpH), indicating that most soils under study have a net negative charge (Van Raij and Peech, 1972; Keng,

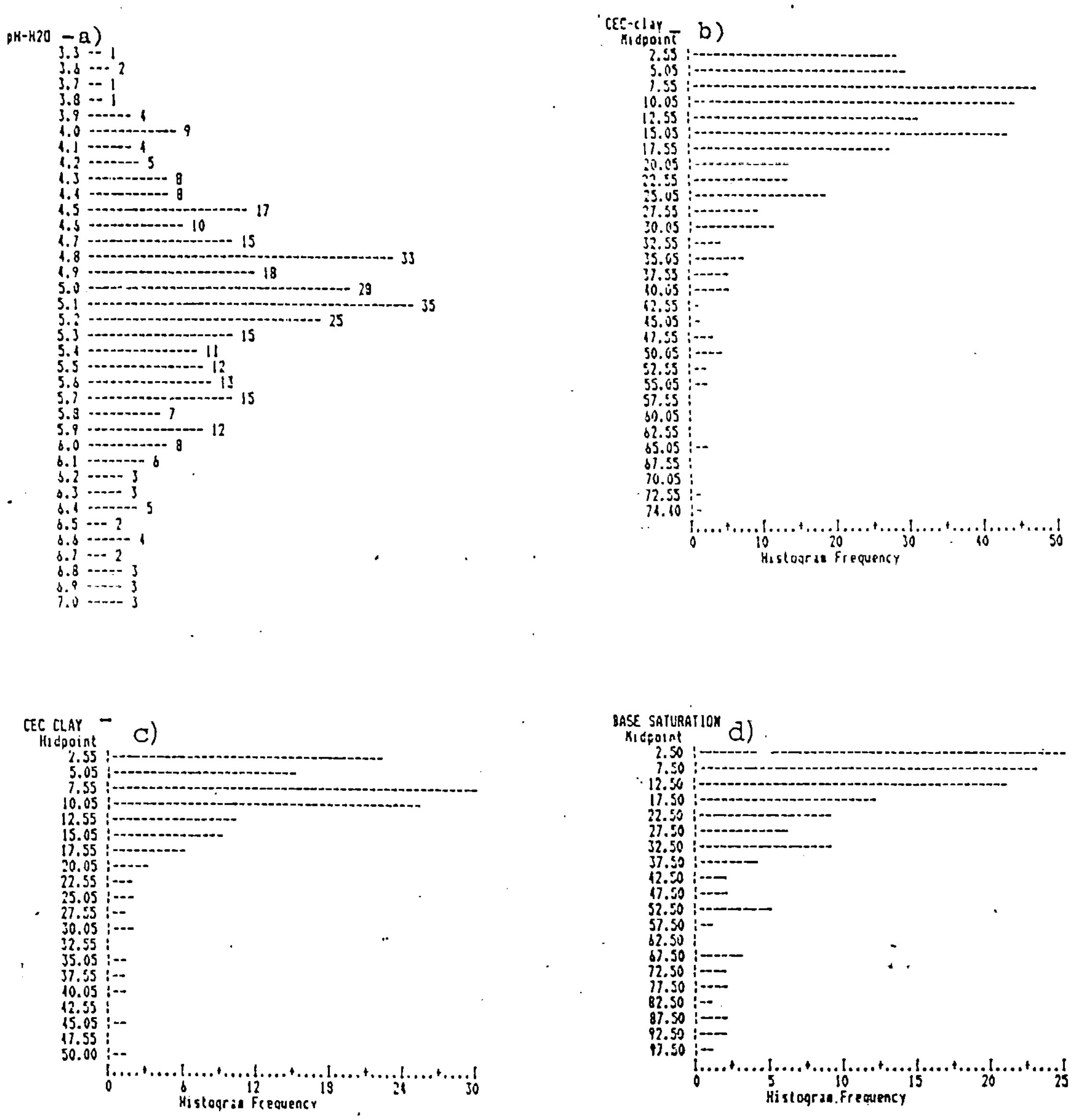

FIG. 7. Frequency distribution of analytical results of pH (*a*) and CEC_{clay} (*b*) for all samples, and CEC_{clay} (*c*) and base saturation (*d*) of feralic B horizons.

1974; Sanchez, 1976; Uehara, 1979; Uehara and Gillman, 1980; Gillman and Uehara, 1980; Bowden et al., 1980). The Ferralsols with a positive ΔpH have a dominantly sesquioxidic mineralogy (BR 15, MZ 2, MY 56, WS 1, ZA 2, US 10). Naturally, a range in mixed composition can be found, in some cases yielding a (nearly) zero ΔpH, e.g. KE 6, Bw Horizon. In addition, the positive charge of sesquioxidic soils may be increased by isomorphous substitution of Fe^{3+} by Ti^{4+} in iron oxihydroxides (Tessen and Jusop, 1982).

Exchangeable bases

The content of exchangeable bases is generally very low in the soils studied (see Table 9). Higher values occur in Eutric Nitisol and eutrophic Rhodic Ferralsols. The lowest in Xanthic, Geric (Acric) and Humic Ferralsols and Ferric Acrisols (See Fig. 8). The mean base saturation is 24% (± 23) for all samples and 22% (± 24) for Ferralic horizons.

TABLE 9. Mean values of exchangeable bases ($cmol_c/kg$).

	Ca^{2+}	Mg^{2+}	Na^+	K^+	Sum	Al^{3+}
All samples	1.2	0.5	0.5	0.1	2.3	1.2
Ferralic B	0.7	0.4	<0.1	0.1	1.3	0.7

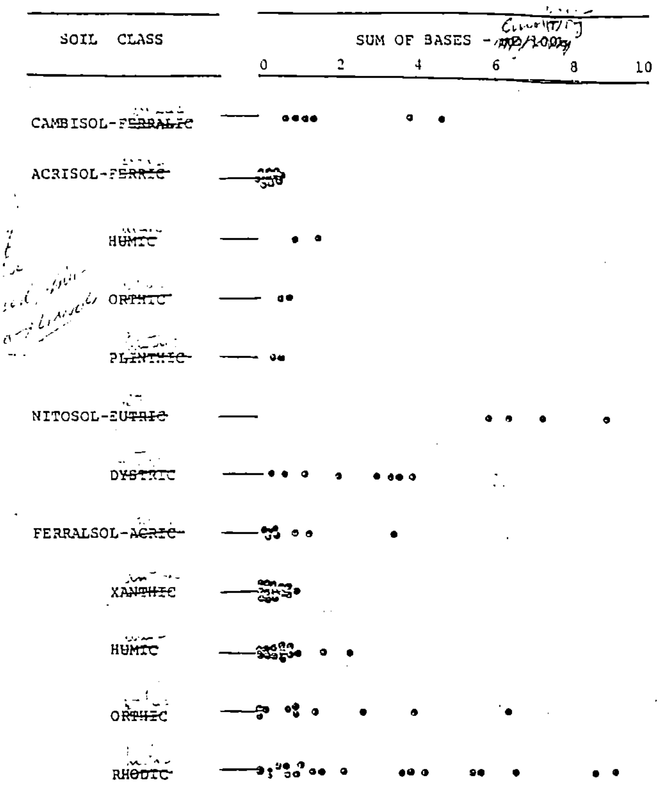

FIG. 8. Distribution of data of sum of bases in the diagnostic subsurface horizons of the soils studied.

Exchangeable Al

The mean values for exchangeable aluminum are also given in Table 9. As expected, values of exchangeable aluminium are very low in Eutric Nitisols and Geric (Acric) Ferralsols and higher but variable in the other soil units (the mean value for all non-Ferralic soils is 2.0 $cmol_c/kg$). The values for exchangeable Al (and Al saturation) in the Ferralic B horizons generally increase in the following order: Geric < Humic < Haplic < Rhodic < Xanthic Ferralsol (Fig.9). In some Ferralsols exchangeable Al (and Al saturation) decreases with depth (BR 3, 8, 9; MY 1, 5) and in others increase with depth (BR 6, 11, 13, SP1; CO 15; GA 4; KE 7; ZM 2, 5, 8). This distribution is an important characteristic to consider for soil management purposes, since exchangeable Al behaves as an inhibitor for plant root development (Ritchey et al. 1980, 1982).

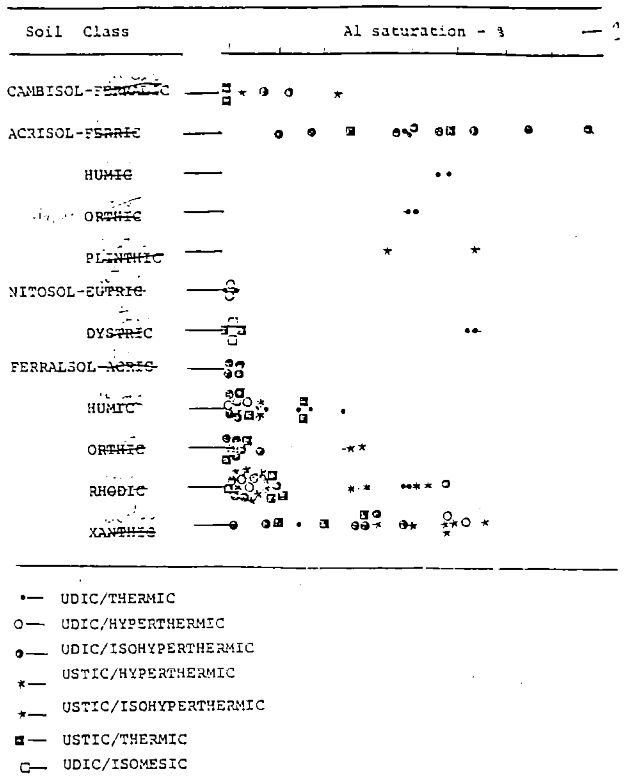

FIG. 9. Distribution of data of Al saturation in the diagnostic subsurface horizons and associated climatic conditions.

Cation Exchange Capacity

The soils under study have a low cation exchange capacity which is related to the mineralogy of the clay fraction and which consists dominantly of kaolinite and oxihydroxides of Fe and Al with low variable surface charge (Berner, 1971; Zelagny and Calhoun, 1971; Uehara, 1979; Bowden et al., 1980; Uehara and Gillman, 1981). The values are lower in Ferralic B horizons (CEC = 4.9 ± 8.5 $cmol_c/kg$) as compared to non-Ferralic B horizons (8.7 ± 5.3 $cmol_c/kg$). Except in four non-Ferralsols, the CEC decreases substantially from the surface to the subsurface

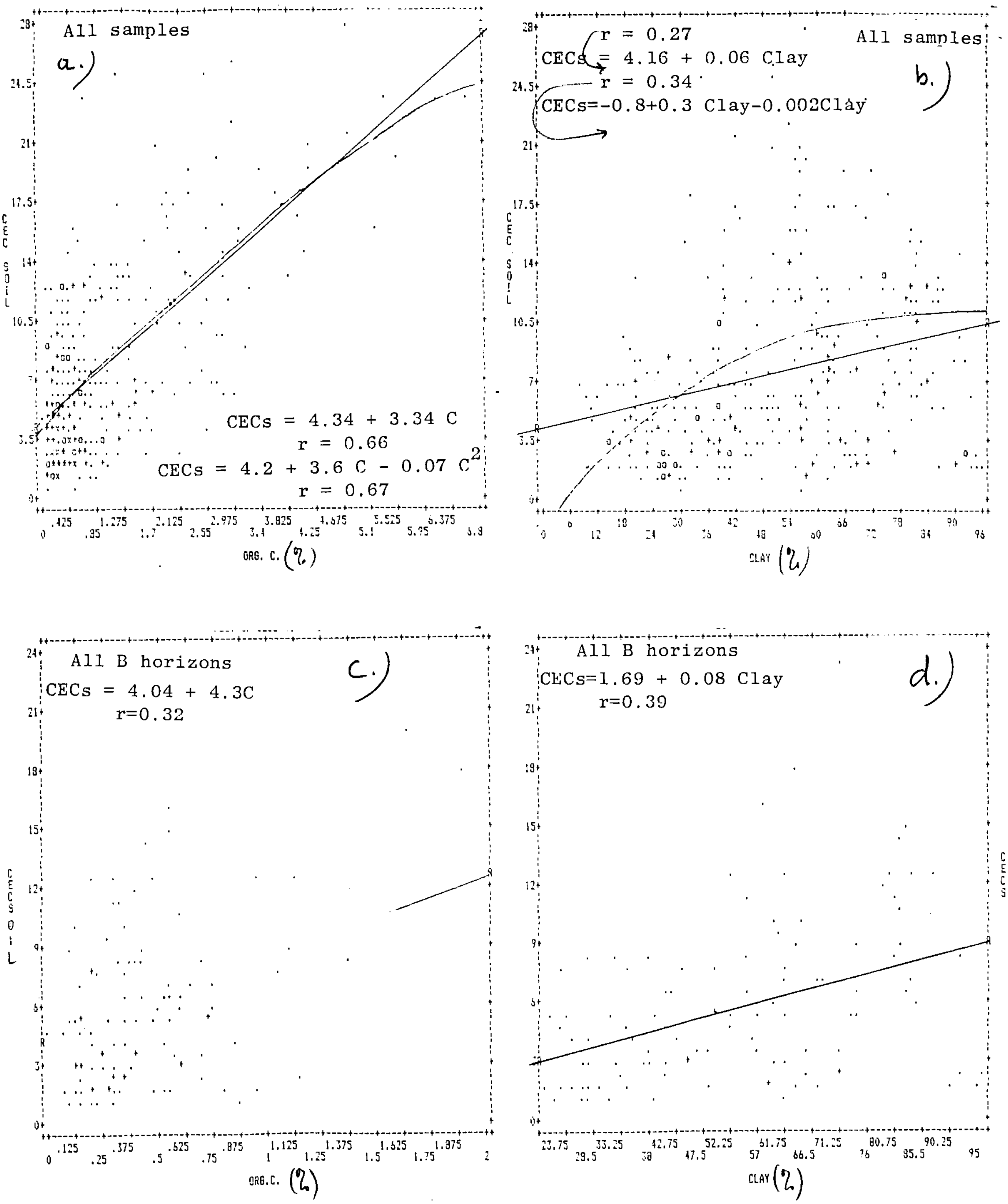

FIG. 10. Correlation coefficients (*r*) between: *a*) CEC of all samples and organic carbon content, *b*) CEC of all samples and clay content, *c*) CEC of all B horizons and organic carbon content, and *d*) CEC of all B horizons and clay content.

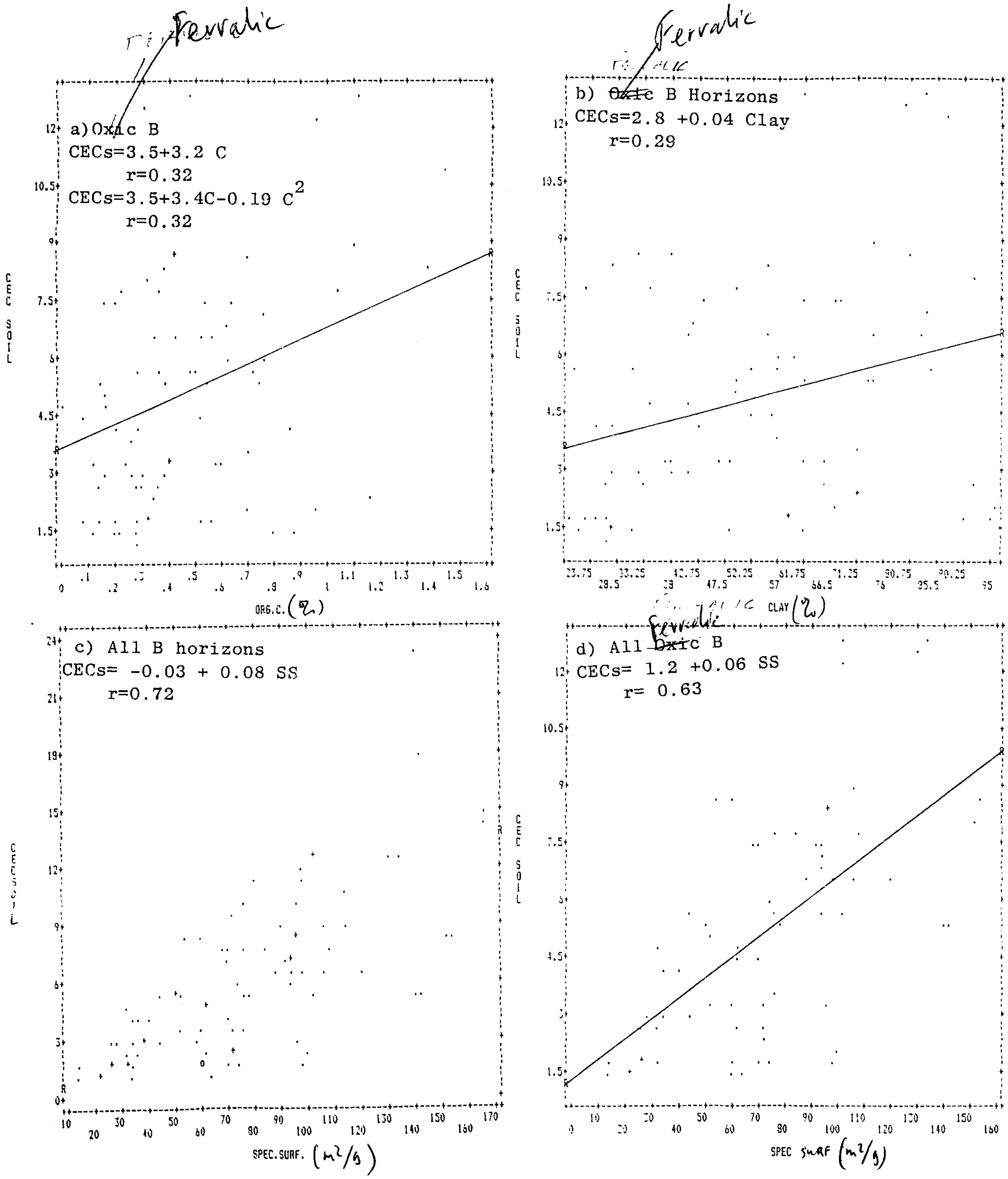

FIG. 11. Correlation coefficients (*r*) between *a*) CEC of ferallic B horizons and organic carbon content, (*b*) CEC of ferallic B horizon and clay content, (*c*) CEC of all B horizons and specific surface area (*SSA*), and (*d*) CEC of ferallic B horizons and specific surface area.

horizons, indicating a strong influence of organic matter on the exchange properties. Higher values for non-ferralic B horizons are related to the presence of 2:1 and 2:1:1 clay minerals with permanent negative charge in these soils.

Organic carbon

The mean content of organic carbon in the surface horizons of the Ferralsols of this study is 2.73% (range: 0.6% - 10.2%). In the B horizons this value is 0.48% (0.07% - 1.37%). Humic and Acric units have higher contents than Orthic, Xanthic and Rhodic units.

The equation of Bennema (1964) and Bennema and Camargo (1979) to estimate the contribution of organic carbon to the CEC, produced very high correlation coefficients ($r > 0.99$, see Fig. 2), indicating that in these soils the exchange properties are related mainly to organic matter and clay content. The same procedure applied to Nitisols, Acrisols and Cambisols, yielded lower correlation coefficients, suggesting that the contribution of organic carbon and clay is not uniform throughout the profile (clay increase with depth and possible change in clay mineralogy and/or composition of organic matter).

The average contribution of each % organic matter to the CEC of the soil is 3.4 $cmol_c$ per kg soil (range: 1.4 to 9.4) while the average CEC of clay is 7.0 $cmol_c$/kg (range: -1.7 to 16.2). This value for organic matter is lower than the "correction factor" of 4.5 in the equation:

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

used to calculate the CEC of the clay fraction corrected for organic matter in the Brazilian System of Soil Classification (EMBRAPA/Brazil, 1981; Camargo, Klamt and Kauffman, 1987). However, the value is about midway the range for humic acids given by Sposito (1989) and happens to equal the mean value (at pH 7) of sixty Wisconsin soils (Bohn et al., 1979).

Note: To avoid confusion it must be realized that the content of *organic matter* is commonly expressed as *% carbon*. When the average carbon content of organic matter is taken to be 50% (Nelson and Sommers, 1982) a convenient conversion factor of 2 can be used. This implies that a CEC contribution of 3.4 $cmol_c$ per % C corresponds with a CEC of organic matter of 170 $cmol_c$/kg.

The CEC of organic matter (expressed per % of carbon) is on the average lower in Geric (range: 1.3 - 3.6 $cmol_c$) and Humic (2.0 - 3.6 $cmol_c$) than in Xanthic (1.6 - 6.8 $cmol_c$) and Rhodic (2.4 - 9.4 $cmol_c$) Ferralsols. The proportional contribution of organic matter in A horizons is found to be high in all soils. This is particularly the case in Acric (53-77%), Humic (39-78%) and Haplic (36-67%) Ferralsols. As to be expected, in the diagnostic subsurface horizons these values are lower: 18% on the average with 12% in Xanthic, 21% in Rhodic, 22% in Acric, and 24% in Humic Ferralsols. The type of vegetation, land use and climatic zones in which Ferralsols occur do not considerably influence the values obtained.

Clearly, the contribution of organic matter to the CEC of Ferralsols should be considered in determining the CEC of their clay fraction. The lack of clear trends in the contribution of organic matter to the exchange properties and the amplitude of variation obtained, suggest that this determination needs to be done for each soil profile individually. In addition, it would seem that the present boundary of a CEC of 16 $cmol_c$/kg clay separating Ferralsols from other soils should be lowered to 13 or 14 $cmol_c$/kg clay .

Regression analysis applied to CEC data resulted in low correlation coefficients between CEC_{clay} and clay content, regardless if all samples ($r = 0.27$; Fig. 10*b*); samples of all B horizons ($r = 0.39$; Fig. 10*c*), or only ferralic B horizons ($r = 0.29$; Fig. 11*b*) were tested. These results reflect the difficulty to disperse some soils with the procedure used to determine particle-size distribution. Higher values ($r = 0.61$) were obtained for non-ferralic B horizons, which is ascribed to their permanent-charge clay mineralogy and less problematic dispersion .

A somewhat higher correlation exists between CEC_{soil} and organic carbon content for all samples ($r = 0.66$, see Fig. 10*a*), but the coefficient decreases when samples of all B horizons ($r = 0.32$, Fig. 10*d*) or ferralic B horizons ($r = 0.32$, Fig. 11*a*) are considered. This points again to the significant contribution of organic matter to the CEC.

By applying stepwise multiple regression analysis, the independent variable with highest correlation to the dependent CEC_{soil}, i.e. organic carbon, was obtained with $r = 0.66$ in the first step. This was improved to r = 0.69 and $r = 0.73$ when the influence of the variables silt and silt and clay were considered in steps two and three respectively. Square and log functions improved the correlation coefficients slightly, such as in the case of CEC_{soil} with clay content, from $r = 0.27$ to $r = 0.34$ (see Fig. 10*b*).

The correlation coefficient between CEC_{soil} of all samples and specific surface area was the highest obtained ($r = 0.72$, see Fig. 11*c*). The r value decreased to 0.63 (Fig. 11*d*) when data of only ferralic B horizons were analysed and to 0.18 when correlating specific surface area with CEC_{clay}, indicating once again the unreliability of the particle-size data.

Extractable Fe and Al

The average dithionite-extractable Fe (Fe_d) is 8.3% (± 6.0) in all samples analysed and that of oxalate extractable Fe (Fe_o) is only 0.24% (± 0.23). In the ferralic B horizons these values are 8.9% ± 6.5 and 0.23 ± 0.22 respectively for Fe_d and Fe_o. Efforts to correlate CEC with different forms of iron and aluminum (oxi)(hydr)oxides (Fe_o, Al_o Fe_d, Al_d) resulted in very low correlation coefficients.

The content of Fe is closely related to parent material (See Fig. 12). Soils weathered from fine intermediate and basic igneous and metamorphic rocks (Ferralsols and Nitisols), show the highest contents of Fe oxides. Xanthic Ferralsols, Cambisols and Acrisols have considerably lower Fe contents than the other soil units studied. Xanthic Ferralsols are predominantly goethitic. The formation of this mineral is favoured by low rates of Fe release, high organic matter and soil moisture contents as well as a low

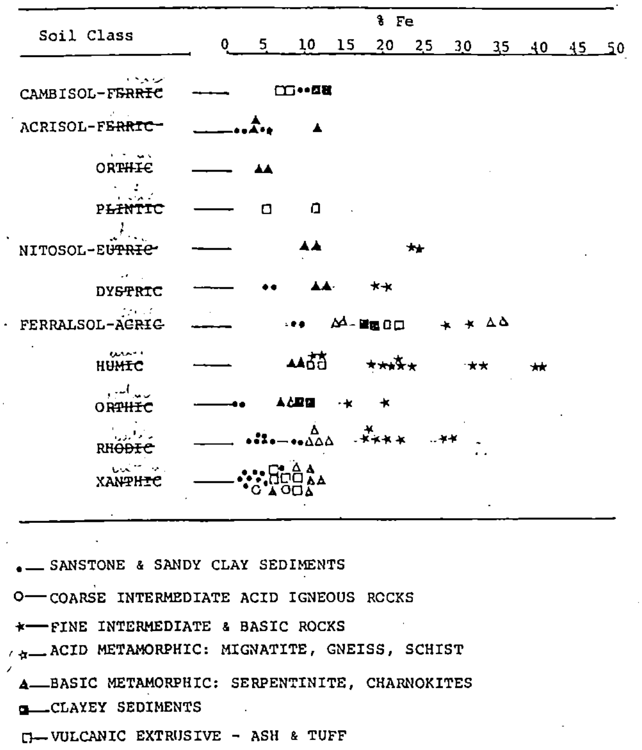

Fig. 12. Distribution of data of dithionite-extractable Fe (Fe_d) in the diagnostic subsurface horizons of soils related to their parent material.

pH (Torrent et al., 1983; Kämpf and Schwertmann, 1983; Schwertmann, 1985). These factors closely match the environmental conditions of Xanthic Ferralsols which are formed mainly from parent material with a low Fe content (sandstone, sandy clay sediments and acidic metamorphic rocks) under moist conditions with a low prevailing pH.

In Ferralsols, the so-called *Fe_o/Fe_d activity ratios* are very low, indicating the low proportion of poorly ordered ("amorphous") forms of Fe (Blume and Schwertmann, 1969). Contents of other kinds of "amorphous" material are also low as indicated by the low Al_o figures.

Based on the CEC of the clay fraction, only one Ferralsol profile (BR 5) meets the requirement for Geric (CEC_{clay} < 1.5 $cmol_c$/kg) Ferralsol. The number increases to fourteen when the criterion $ECEC_{clay}$ < 1.5 $cmol_c$/kg, as used in Soil Taxonomy (SCS/USDA, 1975) to distinguish *Acr* great groups is applied. Eight of these profiles meet also the requirement for Humic (Umbric A horizon or high organic matter content in the B horizon, or both, as used in FAO/UNESCO, 1974). Some very deeply weathered soils with oxidic mineralogy (JM 3; WS 1; US 10) do not meet the requirements for ferralic B horizon when CEC_{clay} is calculated on the basis of clay content obtained without deferration of samples. Thus, the present study corroborates the experience of the pedologist, that the use of exchange properties, such as CEC of the clay (< 16 $cmol_c$/kg clay by NH_4OAc pH 7) to define ferralic horizons and acric properties (<1.5 $cmol_c$/kg clay) depends on good dispersion of samples to enhance particle-size fractionation; which in turn, in many samples, requires removal of organic matter and/or deferration.

1.4.4. Mineralogical composition

In contrast to more soluble components, the contents of SiO_2, Fe_2O_3 and TiO_2 in the soils under study soils are related to the parent material in and from which they formed. The content of SiO_2 (Fig. 13) increases in the following sequence: limestone and ultrabasic rocks < basic igneous and metamorphic < unconsolidated clay < intermediate igneous < acidic igneous, metamorphic, volcanic extrusive, unconsolidated sandy clay, unconsolidated sandy and sandstone. The contents of Fe_2O_3 and TiO_2 in Ferralsols decrease according to the same sequence of parent material. The content of Al_2O_3 does not follow consistently this sequence, varying less with changes in parent material; probably due to the somewhat higher mobility of Al as compared to Fe.

The contents of SiO_2, Al_2O_3, Fe_2O_3 and TiO_2 in the non-Ferralsols (Acrisols, Cambisols, Lixisols and Nitisols) developed from the same type of parent material as the Ferralsols, show a similar distribution, but the content of SiO_2 in these soils is consistently higher, and that of Al_2O_3, Fe_2O_3 and TiO_2 generally lower than in the Ferralsols (Fig. 14). These trends shows that desilication and residual concentration of the metal oxides and hydroxides is stronger in Ferralsols than in the related soils studied, which is consistent with the concept that Ferralsols constitute a group of soils in which weathering proceeded to a more advanced stage than in the other soil group studied.

The average content of SiO_2 in Ferralsols, when related to climatic conditions in which they occur, follows the sequence: perudic/isohyperthermic < udic/hyperthermic and udic/isohyperthermic < torric/isohyperthermic < ustic/hyperthermic and udic/thermic < ustic/isohyperthermic and ustic/thermic; whereas that of Fe_2O_3 and TiO_2, in general, follow a reverse sequence, as shown on Table 10. Although the content of Al_2O_3 in the Ferralsols does not follow the same trend as that of Fe_2O_3 and TiO_2 (the higher contents are found in soils occurring in ustic conditions), in general the influence of climate is also consistent, since desilication and residual concentration of Fe an Ti is stronger where rainfall and temperature are higher.

The content of SiO_2 of the non-Ferralsols found in similar climatic conditions as the Ferralsols, is consistently higher and that of Al_2O_3, Fe_2O_3 and TiO_2 generally lower, indicating again that weathering is more intense in the Ferralsols, confirming this accepted concept.

As shown in Figure 14, the content of SiO_2 in Ferralsols follows the sequence: geric < humic < rhodic, orthic and xanthic; whereas the content of Fe_2O_3 follows an reverse sequence: geric > humic > rhodic > orthic > xanthic. The distribution of Al_2O_3 and TiO_2 in these soils, in general shows very slight variation. This chemical composition is consistent with the concept that Geric Ferralsols are the most deeply weathered soils, having a cation exchange capacity of 1.5 cmol(+) or less per kg of clay.

The non Ferralsols (Acrisols, Nitisols, Lixisols and Cambisols) generally have a higher content of SiO_2 and slightly lower content of Al_2O_3, FeO_3 and TiO_2 than the Ferralsols. The high content of TiO_2 and Fe_2O_3 in Nitisols,

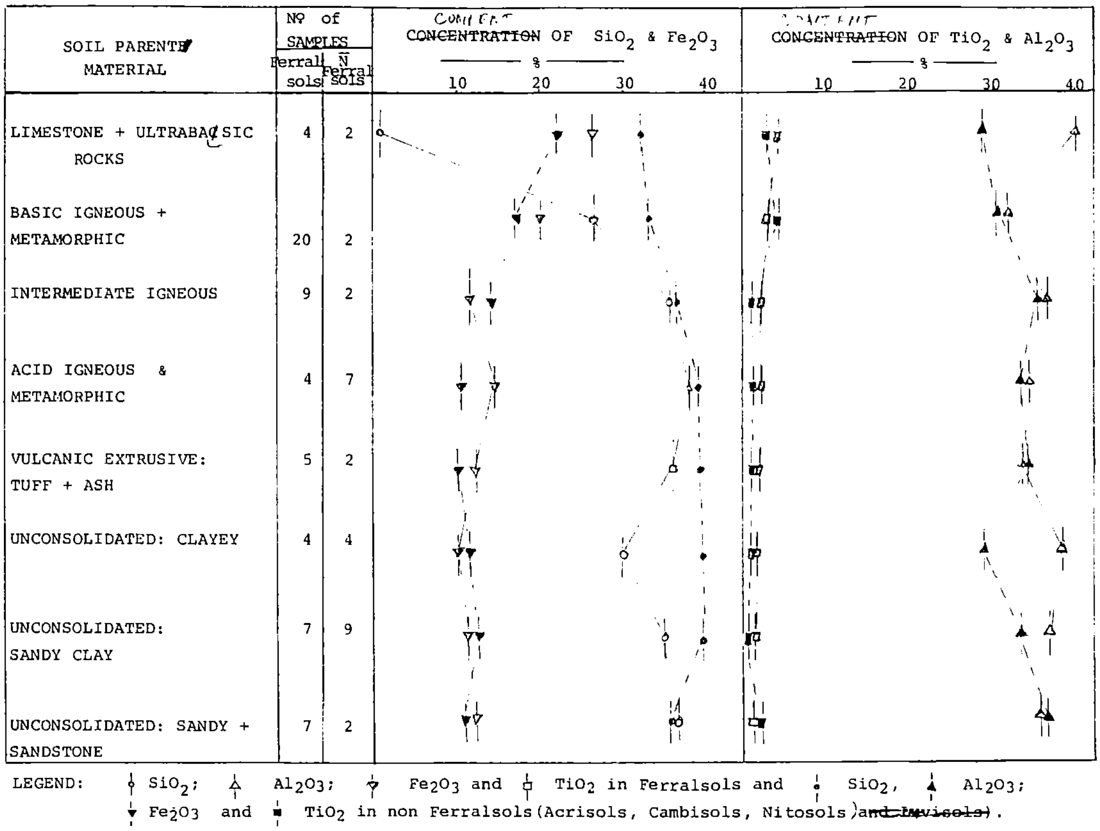

FIG. 13. Contents of SiO_2, Al_2O_3, and TiO_2 in Ferralsols and related soils, in relation to their parent material.

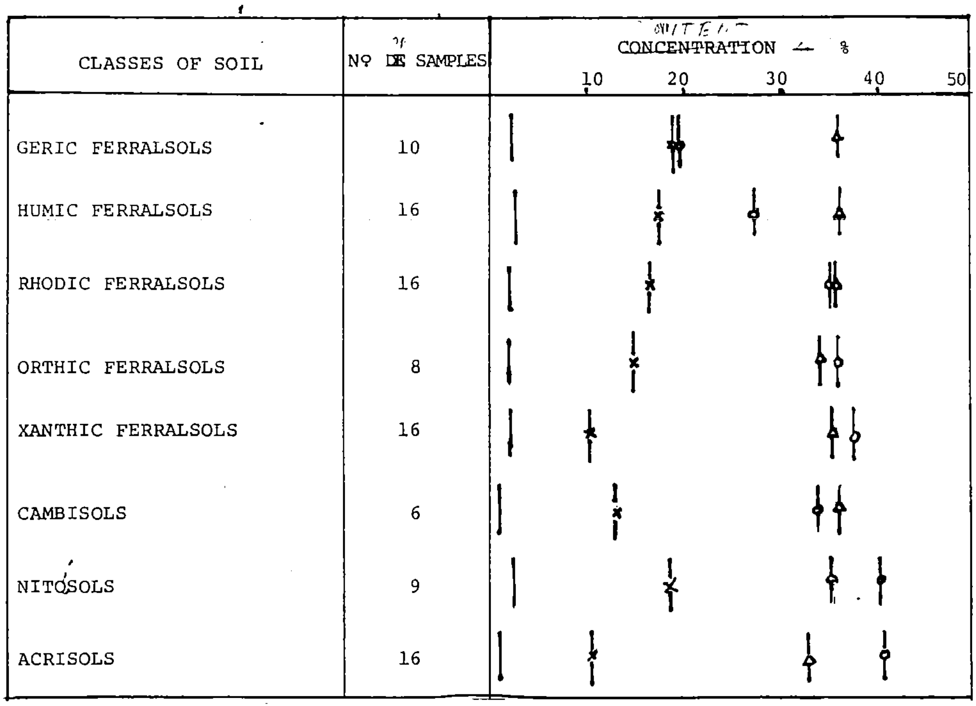

FIG. 14. Average contents of SiO_2 ( ), Al_2O_3 ( ), Fe_2O_3 ( ), and TiO_2 ( ) in B horizons of the Ferralsols and related soils studied.

TABLE 10. Average contents (in wt%) of SiO_2, Al_2O_3, Fe_2O_3 and TiO_2 in Ferralsols and Non-Ferralsols, related to their soil humidity and temperature regimes.

Soil Humidity and Temperature regimes	No. of samples		SiO_2		Al_2O_3		Fe_2O_3		TiO_2	
	Ferral	Non-Ferral	Ferral	Non-Ferral	Ferral	Non-Ferral	Ferral	Non-Ferral	Ferral	Non-Ferral
Udic/Thermic	5	7	31.6	39.7	33.1	32.0	16.9	12.4	2.2	1.2
Udic/Hyperthermic	8	2	29.3	32.3	32.7	28.8	21.2	22.2	3.7	1.0
Udic/Isohyperthermic	15	6	29.7	38.6	33.4	31.3	18.4	12 .5	2.1	2.3
Ustic/Thermic	13	6	36.2	34.8	37.5	37.2	11.8	12.0	1.4	1.3
Ustic/Hyperthermic	8	2	31.4	46.1	36.7	32.4	12.8	6.4	1.8	0.8
Ustic/Isohyperthermic	13	4	35.9	37.5	33.9	33.4	11.8	11.2	1.9	1.3
Perudic/Isohyperthermic	3	2	10.5	39.2	34.7	33.2	27.6	9.9	2.9	0.8
Torric/Isohyperthermic	2	_	30.2	_	31.4	_	19.9	_	2.1	-

is related to their development from parent material rich in iron and titanium minerals.

The former elemental distribution is consistent with the relative mineralogical composition of the clay fraction given in Table 11, since Ferralsols have higher content of gibbsite and hematite and lower content of weatherable minerals than Cambisols, Nitisols, Lixisols and Acrisols. The high content of goethite and hematite in Nitisols, must be ascribed to the fact that this group of soils is developed from iron rich parent material.

Kaolinite is the dominant clay mineral in the soils studied. The lower relative content in Geric and Humic Ferralsols is related to the most advanced stage of weathering of these soil units as expressed by their higher content of gibbsite, goethite and hematite.

Rhodic Ferralsols have a higher proportion of hematite, while xanthic have goethite, confirming the concept of Schwertmann, 1971 and Torrent et al., 1982, which states that the red colour of soils is related to hematite and yellow to goethite. The higher content of goethite than of hematite in the less developed Cambisols, Nitisols, Lixisols and Acrisols agrees with the concept that goethite is the iron oxide more in equilibrium with present (humic) environmental conditions, which favours its formation (Schwertmann, 1971 and 1985).

Based on their morphological and chemical characteristics one profile provisionally classified as Humic, one as Rhodic and one as Orthic Ferralsol, before determination of weatherable minerals, had to be eliminated from the Ferralsol group due to the high content of weatherable

TABLE 11. Mineralogical composition of the clay fraction and content of weatherable minerals in the 50-200 μm fraction of Ferralsols and related soils.

SOIL CLASS		Mineralogical composition of clay fraction*					% weatherable minerals
		Kaolite	Vermicu-lite/chlorite mixed layer	Gibbsite	Goethite	Hematite	
	Geric	1.8	0.1	1.2	1.2	0.5	-
	Humic	1.3	0.2	1.0	0.9	0.6	-
Ferralsols	Rhodic	2.3	0.2	0.3	0.5	0.6	0.8
	Orthic	2.1	0.4	0.5	0.9	0.6	1.0
	Xanthic	2.7	0.4	0.5	0.8	0.3	1.1
Cambisols		2.0	1.4	0.1	0.3	-	19.0
Nitisols		2.4	0.7	0.3	1.0	0.4	1.6
Acrisols		2.7	1.1	0.3	0.9	0.1	0.1

* By semi-quantitative estimation from diffractograms. Notation: 3 = Dominant; 2.5 = moderate to dominant; 2.0 = moderate; 1.5 = moderate to little; 1 = little; < 1 = trace.

minerals in the 50-500μm fraction.

The Cambisols found in subtropical and tropical regions are known to have similar morphological and chemical characteristics as the Ferralsols but contain more than 3 percent weatherable minerals other than muscovite or more than 6 percent muscovite in the 50-500μm fraction (FAO.UNESCO, 1985). The data presented in Table 10 are consistent with this concept, since the Cambisols studied have the highest content of mica/illite in the clay fraction and of weatherable minerals in the 50-500μm fraction.

1.5. Conclusions

Although deeply weathered, Ferralsols still have many properties related to parent material, i.e. particle-size distribution, specific surface area, concentration of SiO_2, Fe_2O_3 and TiO_2 and mineralogical composition. Desilication and residual concentration of oxides and hydroxides is stronger and the content of weatherable mineral is lower in Ferralsols than in Nitisols, Acrisols and Cambisols. This is consistent with the concept that Ferralsols constitute a group of soils in which weathering proceeded to a more advanced stage than in other soil groups studied. Based on the former parameters and the exchange properties studied the geric Ferralsols are the most deeply weathered soil followed by humic > rhodic > orthic and xanthic units.

Rhodic Ferralsols show a dominance of hematite, while in xanthic Ferralsols goethite dominates, whereas in other Ferralsols hematite and goethite occur in virtually even amounts. The relation of type of iron compound to soil colour, makes colour a good parameter to differentiate Ferralsols in units. The hues to define rhodic unit should be lowered from 5YR (as established in the 1988 FAO Revised Legend of the Soil Map of the World) to 3YR or redder and that of xanthic from 7.5YR to 6YR or yellower.

The weak development or absence of clay skins together with the weak development of structureal elements in Ferralsols constitute good acessory parameters to differentiate this group from the Nitisols, Lixisols and Acrisols in which clay skins and structure are strongly developed. Distinction and quantification of these characteristics is however sometimes problematic.

Cation exchange criteria, such as eutrophic, dystrophic, allic, cation exchange capacity (CEC) and effective CEC (ECEC), which are used to differentiate Ferralsols from related soils or to define units, are important soil classification parameters. However, the different methods of analysis used by different laboratories, the difficulty in dispersing sesquioxide-rich soils without deferration and organic matter removal, important to obtain the clay fraction used to calculate the exchange properties, introduce errors in their determination. Organic matter appears to contribute significantly to the CEC of Ferralsols and the correction for the CEC_{clay}, also an important classification criterion, seems to be warranted.

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