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A STUDY OF HIGHLY WEATHERED SOILS OF PUERTO RICO

PART I:

MORPHOLOGY, FORMATION AND CLASSIFICATION

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PEDOLOGIC, MINERALOGIC AND CHEMICAL PROPERTIES OF HIGHLY WEATHERED SOILS OF PUERTO RICO

PART I : MORPHOLOGY, FORMATION AND CLASSIFICATION

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ABSTRACT

The pedology of eleven soils representing the range of highly weathered soils found in Puerto Rico and including six Oxisols, four Ultisols and one Inceptisol ~~are~~ is discussed. The environmental conditions and the profiles studied are described in detail. Soil formation in response to ~~the~~ pedogenetic factors is discussed in terms of accumulation of parent material and solum development. Particular emphasis is placed on the impact of geomorphic factors on pedogenesis.

Laterization in Puerto Rico is shown to be largely a geochemical weathering process rather than the result of pedogenetic alterations. Three occurrences of Oxisols on Miocene, Pliocene and Pleistocene surfaces are ascribed to particular geomorphic conditions, ultrabasic rocks, and pre-weathered sediments, respectively. Ultisols were found to have developed in less intensely

weathered saprolite on more unstable geomorphic surfaces. Approaching perhumid conditions, the Ultisols grade into deeply weathered Inceptisols in which the absence of an argillic horizon is attributed to continuous percolation of water in the profile.

The soils were classified according to U.S. Soil Taxonomy, the FAO/UNESCO Legend for the Soil Map of the World, and the French soil classification system. The rationales for placement in and correlations between these systems and their inherent deficiencies are discussed. The correspondence of the Puerto Rican soils studied with those of other intertropical areas could only be described in general terms due to the scarcity of detailed modern soil maps available for the tropics.

INTRODUCCION

Puerto Rico, the smallest and easternmost island of the Greater Antilles, exhibits an intriguing pedologic diversity. With the exception of Aridisols, all orders established in Soil Taxonomy (Soil Survey Staff, 1970) have been identified in an area which comprises less than 9,000 km^2. Out of the more than 150 soil series recognized on the island, eleven soils representing advanced stages of pedogenic evolution under humid tropical conditions were selected for a comprehensive study of their pedologic, mineralogic and chemical properties. The soils chosen include six Oxisols which encompass the whole range of such soils found in Puerto Rico, four Ultisols typical for the humid uplands, and one Inceptisol from a perhumid area.

The rationale for undertaking this study may be apprehended from a survey of the literature on the soils of Puerto Rico. A scanning of the major publications compiled in a bibliography on soils and agronomy of Puerto Rico (Commonwealth Bureau of Soils, 1969) and in the recently published review of soils research in tropical Latin America (Sanchez, 1972) indicates that a considerable amount of research has been carried out ever the years. However, the comparative paucity of information on soil formation, classification, mineralogy and geomorphology is also obvious,

inspite of the fact that there exist significant contributions by Bonnet (1939), Jeffries et. al. (1953), Briggs (1960), Sivarajasingham (1961), and Daniels et al. (1973).

It was, therefore, the main objective of this study to further elucidate the genesis and classification of some important soils of Puerto Rico and to investigate their mineralogy and chemistry with modern analytical techniques. Part I of this paper is focused on and restricted to the pedologic aspects of the soils selected; their mineralogy and chemistry is discussed in detail in subsequent parts.

MATERIALS STUDIED AND METHODS

Location of Sample Sites

Figure 1 shows the location of the sample sites in Puerto Rico and the classification of the soils studied. The distinct physiographic conditions encountered at these locations are discussed in detail in the chapter to follow. A summary of the environmental characteristics further accompanies the profile descriptions contained in the chapter RESULTS AND DISCUSSION.

Fig. 1. Location of sample sites in Puerto Rico

Field Methods

Most of the profiles were examined and sampled in recently dug pits (sites 1,3,5,6,8,9), employing the standard techniques set forth in the Handbook of Soil Survey Investigations Field Procedures (Soil Survey Staff, 1971). Five profiles (sites 2,4, 7,10,11) were studied and sampled at relatively fresh road-banks. Subsoil samples at sites 1,3 and 5 were collected by auger.

All sola were sampled according to pedogenetic horizons and the parent material was included wherever possible. About 1 kg of all of the 61 samples collected was shipped in field-moist state to Honolulu, Hawaii, for mineralogical and chemical analyses at the Department of Agronomy and Soil Science of the University of Hawaii.

FACTORS OF SOIL FORMATION

Climate

Present Climate

The climate of Puerto Rico is controlled by the island's relief and its location north of the intratropical convergence zone in the path of the trade winds. Thus Puerto Rico is exposed to a considerable air flow of surface winds which originate in the semi-permanent Bermuda-Azores high-pressure cell. Because of deflection due to the Coriolis effect, the trades reach Puerto Rico

relatively persistantly from the east-northeast after having attained a hihg degree of water vapor saturation over the warm currents in subtropical latitudes. As a result of orographic effect, much of this moisture precipitates on the northern windward slopes and highest peaks of the central mountains of Puerto Rico. A large quantity of rainfall occurs, therefore, in these areas, whereas it diminished considerably in the rain shadows on and downwind of the leeward sides of the mountains.

The amount of rainfall recorded at or near the sites studied is a clear reflection of this general pattern. Mean annual precipitation is highest at site 11 in the Luquillo Mountains and at site 7 in the Cordillera Central, there reaching 450 cm and 230 cm, respectively. At lower elevations in the central mountains and along the north-central coast (sites 4, 5, 6, 7, 8, 9, 10) the rainfall decreases to between 165 and 200 cm annually. Sites 2 and 3 receive somewhat less rain (~ 150 cm) due to displacement of the orographic barrier to the south in western Puerto Rico.

Mean annual air temperatures are subject to less local variation but characteristically decrease with increasing altitude. At the lower elevations up to 200 m above sea level (sites 1, 2, 3, 4, 5), mean annual temperatures are about 25°C; intermediate altitudes (sites 6, 8, 9, 10) have temperatures between 23 and 24.5°C; the

highest locations (sites 7, 11) are also the coolest with mean values of 21 and 20 °C.

TABLE I

Climatic data for selected stations in Puerto Rico

Table 1 lists rainfall and temperature data recorded at or near the sample sites. These data indicate the seasonal variation of precipitation following a pattern characterized by drier winters, moderate spring rains, a lull in early summer, and a maximum in September and October. These seasonal variations are difficult to account for but are probably attributable to the migration of the equatorial trough, the relative strength of the high-pressure cells, and changes in air mass movements. The different rainfall distribution at site 1 near Mayaguez reflects the fact that the summer rains are mainly of convectional origin and therefore occur during the hottest months. - Because of the moderating effect of the surrounding ocean, the annual temperature cycle has a range of less than 5 °C, but diurnal fluctuations are more significant and reach 10 °C or more.

On the basis of these data, the climate at the sample sites may be classified as variants of "tropical rainforest climate", and

"tropical rainforest climate, monsoon type" (Af, Am) in Köppen's empirical system (Köppen, 1923). In the explanatory-descriptive system of Strahler (1969) it should be classed as "trade wind littoral climate". According to Thornthwaite's system (1931) the climate at site 11 is wet mesothermal (AB'r); site 7 is humid tropical to mesothermal (B'/BA'W); sites 1, 4, 5, 6, 8, 9, and 10 are humid tropical (BA'r); and sites 2 and 3 are humid to subhumid tropical (Thorp, 1941). - The soil climate may be characterized by isothermic soil temperature regimes at sites 7 and 11, and by isohyperthermic regimes at all other sites. Soil moisture regimes are udic at all locations, but approach ustic at sites 2 and 3.

A discussion of the climate of Puerto Rico would not be complete without mentioning hurricanes. Puerto Rico is stated to experience hurricanes whose centers touch the island on the average of 25 to 30 years (Bogart et al., 1964). The massive circulation of moist air impinging on the island during these storms causes intense rainfall in large amounts resulting in disastrous floods. In addition, severe floods caused by hurricanes passing nearby and tropical disturbances occur about every 5 to 6 years. These events are accompanied by massive landslides, soil creep, uprooting of trees and accelerated erosion which doubless have impact on soil formation.

Paleoclimate

Since time zero of pedogenesis for many of the soils studied was in Tertiary times, it is indispensable to consider the climate during this period of time. While little is known about the climate of ancestral Puerto Rico its broad features can be deduced. It is likely that the major current pattern of the North Atlantic Ocean has not changed appreciably since Tertiary; and the same probably holds true for the principal air circulation pattern. Although the longitudinal position of ancestral Puerto Rico was farther to the east, its location with respect to the equator was similar to that of today. In addition, the relief of Miocene Puerto Rico, as postulated below, was sufficient to intercept the surface winds and to act as an orographic barrier (Briggs, 1960). Temperature were significantly higher in Eocene than today but suffered a gradual decrease approaching Pleistocene. - It is,therefore, reasonable to assume that the climate during Miocene and early Pliocene may not have been greatly different from that of today.

During Pleistocene the climate was subject to greater fluctuations corresponding with glacial and interglacial stages in the high latitudes. It is generally held that during the cold phases of the Quaternary the low latitudes were significantly drier than today which is attributed to an equatorward shift of the jet stream and

reduced oceanic evaporation (Flohn, 1953). However, because of its position in the ocean, it is unlikely that Puerto Rico suffered the same degree of aridity as the continental regions in the tropics. Thus it is conjectured that the climatic record for northern and central Puerto Rico was essentially a pluvial one with subhumid to humid sub-tropical conditions during the glacials and a humid tropical climate during the interglacials.

Vegetation

By virtue of its climate and location Puerto Rico belongs to the Caribbean province within the paleotropical plant kingdom. This province, set up along the lines of floristic coincidence, comprises essentially all of Central America. There is every reason to believe that at the time of Columbus' arrival the island of Puerto Rico was covered by extensive and luxuriant forests. Because today the plant cover is almost entirely controlled by man, the delineation of ecologic zones can only be made by extrapolation from the few remaining relics and by inference from physiographic and climate features. Little and Wadsworth (1964) have distinguished seven types of climax forest in Puerto Rico; three of these characterize the natural vegetation at the study sites.

Tropical moist forest grew in the northern and north-western coastal areas of the island (sites 2, 3, 4, 5). The mostly evergreen

tress of this forest were from 12 to 18 m tall and included corozo palm (Acrocomia media), West Indian locust (Hymenaea courbaril), Spanish cedar (Cedrela odorata) and black olive (Bucida buceras).

Tropical and subtropical moist forest occupied most of the mountainous interior at elevation lower than 750 m and was the typical vegetation at sites 1, 6, 7, 8, 9, and 10. This formation contained about 170 species and probably was the most magnificent forest of Puerto Rico. At its maximum development it reached more than 30 m in height with trees up to 2.5 m in diameter. Prominent species of this forest were tree-fern (Cyathea arborea), trumpet tree (Cecropia peltata), pomshock (Inga laurina), angelin tree (Andira inermis), candlewood (Dacryodes excelsa), and yellow sander (Buchenavia capitata).

Subtropical rain forest characterizes the vegetation at site 11. Because of lower temperatures and poorer drainage this forest is comparatively poor and rarely taller than 20 m. Tree-fern (Cyathea arborea) and sierra palm (Euterpe globosa) dominate over the species encountered in the subtropical moist forest.

Geology

Puerto Rico comprises three geologic provinces (Briggs and Akers, 1965; Briggs, 1969):

(1) A central province of volcanic and plutonic rocks of early Cretaceous to early Tertiary age traverses the island from east to west, underlying most of the mountainous interior. The rocks are chiefly volcaniclastics and lavas of andesitic-basaltic composition, but at many places the volcanic strata have been penetrated by large and small masses of intrusive igneous rocks, mainly granodiorite. In southwestern Puerto Rico the volcanic rocks rest on and are intruded by serpentinite.

(2) A northern limestone province consisting of strata of middle Tertiary to Recent age extends along the north and northwest coasts of the island. The main rock types of this province are limestone, chalky limestone and calcarenite, but layers of marl and dolomite are also present. These bedrocks are, in places, overlain by alluvial, blanket, swamp, and beach deposits.

(3) A southern limestone province dipping southward off the central highland occurs along the south coast in an irregular belt. This province contains rocks similar in description and age to those of the northern province, but Quaternary sediments dominate over Tertiary limestones.

The volcanic rocks originated in a deep marine trough, the Antillean geosyncline. From recently published paleogeographic maps (Dietz and Holden, 1972), it may be assumed that the

formation of this geosyncline and the subsequent volcanism occurring in it were associated with the breakup of the paleozoric super-continent Pangaea. While the location of the trough may have been somewhere near 40° W and 10° N in Lower Cretaceous, the Caribbean plate has since drifted to its present position. -Compressional uplift in the geosyncline caused the deformation and severe faulting of the volcanic rocks during two major orogenies and, in Eocene, the first emergence of the central axis of ancestral Puerto Rico. (For a more detailed discussion, see Beinroth, 1969.)

Of the eleven study sites shown on Fig.1, seven are located in the central axial province, and four in the northern limestone province. The geology at these sites is discussed below in stratigraphic sequence.

Site 1. The serpentinized peridotite underlying the soil at site 1 forms part of the Bermeja complex which occurs in the cores of anticlines southwest and south of Mayaguez. These rocks are either intrusive into or older than the other basement rocks and therefore probably pre-Cenomanian in age (Mattson, 1960). Characteristically, the serpentine is dark green and greenish white in color and intensely sheared and foliated.

Site 9. The parent rock at this site southwest of Aguas Buenas has not been positively identified but is considered a lava

breccia or tuffaceous breccia of andesitic lithology. These rocks are Lower Cretaceous in age and usually extremely shattered by faulting.

Site 10. Clayey terrace deposits of Pleistocene and probably Pliocene age geologically characterize this site near Lake Cidra. The sediments overly and are chiefly derived from the surrounding Lower Cretaceous andesitic volcaniclastics, but also contain some detritus derived from the scattered plutonic outcrops in the vicinity.

Sites 6, 7 and 8. All of these locations occur in formations of Upper Cretaceous age. At site 6 near Barranquitas, this is the Río Orocovis Group of the Perchas Formation (R.P. Briggs, personal communication, 1969), consisting there of dark-bluish-gray basaltic andesite lava with augite phenocrysts in an aphanitic groundmass (Briggs and Gelabert, 1962). - Carreras Siltstone has been mapped at site 8 near Corozal (Nelson, 1967). This rock is mostly dark gray to dark olive thin-bedded siltstone with some thin interbeds of volcanic sandstone of presumably andesitic - basaltic composition. - The formation at site 7 near Jayuya has not been formally named. Although the parent rock is concealed at the sample site, it is assumed to be an andesitic-basaltic lava breccia according to the geologic map (Briggs and Akers, 1965).

Site 11. This site in the Luquillo Mountains is located in a

small outcrop area of Upper Cretaceous and Eocene plutonic rocks. According to field inspection, the parent rock at the sample site is considered a ~~grano~~quartz diorite with hornblende phenocrysts in a finer white groundmass.

Sites 2, 3, 4 and 5. These four study sites occur in the northern limestone province in areas mapped as blanket deposits (Briggs and Akers, 1965). These sediments overly karsted Tertiary limestone and average about 10 m in thickness. They are Pleistocene and probably Pliocene in age and consist of clay and quartz sand in greatly varying proportions. The blanket deposits are not residual from the underlying virtually quartz-free limestone, rather they were initially derived from the volcanic and plutonic rocks of the interior (Briggs, 1966). The textural composition of these sediments reflects the geology of the area of their original provenance. Because the catchment basin of Río Manatí comprises granitic outcrops, the textures at sites 4 and 5 near Manatí are considerably sandier than those at sites 2 and 3 southwest of Isabela where no plutonic rocks occur to the south.

Geomorphology

The presence of areas of coincident mean elevations in Puerto Rico was first recognized by Lobeck (1922) who distinguished a "First or Higher Peneplane" and a "Second or Lower Peneplane."

Later Meyerhoff (1933) coined the terms "St. John Peneplain" and "Caguana Peneplain" for these two erosion surfaces. However, more recent studies indicate that the geomorphic history of Puerto Rico is considerably more complicated (Weaver, 1960).

In brief, an island of highly mountainous aspect and comprising Hispaniola, Puerto Rico and the U.S. Virgin Islands emerged in Upper Eocene after the volcanic, plutonic and orogenic activities had ceased. Subsequently this ancestral landmass underwent degradation and suffered posterosional submergence in Middle Oligocene. There followed a period of stability and quiescene from Upper Oligocene to Middle Miocene during which partial base-leveling occurred on the landmass. The ensuing St. John Peneplain probably reached its broadest development in Middle Oligocene. Briggs (1960) assumed that the peneplain then had a hypothetical mean elevation of 100 m, and that the highest point of the island may have been 1,000 m or more. The St. John Peneplain is now the main skyline feature of the Cordillera Central and lies at maximum elevations averaging 750 to 800 m (Weaver, 1960).

The St. John time was terminated in Upper Miocene by the first of a series of uplifts which raised the island to its present elevation. These stepwise uplifts resulted in rejuvenation of the drainage system and induced new cycles of erosion. It is believed

that the Caguana Peneplain reflects a period of more prolonged stability in Pliocene. The Caguana Peneplain is less conspicuous than the St. John Peneplain and has amean elevation of 470 m. Both peneplains are now strongly dissected and large remnants unaffected by erosion are scarce.

Since the end of Tertiary Puerto Rico has been tectonically essentially stable. Although Meyerhoff (1933) presented evidence that the island had been tilted during Quaternary, more recent studies suggest stability throughout most of Pleistocene (Monroe, 1968). However, eustatic fluctuations of the sea level during this period affected the low-lying coastal areas. On the basis of marine terraces now occurring above sea level, it is concluded that Pleistocene sea levels were, at times, 25, 40, 50, and 65 m above the present level (Monroe, 1968).

The soils selected for this study occur on surfaces of Miocene to Recent age. The geomorphology at the individual sites is discussed below in numerical order.

Site 1. This site is located on Cerro Las Mesas, a prominent landscape feature southeast of Mayaguez. At its highest point at the eastern end, this plateau-like interfluve has an elevation of about 380 m and slopes from there with an average gradient of 3.5 percent to the northwest to its lowest point of roughly 220 m. The

plateau is being encroached by active erosion from all sides resulting in steep and very steep flanks extending from the summit surface to the valley bottoms of streams deeply entrenched along the shattered contact zone of serpentinite and volcanic rocks.

This geomorphic surface can be traced across a V-shaped valley farther to the southeast up to altitudes characteristic for the Caguana Peneplain and is, therefore, correlated with this erosion cycle. Because the Caguana Peneplain cuts clean across Miocene rocks considered to be Helvetian, it must be post-Helvetian (Weaver, 1960) and probably Pliocene in age. The Cerro Las Mesas ridge is believed to be a remanant of the pediment footslope of a surface graded to a Pliocene sea level which was probably 150 m higher relative to the present surface.

It cannot be established with certainty whether the parent material of the soil at site 1 is residual or transported. Because of the absence, or near absence, of quartz veins in the underlying serpentinite, there are no stone lines which could help identify cycles of erosion and deposition. However, on account of the geomorphic position, it must be assumed that a considerable part of the material has been transported and thus constitutes a pedisediment. Still, the peculiar nature of this material leaves no doubt that it is derived almost exclusively from serpentinite rocks.

Sivarajasingham (1960) speculated that Cerro Las Mesas may have been a topographic low in an old landscape. On the assumption that iron-indurated deposits formed in such positions, he conjectured that these erosion resistant layers caused an inversion of relief following the uplift. While petroplinthite (Sys, 1968) was observed along the edges of the Pliocene surface, several recent exposures on Cerro Las Mesas indicate that there exists no continuous ironstone layer. Rather, it would appear that the formation of petroplinthite is restricted to the edge of the old surface, which is also corroborated by Maignien's observations in Africa (1956). It is probable that layers of petroplinthite have retarded slope retreat and, in combination with the erosion resistance of the soils, delayed degradation of the Pliocene surface.

Sites 2, 3, 4 and 5. These sites are discussed jointly because they are all located in the area of blanket deposits. These sediments occur north of an east-west extending belt of Tertiary limestones with superimposed kegelkarst and doline karst topography, and are associated with alluvial sands, gravels, clays in flood plains, swamp muck in filled lagoons, and dunes near the coast (Briggs, 1966). The blanket deposits normally form broad undulating plains as at sites 3 and 4, but are also found in intrakarst features as at site 5, located in large uvala. Site 2 lies at the base of a subconical karst

lower on the geologic boundary between blanket deposits and Aymamon limestone.

The blanket deposits originated in a concurrent process of uplift, karstation of emerging limestones, erosion in the interior, and littoral redistribution of sediments along the coast. Most of them rest on the Miocene Aymamon and Camuy limestones, and are considered Miocene to Recent in age (Briggs, 1966).

In northwestern Puerto Rico (site 3), the blanket deposits rest on a marine degradational terrace and occur at considerable higher elevations than those to the east (sites 4 and 5). This may be due to tilting of the island in Pliocene. The low tableland southwest of Isabela lies at an average elevation of 120 m, well above the reach of eustatic fluctuations, and is separated from the ocean by a precipice. In addition, there exist no major streams that could have brought detritus to this plateau in Pleistocene. Assuming tectonic stability during Pleistocene, it is concluded that the geomorphic surface at site 2 is essentially Pliocene.

Site 5, lying at 83 m above sea level, was probably not affected by glacially controlled advances of the sea. It is, therefore, believed that the geomorphic surface at this location is late Pliocene to early Pleistocene in age. - Because of their low altitude of 50 m, it must be assumed that the blanket deposits at site 4 were reworked

and redistributed during Quaternary periods of high sea levels. Consequently, the age of this geomorphic surface is late Pleistocene.

The presence of recent dolines in the area of blanket sands suggests that karstation is continuing on the underlying limestones. The resulting subsidence of the deposits and their probable local redistribution by wind and water during Pleistocene could be used as an argument to date all surfaces on the blanket deposits as Pleistocene.

Site 6. The geomorphology of the small watershed near Barranquitas where this site is located has been studied in considerable detail (Briggs, 1960; Daniels et al., 1973). According to these investigations, the geomorphic surface at site 6 is of Middle Miocene age. It is associated with a series of other Tertiary surfaces in terrace positions of what is considered the remnant of the upper catchment area of a broad valley on the St. John Peneplain.

The preservation of the old landscape is ascribed to particular structural and tectonic conditions which retarded the upstream migration of the knickpoint resulting from the rejuvenation of the drainage system induced by the Upper Miocene uplift. This knickpoint constitutes a local base level and protected the area upstream of it from the severe dissection to which the surrounding uplands were subjected since Pliocene.

The dating of the geomorphic surface can only be done by inference employing the following reasoning. When the stage of the denundation of a landmass approaches base level, the rate of erosion diminishes and residual weathering products accumulate. Also, the streams of mature landscapes are of low competence and carry less and finer sediments than during periods of rapid downcutting. -During the degradation of the ancestral landmass of Puerto Rico the northern coast must have been some 10 to 15 km farther inland, roughly at the present contact of the marine calcareous sequence and the volcanic-plutonic core. Because of this proximity, the erosive situation in the hinterland should be directly reflected in the composition of the sediments forming offshore. The formation of pure limestone should, therefore, coincide with a period of very little erosion. On this rationale, Briggs (1960) concluded that the broadest development of the St. John Peneplain must have been in Middle Miocene when the exceptionally pure Aymamon limestone formed.

The surfaces in the small watershed studied are at elevations between 560 and 615 m (Daniels et al., 1973) and thus considerably lower than the mean maximum of the St. John Peneplain of 760 m as postulated by Weaver (1960). However, the correlation of these surfaces with the St. John Peneplain appears to be valid because.

they are considered part of a former valley and because the altitude of the peneplain is subject to significant local variation.

Site 6 occupies a concave upper footslope of a geomorphic surface that is assumed to be largely erosional. However, this position does not exclude the possibility that the parent material of the soil at this site contains local colluvium. The lack of field evidence for lithologic discontinuities is not conclusive because the parent rock yields no stone lines and because the colluvium was presumably derived from identical lateritic material. Although the geomorphic surface at this site is considered Tertiary in age and configuration, it is probable that minor additions of fresh material occurred sporadically during Quaternary.

Site 7. The soil at this site, located at an elevation of 740 m in the central mountains, was sampled at the edge of a narrow interfluve at the shoulder of a Recent erosion surface. The geomorphic relations at this location are obscured by severe dissection and have not been studied in any detail.

As the interfluve surface lies within the altitude range of the St. John Peneplain, a point could be made to consider its central part as a remnant of this erosion cycle. If so, it must have been the upper backslope of a surface whose footslope and lower backslope have been consumed by erosion. However, it appears unreasonable

to assign a Miocene age to this surface, because it is unlikely that a backslope of 30 percent has been stable over some 20 million years under humid tropical conditions. But the surface must be older than Recent since it does not grade consistently to the present drainage. . Because of the relative thickness of the weathering mantle, the geomorphic surface at site 7 is tentatively considered to be Pliocene to early Pleistocene in age.

Site 8. This site near Corozal is located to the south of a broad subsequent depression that developed in the unconsolidated basal conglomerates and clays between the Tertiary limestones and the Cretaceous volcanic-plutonic core. The sample site occupies a flat part of a narrow interfluve sloping to the north with an average gradient of 10 percent.

No geomorphic studies are available for this location, but the interfluve is considered a remanant of a surface graded to a local base level in the valley to the north and leading to the summit surface of the Caguana Peneplain to the south. Erosion caused by the rejuvenation of the drainage system following the post-Caguana uplift, resulted in strong dissection of this Pliocene surface. At the sample site, present erosion infringes perpendicular to the interfluve causing its flattening at this place. The soil at site 8 thus occupies a truncated Pliocene surface.

Site 9. This site is located at the upper convexity of a moderately sloping erosion surface encroaching on an area of generally flat topography with thick regoliths that lies slightly above 500 m elevation. In the absence of detailed geomorphic investigations, the landscape relations at this location are subject to speculation. It is possible that the smooth surface at 500 m is a correlative of the St. John Peneplain as it occurs above the level of the Caguana Peneplain. The surface truncating it must necessarily be younger. However, this surface is also older than the Recent surfaces which, in turn, encroach on it. It is thus conjectured that the geomorphic surface at site 9 is associated with the Caguana erosion cycle and is, therefore, Pliocene in age.

Site 10. This site east of Lake Cidra is located in an area of smooth topography that has the aspect of a broad valley. The sample site is on an almost plane surface considered a terrace and adjacent to the shoulder of an erosion surface cutting into this terrace. An account of its elevation of 450 m, this terrace is believed to have formed during the Caguana erosion cycle and is thus essentially Pliocene in age. As there probably has occurred some alluviation in this area during Pleistocene and because late Pleistocene to Recent erosion surfaces are dissecting it, the geomorphic surface at site 10 is considered Pliocene to early Pleistocene in age.

-Although no field work was carried out to substantiate this point, it is assumed that the parent material of the soil at this site is predominantly a terrace sediment.

Site 11. The term monadnock has been employed by Lobeck (1922) to characterize the very strongly dissected and steeply sloping highest peaks of the Luquillo mountains where this site is located. (Although the usage of this term is questionable in this case, it has since been retained.) The sample site occupies a small bench in strongly slpping and highly dissected terrain with abundant evidence for instability. The geomorphic surface at this site is, therefore, doubtless of Recent age.

RESULTS AND DISCUSSION

Soil Morphology

In view of the paucity of detailed profile descriptions of tropical soils found in the literature, an effort has been made to accurately describe the pedons studied. Employing mainly the terms and criteria as defined in the Soil Survey Manual (Soil Survey Staff, 1951), the description of each horizon contains the following morphological properties in the order listed: moist and dry soil colors with Munsell notations; soil texture; grade, size and class of soil structure; soil consistence when wet, moist and dry; clay films

and pressure faces; failure; other characteristics; and lower boundary. Two new terms are used to describe the rate of failure of natural fabric. Abrupt failure means that no plasticity is observed prior to failure. Stress builds up as the piece of soil is squeezed and dissipates qu ly as the soil breaks apart into numerous fragments or peds due to failure along natural planes of weakness. In semiplastic failure, deformation is readily observed prior to rupture (Soil Survey Staff, 1967).

Although the development and publication of the Soil Survey Manual marked a significant accomplishment for describing soils with considerable precision and clarity (Cline, 1961), some properties defy accurate evaluation in the field. For example, in Oxisols the recognition of clay skins and the distinction between clay films and stress cutans is often a matter of subjective judgement. However, as the presence of clay films is one of the main criteria for identifying argillic horizons and thus carries great weight as a differentiating criterion at high taxonomic levels, positive identification is crucial. Yet in some of the soils studied this was impossible on the basis of field methods. The respective field observations reported below for the soils at sites 1, 3, 4, 6 and 11 are, therefore, subject to change upon thin-section studies. - The appraisal of the grade of structure is also somewhat subjective,

particularly in the case of the Oxisols described. As discussed later, this may be reflected in the classification of these soils.

The lower oxic horizon of the soil at site 5 exhibits a fluffy consistence, described by Sys (1972) as having the feeling of flour, and called "farineux" by French pedologists. Since this is typical for many uncultivated Oxisols (A. Van Wambeke, personal communication, 1973), the introduction of a new descriptive term for this phenomenon may be warranted.

The profile descriptions that follow also include a summary of the main environmental conditions, and are arranged in numerical order of the sample sites shown on Fig. 1.

Site 1 NIPE SERIES

General Characterization

Classification

US Soil Taxonomy		
Subgroup	:	Typic Acrorthox
Family	:	Clayey, oxidic, isohyperthermic
FAO/UNESCO Legend	:	Humic Ferralsols
French System (CPCS)		
Classe	:	Sols Ferrallitiques
Sous-classe	:	Fortement désaturés en (B)
Groupe	:	Humifères
Sous-groupe	:	Modal (X /321)
USDA 1938 Great Group	:	Laterite soils

Location of Sample Site

Latitude	:	18° 11' 2" N
Longitude	:	67" 6' 10" W
Elevation above sea level	:	350 m
General description	:	W Puerto Rico, Municipality Mayaguez, Barrio Quebrada Grande; USGS Quadrangle Rosario; Cerro Las Mesas, 40 m S of km 5.45 on highway PR 349

Climate

Mean annual rainfall	:	~ 200 cm
Mean annual air temperature	:	~ 24° C
Thornthwaite type	:	BA'W - humid tropical, dry winters

Vegetation and Land Use

Natural vegetation : Tropical moist forest

Land use and crop : Cleared but idle--brush and grass predominantly used for suburban residential purposes

Parent Material and Geology

Parent material : Strongly weathered saprolite

Parent rock : Serpentinized peridotite

Geologic formation : Bermeja Complex, Early Cretaceous

Geomorphology

Slope : 2%

Aspect : W

Landform : Planar wide interfluve

Geomorphic surface : Remnant of erosional/depositional surface of post-Helvetian and probably Pliocene age; correlates with "Caguana Peneplain"

Occurrence in Puerto Rico

Nipe series is of minor extent in the humid outcrop areas of serpentinite in western Puerto Rico

Principal Associated Soils

Typic Haplorthox, Tropeptic Haplorthox, Typic Eutropepts, Typic Dystropepts, Serpentinite Rockland

Remarks

Soil Taxonomy classification unsatisfactory (see text). Horizons A1 through B22 sampled from a pit, horizons B23 and C1 sampled by auger. Sample site is located approx. 250 m N of the SCS type location of Nipe series, see SSIR No. 12, pp. 154 - 155.

Profile Description

A1
0-25 cm

Reddish brown (2.5YR 4/4, moist; 5YR 4/4, dry) clay; moderate to moderately strong very fine subangular blocky and fine granular structure; nonsticky, slightly plastic, friable, hard consistence; clear smooth boundary.

B1
25-40 cm

Weak red to reddish brown (10R to 2.5YR 4/4, moist) and red (10R to 2.5YR 4/6, dry) clay; weak to moderate fine and very fine angular blocky structure; slightly sticky, slightly plastic, friable to very friable, hard consistence; no clay films or pressure faces; abrupt failure; gradual smooth boundary.

B21
40-70 cm

Dusky red to red (10R 3.5/5, moist) and red (10R 4/6, dry) clay; weak to moderate fine and very fine angular and sub-angular blocky structure; slightly sticky, slightly plastic, friable to very friable, hard to slightly hard

consistence; no clay films or pressure faces; abrupt failure; gradual smooth boundary.

B22
70-95 cm

Weak red to red (10R 4/5, moist) and red (10R 4/6, dry) clay; in part massive but predominantly weak fine and very fine angular and subangular blocky structure; slightly sticky, slightly plastic, friable, slightly hard consistence; no clay skins or pressure faces; abrupt failure; gradual smooth boundary.

B23
95-120 cm

Dusky red to weak red (10R 3.5/4, moist) and red (10R 4/6, dry) clay; in part massive but mainly weak fine and very fine angular and subangular blocky structure; slightly sticky, slightly plastic, friable, slightly hard consistence; no clay films or pressure faces; abrupt failure; clear smooth boundary.

C1
~~B24~~
120-160 cm

Dusky red to dark red (10R 3/5, moist) and weak red to red (10R 4/5, dry) clay; moderate (strong when dry) fine and very fine angular and subangular blocky structure; slightly sticky; slightly plastic, firm, slightly hard to soft consistence; abundant coatings on ped faces that are probably stress cutans; few yellowish-red streaks; abrupt failure.

Site 2 MATANZAS SERIES

General Characterization

Classification

US Soil Taxonomy		
Subgroup	:	Tropeptic Eutrorthox
Family	:	Clayey, ~~oxidic~~ kaolinitic, isohyperthermic
FAO/UNESCO Legend	:	Orthic Ferralsols
French System (CPCS)		
Classe	:	Sols Ferrallitiques
Sous-classe	:	Faiblement désaturés en (B)
Groupe	:	Rajeunis
Sous-groupe	:	Avec erosion (X/143)
USDA 1938 Great Group	:	Reddish-Brown Lateritic soils

Location of Sample Site

Latitude	:	18° 26' 40" N
Longitude	:	67° 8' 32" W
Elevation above sea level	:	160 m
General description	:	Northwest Puerto Rico;

Municipality Aguadilla, Barrio Camaceyes, USGS Quadrangle Aguadilla; road bank at south side of km 124.95 on highway PR 2

Climate

Mean annual rainfall	:	~ 140 cm

Mean annual air temperature : ~ 25° C

Thornthwaite type : B/CA'r - subhumid to humid tropical

Vegetation and Land Use

Natural Vegetation : Tropical moist forest

Land use and crop : Noncommercial woodland

Parent Material and Geology

Parent material : Clay sediments mixed with residuum and colluvium from limestone

Geologic formation : Blanket Deposits of chiefly Pleistocene age derived from mainly andesitic volcaniclastics; laterized in previous weathering cycle; unconformably overlying Miocene limestones

Geomorphology

Slope : 5%

Aspect : N

Landform : Concave footslope at limestone hill

Geomorphic surface : Contact of Pleistocene depositional surface upon Early Pleistocene marine degradation terrace and cone-shaped, karsted Miocene limestone hills

Occurrence in Puerto Rico

Matanzas series is of minor extent in the northern and northwestern coastal areas of Puerto Rico

Principal Associated Soils

Tropeptic Haplorthox, Tropeptic Eutrorthox, Lithic Tropudalfs

Limestone Rockland

Remarks

Sampled from road bank at SCS type location for Matanzas series; see SSIR No. 12 pp 158-159.

PROFILE DESCRIPTION

A1 0-35 cm	Dark reddish brown (2.5 YR 3/4, moist) and red (2.5YR 4/6, dry) clay; moderate fine subangular blocky structure; slightly sticky, slightly plastic, firm to friable, slightly hard to hard consistence: few pressure faces; clear smooth boundary.
B21 35-70 cm	Weak red to reddish brown (10R-2.5YR 4/4, moist) and red (10R-2.5 YR 4/6, dry) clay; moderate to weak fine and medium subangular blocky structure breaking to fine and very fine granules; slightly sticky, slightly plastic to plastic, friable to firm, hard to slightly hard consistence; no clay films; few pressure faces; abrupt failure; gradual smooth boundary.
B22 70-100 cm	Red (10R 4/5 to 2.5YR 4/6, moist; 10R-2.5YR 5/6, dry) clay; weak fine and medium subangular blocky

structure breaking to fine and very fine granules; slightly sticky, slightly plastic, friable, hard to slightly hard consistence; no identifiable clay films; few pressure faces; abrupt failure; abrupt irregular boundary.

IIR White, hard limestone

Site 3

COTO SERIES

General Characterization

Classification

US Soil Taxonomy		
Subgroup	:	Tropeptic Haplorthox
Family	:	Clayey, kaolinitic, isohyperthermic
FAO/UNESCO Legend	:	Humic Ferralsols
French System (CPCS)	:	
Classe	:	Sols Ferrallitiques
Sous-classe	:	Moyennement désaturés en (B)
Groupe	:	Typiques
Sous-groupe	:	Faiblement rajeuni (X/215)
USDA 1938 Great Group	:	Reddish-Brown Lateritic soils

Location of Sample Site

Latitude	:	18° 28' 2" N
Longitude	:	67° 3' 25" W
Elevation above sea level	:	131 m
General description	:	Northwest Puerto Rico,

Municipality Isabela, Barrio Guerrero, USGS Quadrangle Moca, Agr. Exp. Substation Isabela; 400 m N of km 115.2 on highway PR 2

Climate

Mean Annual rainfall	:	170 cm

Mean annual air temperature : 25° C

Thornthwaite type : B/CA'r - subhumid to humid tropical

Vegetation and Land Use

Natural vegetation : Tropical moist forest

Land use and crop : Experiment site -- citrus, sugarcane

Parent Material and Geology

Parent material : Clay sediments

Geologic formation : Blanket Deposits of chiefly Pleistocene age derived mainly from andesitic volcaniclastics; laterized in previous erosion cycle; unconformably overlying Miocene limestones

Geomorphology

Slope : 0

Aspect : -

Landform : Slightly undulating plain

Geomorphic surface : Depositional surface of mainly Pleistocene age; sediments deposited on a marine degradation terrace at Lake Tertiary/Early Pleistocene age; occacional dolines

Occurrence in Puerto Rico

Coto series is of moderate extent in the northwestern coastal areas of Puerto Rico

Principal Associated Soils

Tropeptic Eutrorthox, Typic Palehumults, Lithic Tropodalfs

Remarks

Sampled in a pit located 500m NW of SCS pit S63PR-6-1, see SSIR No 12, pp. 174-175

PROFILE DESCRIPTION

AP 0-13 cm	Dark brown to brown (7. 5YR 4. 5/~~5~~4, moist) and brown (7. 5YR 5/4, dry) clay; moderate fine granular and very fine subangular blocky structure; slightly sticky, slightly plastic, friable, slightly hard to hard consistence; clear smooth boundary.
A12 13-25 cm	Strong brown (7. 5YR 5/6, moist) and strong brown to reddish yellow (7. 5YR 5. 5/6, dry) clay; weak to moderate fine and very fine subangular blocky structure; slightly sticky, slightly plastic, friable, slightly hard to hard consistence; no clay films or pressure faces; few fine hard black nodules; gradual smooth boundary.
B21 25-45	Strong brown to yellowish red (7. 5YR 5/7 to 5YR 5/8, moist) and reddish yellow (7. 5YR 6/6, dry) clay, weak fine and very fine subangular blocky structure approaching massive structure; slightly sticky, slightly plastic friable hard to slightly hard consistence; very few

pressure faces, probably no clay skins, few reddish brown coatings in root channels; few fine black nodules; abrupt failure; gradual smooth boundary.

B22
45-65 cm

Yellowish red (5YR 5/6, moist) and reddish yellow (5YR to 7.5 6/6, dry) clay; structure and consistence as in B21; few pressure faces; few coatings in root channels; few fine black nodules; abrupt failure; gradual smooth boundary.

B23
65-90 cm

Yellowish red (5YR 5/6, moist) and reddish yellow (7.5YR 6/6, dry) clay, weak fine and very fine subangular blocky structure; slightly sticky, slightly plastic, friable, slightly hard to hard consistence; few pressure faces, few coatings in root channels; few fine black nodules; abrupt failure; gradual smooth boundary.

B24
90-120 + cm

Yellowish red to reddish yellow (5YR 5.5/6, moist) and reddish yellow (7.5YR 6/6, dry) clay; moderate fine subangular blocky structure breaking to very fine angular blocky and granular aggragated; slightly sticky, slightly plastic, friable, hard to slightly hard consistence; common shiny ped faces, possibly some thin discontinuous clay films; common fine black nodules and streaks; abrupt failure.

Site 4 BAYAMON SERIES

General Characterization

Classification

US Soil Taxonomy		
Subgroup	:	Tropeptic Haplorthox
Family	:	Clayey, kaolinitic, isohyperthermic
FAO/UNESCO Legend	:	Orthic Ferralsols
French System (CPCS)		
Classe	:	Sols Ferrallitiques
Sous-classe	:	Faiblement désaturés en (B)
Groupe	:	Typiques
Sous-groupe	:	Faiblement rajeuni (X/114)
USDA 1938 Great Group	:	Reddish-Brown Lateritic soils

Location of Sample Site

Latitude	:	18° 26' 5" N
Longitude	:	66° 33' 19" W
Elevation above sea level	:	50 m
General description	:	North-central Puerto Rico;

Municipality Barceloneta, Barrio Florida Afuera, USGS Quadrangle Barceloneta; road bank on south side of highway PR 2 at km 56. 75

Climate

Mean annual rainfall	:	∿ 165 cm

Mean annual air temperature : ~ 25°C

Thornthwaite type : BA'r - humid tropical

Vegetation and Land Use

Natural vegetation : Tropical moist forest

Land use and crop : Mainly cultivated to pineapple

Parent Material and Geology

Parent material : Clay sediments

Geologic formation : Blanket Deposits of chiefly Pleistocene age derived mainly from andesitic volcaniclastics and plutonic rocks; laterized in previous erosion cycle; unconformably overlying Miocene limestones

Geomorphology

Slope : ~ 2%

Aspect : N

Landform : Undulating plain

Geomorphic surface : Probably a marine terrace that originated in Pleistocene, containing some dolines

Occurrence in Puerto Rico

Bayamon series is of moderate extent in the northern coastal plains of Puerto Rico

Principal Associated Soils

Tropeptic Eutrorthox, Plinthic Tropudalfs, Limestone Rockland

Remarks

Sampled from a road bank

PROFILE DESCRIPTION

A1
0-20 cm

Reddish brown (5YR 4. 5/4, moist; 5YR 5/4, dry) sandy clay; moderate medium subangular and angular blocky, and in places strong medium platy structure; slightly sticky, slightly plastic, firm, hard to very hard consistence; few fine black nodules; common thin black streaks and coatings on ped faces; abundant bleached quartz grains; clear smooth boundary.

B-21
20-40 cm

Yellowish red (5 YR 5/6, moist) and yellowish red to reddish yellow (5 YR 5. 5/6, dry) clay; weak fine subangular blocky structure approaching massive structure, slightly sticky to sticky, slightly plastic to plastic, friable, slightly hard consistence; no clay films, very few pressure faces; few hard black nodules up to 4 mm in diameter; abrupt failure; gradual smooth boundary.

B22
40-70 cm

Yellowish red (5 YR 5/6, moist) and reddish yellow (5 YR 6/6, dry) clay; weak to moderate medium and

fine subangular blocky structure; slightly sticky to sticky, slightly plastic to plastic, friable, slightly hard consistence; few bridges of clay, few pressure faces; few to common hard black nodules as above; abrupt failure; gradual smooth boundary.

B3
70-130 + cm

Red (2.5 YR 5/6, moist) and light red to reddish yellow (2.5 YR to 5 YR 6/6, dry) clay loam; in some parts massive but mainly with moderate fine angular and subangular blocky structure; slightly sticky, slightly plastic, friable, slightly hard consistence; common thin continuous clay films; few black nodules; few small red (10 R 5/6) pieces with yellow streaks and pressure faces that resemble saprolite, abrupt failure.

Site 5 PIÑA SERIES

General Characterization

Classification

US Soil Taxonomy		ultic
Subgroup	:	Typic Haplorthox
Family	:	Fine-loamy, oxidic, isohyperthermic
FAO/UNESCO Legend	:	Orthic Ferralsols
French System (CPCS)		
Classe	:	Sols Ferrallitiques
Sous-classe	:	Fortement désaturés en (B)
Groupe	:	Typiques
Sous-groupe	:	Modal (X/311)
USDA 1938 Great Group	:	Reddish-Brown Lateritic soils

Location of Sample Site

Latitude	:	18° 25' 45"N
Longitude	:	66° 26' 56"W
Elevation above sea level	:	83 m
General description	:	North-central Puerto Rico; Municipality Vega Baja, Barrio Pugnado Afuera, USGS Quadrangle Manatí; Fundador Farm, adjacent to hihgways PR 670 and 672

Climate

Mean annual rainfall	:	~ 165 cm
Mean annual air temperature	:	~ 25°C
Thornthwaite type	:	BA'r - humid tropical

Vegetation and Land Use

Natural vegetation : Tropical moist forest

Land use and crop : Experiment site --corn; usually cultivated to pineapple

Parent Material and Geology

Parent material : Sandy clay sediments

Geologic formation : Blanket Deposits of chiefly Pleistocene age derived mainly from andesitic volcaniclastics and plutonic rocks; laterized in previous weathering cycle; unconformably overlying Miocene limestones

Geomorphology

Slope : 0

Aspect : -

Landform : Slightly undulating plain

Geomorphic surface : Depositional surface of Pleistocene age in large uvala surrounded by cone-shaped, karsted limestone hills

Occurrence in Puerto Rico

Piña series is of minor extent in the northern coastal areas of Puerto Rico

Principal Associated Soils

Tropeptic Haplorthox, Tropeptic Eutrorthox, Plinthic Tropudults,

Limestone Rockland

Remarks

Piña series is tentative and not officially correlated by SCS.

Sampled in a pit.

PROFILE DESCRIPTION

Ap 0-20 cm	Reddish brown (5YR 4/4, moist; 5YR 5/4, dry) sand; weak fine subangular blocky structure breaking to fine and very fine granules; nonsticky, nonplastic, very friable to loose, slightly hard to soft consistence: clear smooth boundary.
Ap + B21 20-34 cm	Mechanical mixture of Ap and B21 material caused by deep-plowing; elongated lensed of B21 material up to 10 cm long and 4 cm thick account for 10-15 percent; abrupt smooth boundary.
B21 34-60 cm	Red to yellowish red (2.5 YR 4/8 - 5YR 4/8, moist) and yellowish red (5YR 4/8, dry) sandy clay loam; massive to very weak fine and medium subangular blocky structure breaking to fine and very fine granules; slightly sticky, slightly plastic, very friable, hard to very hard consistence; no clay films: abrupt failure; few, fine, soft black streaks giving

strong effervescence with hydrogenperoxide; gradual smooth boundary.

B22 60-90 cm	Red(2. 5YR 4/6, moist; 2. 5YR 5/6, dry) sandy clay loam; massive to very weak fine and medium subangular blocky structure breaking to fine and very fine granules; slightly sticky, slightly plastic, very friable, hard consistence, no clay films, abrupt failure, few black streaks as above, gradual smooth boundary.
B23 90-125 + cm	Red (2. 5YR 4/6, moist 2. 5 YR 5/6, dry) sandy clay loam; massive to very weak fine and medium subangular blocky structure breaking to fine and very fine granules; slightly sticky, slightly plastic, loose to very friable, hard, no clay films, abrupt failure; few black streaks as above.

Site 6 CATALINA SERIES

General Characterization

Classification

US Soil Taxonomy		
Subgroup	:	Tropeptic Haplorthox
Family	:	Clayey, ~~oxidic~~ kaolinitic isohyperthermic
FAO/UNESCO Legend	:	Humic Ferralsols
French System (CPCS)		
Classe	:	Sols Ferrallitiques
Sous - Classe	:	Moyennement désaturés en (B)
Groupe	:	Typiques
Sous - groupe	:	Humique (X/217)
USDA 1938 Great Group	:	Reddish - Brown Lateritic soils

Location of Sample Site

Latitude	:	18° 14' 31" N
Longitude	:	66° 16' 40" W
Elevation above sea level	:	607 m
General description	:	East - central Puerto Rico;

Municipality Barranquitas, Barrio Quebradillas, USGS Quadrangle Barranquitas; 550 m SE of km 9.7 on highway PR 152

Climate

Mean annual rainfall	:	~ 160 cm

Mean annual air temperature : ~ 22.5 °C

Thornthwaite type : BA'r - humid tropical

Vegetation and Land Use

Natural vegetation : Tropical to subtropical moist forest

Land use and crops : Experiment site -- corn; usually cultivated to subsistence crops such as plantains, bananas, yams, tanniers, and pasture

Parent Material and Geology

Parent material : Strongly weathered saprolite

Parent rock : Chloritized basaltic-andesitic lava flow breccia

Geologic formation : Formation "L", Upper Cretaceous

Geomorphology

Slope : 7%

Aspect : SE

Landform : Concave upper footslope

Geomorphic surface : Erosion/deposition surface of mid-Miocene age; remnant of "St. John Peneplain"; no field evidence of discontinuity between solum and regolith

Occurrence in Puerto Rico

Catalina series is of small extent on stable surfaces in the humid, volcanic central uplands of Puerto Rico

Principal Associated Soils

Orthoxic Tropohumults, Typic Tropohumults, Dystropeptic Tropudults, Typic Eutropepts

Remarks

Sampled in a pit located 40 m NE of SCS pit S 59 PR-10-7, see SSIR No. 12, pp. 164-167

Profile Description

Ap 0 - 16 cm	Reddish brown (5YR 4/4, moist; 5YR 5/4, dry) clay; weak fine granular and subangular blocky structure; slightly sticky to sticky, slightly plastic to plastic, friable to very friable, slightly hard consistence; clear wavy boundary.
B21 16 - 35 cm	Reddish brown to red (2.5YR 4/5, moist) and red (2.5YR 5/6, dry) clay; moderate fine angular and subangular blocky structure; slightly sticky, slightly plastic, friable, slightly hard consistence; common shiny pressure faces, probably no clay films; semiplastic to abrupt failure; gradual smooth boundary.

B22 35 - 60 cm	Red (2.5YR 4/6, moist) and light red (2.5YR 6/6, dry) clay, moderate fine subangular blocky and angular structure; slightly sticky, slightly plastic, friable, slightly hard consistence; common pressure faces, probably no clay films; abrupt failure, gradual smooth boundary.
B23 60 - 80 cm	Red (2.5YR 4.5/6, moist) and light red (2.5YR 6/6, dry) clay; moderate fine subangular blocky structure breaking to fine and very fine granules; slightly sticky, slightly plastic, firm to fraible, slightly hard to soft consistence; common shiny pressure faces and possibly some clay films; abrupt failure; gradual smooth boundary.
B24 80 - 120 cm	Red (2.5YR 4/6, moist) and light red (2.5YR 6/6, dry) clay; weak fine subangular blocky structure; slightly sticky, slightly plastic, firm to friable, slightly hard to soft, consistence, common reflective ped surfaces and possibly some clay films; abrupt failure; gradual smooth boundary.
B25 120 - 145 cm	Reddish brown (2.5YR 4/4, moist) and red (2.5YR 5/6, dry) clay; moderate fine subangular blocky structure; slightly sticky, slightly plastic, firm,

slightly hard consistence; common pressure faces and possibly few thin clay films; occasional gravel-sized friable yellow saprolite pieces; abrupt failure; gradual smooth boundary.

B26 145 - 180 cm	Red to yellowish red (2.5YR to 5YR 4/6, moist) clay, weak fine blocky structure; slightly sticky to nonsticky, slightly plastic, firm, slightly hard consistence; common pressure faces, possible faint patchy clay films; abrupt failure; arbitrary boundary.
C1 180 - 250 cm	Yellowish red (5YR 4/6, moist) with 30 percent reddish brown clay; less than 2 percent saprolite; examined by auger.
C2 250 - 300 cm	Red (2.5YR 4/6, moist) with 30 percent yellowsih red (5YR 4/6) clay; less than 2 percent saprolite; examined by auger.
C3 300-370 cm	Red (2.5YR to 10R 4/6, moist) clay with 10 percent saprolite; examined by auger.
C4 370-450 cm	Weak red (10R 4/4, moist) clay with 20 percent saprolite; examined by auger.

C5 450-600 cm	Silty clay loam - saprolite; examined by auger.
C6 600-650 + cm	Silty clay loam - saprolite; examined by auger.

Note: Descriptions for horizons B26 through C6 adapted from SCS description of nearby profile S59PR-10-7.

Site 7 LOS GUINEOS SERIES

General Characterization

Classification

US Soil Taxonomy Subgroup	:	Epiaquic Orthoxic Tropohumults
Family	:	Clayey, kaolinitic, isothermic
FAO/UNESCO Legend	:	Humic Acrisols
French System (CPCS) Classe	:	Sols Ferrallitiques
Sous-classe	:	Moyennement désaturés en (B)
Groupe	:	Typiques
Sous-groupe	:	Humique (X/217)
USDA 1938 Great Group	:	Red and Yellow Podzolic soils

Location of Sample Site

Latitude	:	18° 14' 45" N
Longitude	:	66° 34' 24" W
Elevation above sea level	:	740 m
General description	:	Central Puerto Rico; Municipality Jayuya, Barrio Mameyes Arriba, USGS Quadrangle Jayuya; Pesero's farm, approx. 300 m NW of km. 55 on highway PR 530

Climate

Mean annual rainfall	:	~ 230 cm
Mean annual air temperature	:	~ 21° C

Thornthwaite type	:	B'/BA'w - humid mesothermal, drier winters

Vegetation and Land Use

Natural vegetation	:	Subtropical moist forest
Land use and crop	:	Experiment site. --corn; usually in pasture

Parent Material and Geology

Parent material	:	Highly weathered saprolite
Parent rock	:	Andesitic-basaltic volcaniclastics
Geologic age	:	Upper Cretaceous

Geomorphology

Slope	:	30%
Aspect	:	N
Landform	:	Shoulder of interfluve
Geomorphic surface	:	Upper backslope of a recent erosion surface cutting into remnants of a probably Late Tertiary erosion surface

Occurrence in Puerto Rico

Los Guineos series is of moderate extent in the high and perhumid volcanic uplands of central Puerto Rico

Principal Associated Soils

Dystropeptic Tropudults, Typic Humitropepts

Remarks

Sampled from a bank of a farm road

PROFILE DESCRIPTION

A1 0-8 cm	Yellowish brown (10YR 5/6, moist) and brownish yellow (10YR 6/6, dry) ~~silty~~ clay; moderate fine subangular blocky structure; slightly sticky, slightly plastic, friable, slightly hard to hard consistence; clear smooth boundary.
B21 8-25 cm	Brownish yellow to reddish yellow (10YR 6/6 to 7. 5YR 6/6, moist) and brownish yellow to yellow (10YR 6. 5/6, dry) clay; moderate medium and fine subangular blocky structure; slightly sticky, slightly plastic, friable hard consistence; few thin patchy clay films on ped surfaces and in root channels; semiplastic failure; gradual smooth boundary.
B22t 25-45 cm	Yellowish red to reddish yellow (5YR 5. 5/6, moist) and reddish yellow (7. 5YR 6. 5/~~6~~7) clay with few faint fine and medium yellow mottles; moderate medium subangular blocky structure; slightly sticky, slightly plastic to plastic, friable, hard consistence; few to common thin discontinuous clay films; semiplastic failure; gradual smooth boundary.

B31
45-65 cm

Yellowish red (5YR 5/6, moist) and reddish yellow (7.5YR 6.5/6, dry) clay with common faint, fine and medium yellow mottles; moderate fine and medium angular and subangular blocky structure; slightly sticky, slightly plastic to plastic, firm to friable, slightly hard consistence; few thin discontinuous clay films; semiplastic failure; gradual wavy boundary.

B32
65-90 cm

Red to yellowish red (2.5YR to 5YR 5/6, moist) and reddish yellow (5YR 6/7) clay with common to many distinct, fine and medium yellow mottles; moderate fine angular and subangular blocky structure; slightly sticky, slightly plastic, friable, slightly hard consistence; common thin discontinuous clay films or pressure faces; semiplastic failure; gradual wavy boundary.

C1
90-150

Reddish yellow (5YR 6/7, moist; 5YR to 7.5YR 6/7, dry) clay with many faint, fine and medium yellow mottles; moderate to strong fine and medium angular blocky structure; slightly sticky, slightly plastic, friable, slightly hard consistence; many thin clay films or pressure faces; semiplastic to abrupt failure; gradual wavy boundary.

C2 150-200	Reddish yellow (5YR 6/6, moist; 5YR 7/6, dry) silty clay with mottles as above; moderate medium subangular and angular blocky structure; slightly sticky, slightly plastic, friable, slightly hard consistence; few to common thin clay films or pressure faces; semiplastic failure; gradual wavy boundary.
C3 200-250 + cm	Mixed yellow, red, brown and white colors of saprolite, when crushed reddish yellow (5YR 6/8, moist) and pink to reddish yellow (5YR 7/4 to 5YR 7/6, dry) silty clay loam-saprolite; massive structure sith saprolite fabric; slightly sticky to nonsticky, slightly plastic, friable, soft consistence.

Site 8 CARRERAS SERIES

General Characterization

Classification

? ombroid,

US Taxonomy Subgroup	:	Typic Tropohumults
Family	:	Clayey. mixed, isohyperthermic
FAO/UNESCO Legend	:	Humic Acrisols
French System (CPCS) Classe	:	Sols Ferrallitiques
Sous-classe	:	Moyennement désaturés en (B)
Groupe	:	Rajeunis
Sous-groupe	:	Avec erosion (X/253)
USDA 1938 Great Group	:	Reddish-Brown Lateritic soils

Location of Sample Site

Latitude	:	18° 19' 14" N
Longitude	:	66° 21' 32" W
Elevation above sea level	:	250 m
General description	:	North-central Puerto Rico; Municipality Corozal, Barrio Padilla, USGS Quadrangle Corozal; Agr. Exp. Substation Corozal, approx. 1 km SW of headquaters

Climate

Mean annual rainfall	:	200 cm

Mean annual air temperature : 24.5°C

Thornthwaite type : BA'r-humid tropical

Vegetation and Land Use

Natural vegetation : Tropical moist forest

Land use and crop : Experiment site -- corn; normally in pasture or cultivated to subsistence crops

Parent Material and Geology

Parent material : Moderately weathered saprolite

Parent rock : Andesitic volcanic siltstone

Geologic formation : Carreras Siltstone, Upper Cretaceous/Lower Tertiary

Geomorphology

Slope : 2%

Aspect : N

Landform : Hilltop, nose of interfluve

Geomorphic surface: : Interfluve in an area of bench-like surfaces of probably Late Tertiary age undergoing present erosion

Occurrence in Puerto Rico

Carreras series is of small extent in the central humid volcanic uplands of Puerto Rico

Principal Associated Soils

Aquic Tropudults, Dystropeptic Tropudults, Typic Eutropepts

Remarks

Carreras series is tentative and not oficially correlated by SCS.

Sampled in a pit

PROFILE DESCRIPTION

Ap 0-14 cm	Dominantly reddish brown (5YR 4/4, moist) mixed with dark brown (7. 5YR 4/4, moist) and reddish yellow (5YR 6/6, dry) clay; moderate to strong fine angular and subangular blocky structure; sticky, plastic, firm to friable, hard consistence; clear wavy boundary.
B21t 14-28 cm	Yellowish red (5YR 4. 5/6, moist) and reddish yellow (5YR 6/6, dry) clay with common fine distinct red and few to common fine light grey mottles; moderate to strong medium prismatic structure breaking to fine subangular blocky peds; sticky, plastic, firm to friable, hard to very hard consistence; few thin clay films; common dark brown (7. 5YR 4/4) coatings on ped surfaces; semiplastic failure; gradual wavy boundary.

B22t 28-55 cm	Yellowish red (5YR 5/7, moist) and reddish yellow (5YR 6/7, dry) clay with common faint and distinct fine red and yellow mottles; moderate to strong medium subangular blocky structure; sticky, plastic, firm to friable, hard consistence; few patchy clay films; few dark brown coatings on ped surfaces; semiplastic to plastic failure; gradual wavy boundary.
B3 55-80 cm	Red (2.4YR 5/6, moist) and reddish yellow (5YR 6.5/6, dry) silty clay; moderate, medium, subangular blocky structure; slightly sticky, slightly plastic, firm to friable, hard consistence; common clay films; common quartz grains, and common very small yellowish rock fragments; semiplastic failure; gradual smooth boundary.
C1 80-110	Red (2.5YR 5/8, moist) and reddish yellow (5YR 7/6, dry) silty clay loam-saprolite; massive structure, saprolite fabric; slightly sticky, slightly plastic, friable, slightly hard to hard consistence; few clay films, many yellowish rock fragments and coarse quartz grains; abrupt failure; gradual smooth boundary.
C2 110-125+cm	Variegated yellow, red and white colors of saprolite, crushed color yellowish red (5YR 5/8, moist) and

pink to reddish yellow (5YR 7/5, dry) silty clay loam - saprolite; massive structure, saprolite fabric; slightly sticky, slightly plastic, friable, hard to slightly hard consistence; no clay films; about 10 percent friable rock fragments and common coarse quartz grains; abrupt failure.

Site 9 DAGUEY SERIES

General Characterization

Classification

US Soil Taxonomy Subgroup	:	Orthoxic Tropohumults
Family	:	Clayey, kaolinitic, isohyperthermic
FAO/UNESCO Legend	:	Humic Acrisols
French System (CPCS) Classe	:	Sols Ferrallitiques
Sous-classe	:	Moyennement désaturés en (B)
Groupe	:	Typiques
Sous-groupe	:	Humique (X/217)
USDA 1938 Great Group	:	Reddish-Brown Lateritic soils

Location of Sample Site

Latitude	:	18° 13' 50" N
Longitude	:	66° 10' 2" W
Elevation above sea level	:	500 m
General description	:	East-central Puerto Rico, Municipality Aguas Buenas, Barrio Bayamoncito, USGS Quadrangle Comerio; approx. 1 km E of km 3 on highway PR 791, opposite main entrance to Vicente's farm

Climate

Mean annual rainfall	:	~ 200 cm

Mean annual air temperature : ~ 23.5° C

Thornthwaite type : BB'r-humid mesothermal

Vegetation and Land Use

Natural vegetation : Tropical moist forest

Land use and crop : Pasture, coffee, subsistance crops

Parent Material and Geology

Parent material : Strongly weathered saprolite

Parent rock : Andesitic-basaltic volcaniclastics

Geologic age : Lower Cretaceous

Geomorphology

Slope : 12%

Aspect : NE

Landform : Concave upper backslope

Geomorphic surface : Remnant of Tertiary erosion surface, possibly correlates with youngest erosion cycle of "St. John Peneplain"

Occurrence in Puerto Rico

Daguey series is of limited extent in the humid volcanic uplands of east-central Puerto Rico

Principal Associated Soils

Typic Tropohumults, Dystropeptic Tropudults, Typic Eutropepts

Remarks

Sampled at bank of farm road

PROFILE DESCRIPTION

A 0-10 cm	Brown to dark brown (7. 5YR 4/4, moist) and strong brown (7. 5YR 5/6, dry) clay with common faint fine red mottles; moderate fine subangular blocky structure; slightly sticky to sticky, slightly plastic to plastic, friable, slightly hard to hard consistence; gradual wavy boundary.
B21t 10-30 cm	Red to yellowish red (2. 5YR 4/8 to 5YR 4/8, moist) and yellowish red (5YR 5/6, dry) clay; moderate fine angular and subangular blocky structure; slightly sticky to sticky, slightly plastic to plastic, friable, slightly hard to hard consistence; common thin clay films; few slope parallel shear planes; semiplastic failure; gradual smooth boundary.
B22 30-60 cm	Red (2. 5YR 4/6, moist, 2. 5YR 5/6, dry) clay; moderate fine subangular blocky structure, slightly sticky, slightly plastic, friable, slightly hard consistence; few thin clay films and pressure faces; few yellow streaks, semiplastic to abrupt failure; gradual smooth boundary.

B3 60-95 cm	Red (2.5YR 4/6, moist; 2.5YR 5/6, dry) clay; weak to massive medium subangular blocky structure breaking to fine granules; slightly sticky, slightly plastic, friable to firm, slightly hard consistence; few clay films or pressure faces; common fine yellow saprolite specks; abrupt failure; gradual smooth boundary.
C1 95-140 cm	Red (2.5YR 4/6, moist) matrix with about 25 percent white and yellowish colors of saprolite, browish yellow (10YR 5/6, dry and crushed) silty clay loam-saprolite; massive structure with saprolite fabric; slightly sticky, slightly plastic, friable to very friable, slightly hard to soft consistence; many white streaks similar tomycelium; abrupt failure; diffuse smooth boundary.
C2 140-200 + cm	Yellowish red (5YR 4/6, moist) with about 50 percent white and yellowsich white saprolite of silty clay loam texture; massive structure, original rock fabric; slightly sticky to nonsticky, slightly plastic to non-plastic, friable, soft to slightly hard consistence; abrupt failure.

Site 10 TORRES SERIES

General Characterization

Classification

US Soil Taxonomy Subgroup	:	Orthoxic Tropudults
Family	:	Clayey, mixed, isohyperthermic
FAO/UNESCO Legend	:	Orthic Acrisols
French System (CPCS) Classe	:	Sols Ferrallitiques
Sous-classe	:	Moyennement desaturés en (B)
Groupe	:	Typiques
Sous-groupe	:	Humique (X/217)
USDA 1938 Great Group	:	Reddish-Brown Lateritic soils

Location of Sample Site

Latitude	:	18°12' 3" N
Longitude	:	66°7' 5" W
Elevation above sea level	:	450 m
General description	:	East-central Puerto Rico;

Municipality Cidra, Barrio Bayamón, USGS Quadrangle Caguas; 10 km WSW of Caguas, N of highway PR 172; Soltero's Farm

Climate

Mean annual rainfall	:	~ 200 cm

Mean annual air temperature : ~ 23° C

Thornthwaite type : BB'r-humid mesothermal

Vegetation and Land Use

Natural Vegetation : Tropical moist forest

Land use and crop : Experiment site--corn; generally used for sugarcane and pasture

Parent Material and Geology

Parent material : Highly weathered, fine-textured sediments derived from predominantly andesitic volcaniclastics and plutonic rocks of Lower Cretaceous age

Geomorphology

Slope : 5%

Aspect : N

Landform : Planar terrace, pit adjacent to shoulder

Geomorphic surface : Probably a depositional surface of Pliocene age associated with the "Caguana Peneplain", now undergoing dissection

Occurrence in Puerto Rico

Torres series is of small extent in humid volcanic upland of eastern

Puerto Rico

Principal Associated Soils

Typic Tropohumults, Aquic Tropohumults Orthoxic Tropohumults, Dystropeptic Tropudults

Remarks

Sampled in a pit

PROFILE DESCRIPTION

Ap 0-10 cm	Brown to dark brown (10YR 4/3, moist) and brown (10YR 5/3, dry) clay; strong fine crumb structure; sticky, plastic, very friable, hard to slightly hard consistence; abrupt wavy boundary.
B21t 10-30 cm	Brown (7.5YR 5/4, moist) and light yellowish brown (10YR 6/4, dry) clay; moderate medium columnar structure breaking to fine subangular granules; sticky, plastic, friable, hard to verv hard consistence; common thick clay films; few very fine hard black nodules; semiplastic failure; gradual wavy boundary.
B22t 30-50 cm	Yellowish red (5YR 5/6, moist) and reddish yellow (5YR 6/6, dry) clay; moderate fine and medium angular and subangular blocky structure; slightly sticky, slightly plastic, friable hard to very hard

consistence; common thin patchy clay films; semi-plastic failure; gradual smooth boundary.

B23t 50-90 cm	Yellowish red (5 YR 5/6, moist) and reddish yellow (YR 6/6, dry) clay; moderate fine and medium sub-angular blocky structure; slightly sticky, slightly plastic, friable, slightly hard consistence; few thin patchy clay films; semiplastic failure; gradual smooth boundary.
B3 90-125 + cm	Yellowish red (5YR 5/7, moist) with some reddish yellow (7. 5YR 6/8, moist) and reddish yellow (5YR 6/6, dry) silty clay loam; weak medium sub-angular blocky structure breaking to fine and very fine granules; slightly sticky, slightly plastic, friable, slightly hard consistence; many quartz grains and angular quartz fragments; very few soft black nodules; few yellow streaks; abrupt failure.

Site 11 PICACHO SERIES

General Characterization

Classification

US Soil Taxonomy Subgroup	:	Udoxic Humitropepts
Family	:	Clayey, mixed, isothermic
FAO/UNESCO Legend	:	Ferralic Cambisols
French System (CPCS) Classe	:	Sols Ferrallitiques
Sous-classe	:	Moyennement désaturés en (B)
Groupe	:	Rajeunis
Sous-groupe	:	Avec erosion (X/253)
USDA 1938 Great Group	:	Red and yellow Podzolic soils

Location of Sample Site

Latitude	:	18° 17' 45" N
Longitude	:	65° 47' 30" W
Elevation above sea level	:	750 m
General description	:	Northeast Puerto Rico;

Municipality Naguabo, Barrio Río Blanco, USGS Quadrangle - El Yunque; Luquillo National Forest; 20 m W of km 15. 7 on highway PR 191

Climate

Mean annual rainfall	:	~ 450 cm

Mean annual air temperature : ~ 20°C

Thornthwaite type : AB'r-wet mesothermal

Vegetation and Land Use

Natural vegetation : Subtropical rainforest

Land use and crop : National forest -- virgin vegetation

Parent Material and Geology

Parent material : Strongly weathered saprolite

Parent rock : ~~Gran~~ Quartz odiorite

Geologic age: : Late Cretaceous/Eocene

Geomorphology

Slope : 20%

Aspect : SW

Landform : Shoulder

Geomorphic surface : Small bench-like surface in strongly dissected and steeply sloping monadnock

Occurrence in Puerto Rico

Picacho series is of minor extent in the granitic areas of tropical rain forests in NE and central Puerto Rico

Principal Associated Soils

Eqiaquic Orthoxic Tropohumults, Aquultic Tropohumults, Equiaquic Palehumults, Lithic Tropaquepts, Typic Humitropepts

Remarks

Picacho series should be classified as Epiaquic Humoxic Tropohumults (USDA) and Humic Acrisols (FAO), if thin sections should reveal clay films. Sampled from a road cut.

PROFILE DESCRIPTION

A 0-18 cm	Dark yellowish brown (10YR 4/4, moist) and brownish yellow (10YR 6/6, dry) sandy clay loam with common distinct fine and medium yellowish red mottles; moderate fine subangular blocky structure; slightly sticky, slightly plastic, friable, hard consistence; common silvery flakes looking like mica; clear wavy boundary.
B21 18-35 cm	Brownish yellow (10YR 6/8, moist) and brownish yellow to yellow (10YR 6. 5/7, dry) clay with common faint and distinct fine red and few faint fine grey mottles; moderate medium subangular blocky structure; slightly sticky, slightly plastic, friable, hard consistence; no clay films observed; common silvery flakes; semiplastic failure; clear wavy boundary.
B22 35-60 cm	Brownish yellow (10YR 6/6, moist) and yellow (10YR 7/8, dry) clay with few distinct fine red

mottles; slightly sticky, slightly plastic, friable, hard consistence; no clay films observed, very thin red friable iron laminae arranged in an oblique layer that could reflect original rock structure; common silvery flakes; semiplastic failure; gradual wavy boundary.

B3
60-85 cm

About 50 percent yellowish red (5 YR 5/8, moist) and 50 percent brownish yellow (10YR 6/8, moist) and yellow (10YR 7/8, dry and crushed) silty clay loam; massive to weak fine and medium subangular blocky structure; slightly sticky, slightly plastic, friable, slightly hard to hard consistence; no clay films, many silvery flakes; semiplastic failure; gradual smooth boundary.

C1
85-130 cm

About 75 percent yellowish red (5YR 5/8, moist) and 25 percent brownish yellow (10YR 6/8, moist) and reddish yellow (7. 5YR 6. 5/7, dry and crushed) silty clay loam; massive structure with saprolite fabric; slightly sticky, slightly plastic, firm to friable, slightly hard consistence; abundant silvery flakes; abrupt failure; gradual smooth boundary.

Reddish yellow (5YR 6/7, moist: 7. 5YR 7/6. dry)

130-165 cm	silty clay loam-saprolite with few fine red and common fine black soft mottles; structure and consistence as in C1; abundant silvery flakes; gradual smooth boundary.
C3 165-200+cm	Variegated colors of saprolite, dominantly yellowish red (5YR 5/8, moist) and reddish yellow (7.5YR 6/8, moist) and reddish yellow (7.5YR 7/8, dry and crushed) silty clay loam-saprolite; massive structure with saprolite fabric; slightly sticky to nonsticky, slightly plastic, friable, slightly hard consistence; abundant silvery flakes.

Soil Classification

The soils of Puerto Rico were first mapped, named and classified by Roberts et al. (1942). In this survey the soils selected for the present study were identified as the following series: Nipe (site 1), Matanzas (site 2), Bayamon (sites 4 and 5), Catalina (sites 6,8,10), Cialitos (site 9), and Los Guineos (sites 7 and 11). Roberts et al. (1942) classified these series according to the USDA soil classification of 1938 (Baldwin et al., 1938) into the great soil groups of Laterite Soils (Nipe), Reddish-Brown Lateritic Soils (Bayamon, Catalina, Matanzas), Yellowish-Brown Lateritic Soils (Coto), and Red Yellow Podzolic Soils (Los Guineos).

While all of these series have been retained in the modern soil survey of Puerto Rico now carried out by the Soil Conservation Service, their definitions have been considerably refined. In the process, the soils at sites 9,10 and 11 were correlated with the recently established series of Daguey, Torres, and Picacho, respectively. Two new series, Piña and Carreras, are proposed for the soils at sites 5 and 8. With the exception of these two not officially recognized series, all other series included in this study have been finally classified and correlated nation-wide (Soil Survey Staff, 1972).

Table II shows the placement of the eleven soils studied in three important classification systems currently used in the tropics. These are the U.S. Soil Taxonomy of the National Cooperative Soil Survey (Soil Survey Staff, 1970); the Legend for the FAO/UNESCO Soil Map of the World (FAO, 1970); and the 1967 edition of the French classification scheme edited by the Commission de Pedologie et de la Cartographie des Sols (1967). The rationales and criteria for the classification presented in Table II is briefly discussed below.

Soil Taxonomy

Oxisols. Subsurface horizons of the Nipe, Matanzas, Coto, Bayamon, Piña, and Catalina series meet the requirements for oxic horizons a defined by the Soil Survey Staff (1970). Consequently these soils are classed as Oxisols. Since none of these Oxisols have plinthite, or a torric, ustic or aquic moisture regime, they cannot be Aquox, Torrox or Ustox. Although some contain sufficient organic carbon to quality for Humox, their isohyperthermic temperature regime precludes their classification into this suborder. Thus of all of the Oxisols studied key out as Orthox. Because they lack sombric or umbric horizons and sheets of gibbsite, these Orthox must be classified into the great groups of either Acrothox, Eutrorthox or Haplorthox.

The Nipe series (site 1) meets the criteria for Acrorthox as regards cation retention capacity but has definitely a discernible

structure in all oxic horizons and should, therefore, not be classified as an Acrorthox. However, the low cation retention capacity prevents the placement in the Haplorthox or Eutrorthox. Because cation retention is considered a more important and also less subjective criterion than structure, the Nipe series is classified as Acrorthox. This great group has only two subgroups, Typic and Plinthic. Since the Nipe series contains no plinthite, it must be considered a Typic Acrorthox.

Although this is the Soil Conservation Service's official and final classification (Soil Survey Staff, 1967 and 1972), it is unsatisfactory. The massive structure described by Koch (Soil Survey Staff, 1967, p. 155) at the now inaccessible type location of Nipe could not be detected in any of the profiles inspected in the area mapped as Nipe near the type location on Cerro Las Mesas. It appears that massive structure, if it exists, is the exception rather than the rule. While the Nipe series should thus be re-classified, a placement other than Typic Acrorthox would not be logical. It is therefore suggested to re-define the structure requirement of the Acrorthox and to establish a Tropeptic subgroup for Acrorthox with discernible structure, in analogy with the Eutrorthox and Haplorthox. These proposed changes seem necessary for a satisfactory taxonomic placement of the Nipe series, and reflect the fact that the classification

of Oxisols had lagged behind that of other orders and is still far from completion, as pointed out by the Soil Survey Staff (1970).

The classification of the other Orthox studied presents no problems. The Matanzas series (site 2) is a Eutrorthox because it has a base saturation of more than 35 percent. The shallow oxic horizon and its moderate structure account for the classification of the Matanzas series as Tropeptic Eutrorthox.

The Coto, Bayamon, Piña, and Catalina series (sites 3, 4, 5, 6) key out as Haplorthox. The central concept or Typic subgroup is well represented in the Piña series, consequently classified as a Typic Haplorthox. Although the texture of the oxic horizon has been determined as sandy clay loam, it is approaching sandy loam. The Piña series is, therefore, intergrading to Quartzipsammentic Haplorthox.

The Coto, Bayamon and Catalina series cannot be placed in the Typic Haplorthox since all or some subhorizons of the oxic horizons exhibit a moderate structure within 1.25 m depth, and hence are classified as Tropeptic Haplorthox. Judging from the climatologic record at site 3, it appears likely that the moisture regime is ustic. If further studies confirm this conjecture, the Coto series should be classified as Tropeptic Haplustox.

The particle size, mineralogy and soil temperature classes contained in the family names presented in Table II are based on analytical and meteorological data. The soil mineralogy in particular has been studied in considerable detail by Jones et al. (see part II). According to these data, the Nipe and Piña series have oxidic mineralogy, and the Matanzas, Coto, Bayamon and Catalina series are kaolinitic. This is only in partial agreement with the Soil Survey Staff's classification (1967, 1972) which assigns oxidic mineralogy to the Catalina and Matanzas series.

Ultisols. The Los Guineos, Carreras, Daguey, and Torres series (sites 7,8,9,10) have warmer than isomesic temperature regimes and argillic horizons with base saturations of less than 35 percent and are as a consequence classified as Ultisols. At the suborder level the Ultisols studied key out as Humults and Udults since they do not qualify for Aquults, Ustults or Xerults as they all have Udic moisture regimes. The Los Guineos, Carreras and Daguey series are Humults because their organic carbon content in the upper 15 cm of their argillic horizons exceeds 0.9 percent. The Torres series fails to meet this criterion and belongs, therefore, to the suborder of the Udults. All of the Humults studied have been classified as Tropohumults because they have isothermic and isohyperthermic temperature regimes but lack the sombric horizon

required for Sombric-humults, the clay distribution in the argillic horizon characterizing Palehumults, and the plinthite typical for Plinthohumults. For similar reasons, the Udults have been placed into the great group of Tropudults.

The Carreras series meets all criteria for the central concept of the Tropohumults and is therefore a Typic Tropohumult. Although the subsoil shows some low chroma mottles, it is not believed to be water saturated at some time of the year. While thus intergrading to the Aquic Tropohumults, the morphologic evidence is not considered sufficient to warrant the classification of the Carreras series into this subgroup without further soil water studies. The argillic horizon of this soil is only about 40 cm thick. However, unlike in the Tropudults where a Dystropeptic subgroup is recognized, there exists no subgroup in the Tropohumults to differentiate Tropohumults with thin argillic horizons. It is, therefore, proposed to establish a subgroup of Dystropeptic Tropohumults.

The Los Guineos series diverges from the Typic Tropohumults in that it has hues of 10 YR becoming redder with depth and less than 24 meq CEC/100 g clay in the argillic horizon. It is since classified as Epiaquic Orthoxic Tropohumults. On the basis of laboratory data from a different site, the Soil Survey Staff (1972) classified the Los Guineos series as Epiaquic Tropohumults. The Daguey series

also has a clay fraction with low activity justifying its classification as Orthoxic Tropohumults.

The Torres series has been classified by the Soil Survey Staff (1972) as Orthoxic Palehumults. However, the Torres soil sampled for this study does not have the thick argillic horizon nor the clay distribution required for this subgroup. The analytical data further indicate that the organic carbon content in the upper 15 cm of the argillic horizon is too low to permit the classification as Humult. Because the cation exchange capacity is less than 24 meq/100 g clay in the upper argillic horizon, the Torres series has been classified as Orthoxic Tropohumults.

The classification at the family level listed in Table II shows that the Los Guineos and Daguey series have kaolinitic mineralogy, whereas the mineralogy class of the Carreras and Torres series is mixed. The Soil Survey Staff (1972) considered the Daguey and Torres series to be oxidic, and the Los Guineos series to have mixed mineralogy. According to the data by Jones et al. presented in part II, these classifications should be re-examined.

Inceptisols. In the Picacho series at site 11, no argillic horizon could be identified with certainty in the field. There is, moreover, evidence of original rock structure in the subsoil. Although these observations are subject to confirmation by pending

micro-morphological studies, the subsurface horizon of this soil is considered a cambic horizon. Consequently the Picacho series is classified as an Inceptisol. In the absence of an aquic moisture regime and a plaggen epipedon, but having a bulk density of more than 0.85 g/cc and an isothermic temperature regime, the Picacho series qualifies for the suborder Tropepts.

In the key to great groups of Tropepts, it meets the requirements for the first great group, the Humitropepts, because it has a base saturation of less than 50 percent and contains more than 12 kg organic carbon in the top cubic meter. The Picacho series also has less than 24 meq CEC/ 100 g clay which accounts for its placement in the subgroup of Udoxic Humitropepts. At the family level, this soil is classified as clayey, mixed, isothermic.

The Soil Survey Staff (1972) classified this series as Aquic Tropohumults presumably on the basis of the presence of an argillic horizon as indicated by clay films. While this is considered a misjudgement, it reflects the importance and decisive role assigned to clay skins as a differentiating criterion.

In many tropical soils clay skins, however, are frequently difficult to assess with certainty in the field. Moreover, the analytical procedure required to positively identify cutans is tedious, and few laboratories in the tropics are equipped for micro-morphological

studies. The indirect use of this soil feature as a diagnostic criterion at the highest categories of Soil Taxonomy is, therefore, subject to critique. It is further evident from the preceeding discussion that the classification of soils in Soil Taxonomy is based largely on properties of the subsoil. Since soils with mollic or umbric epipedons are of limited extent in the tropics, one more often than not classifies subsoils rather than soils per se. Thus, in the case of the Nipe series, the classification is based on an oxic horizon that starts at 40 cm depth and does not reflect the properties of the overlying horizons. From a pragmatic agricultural point of view it must be considered a deficiency of Soil Taxonomy that the edaphic properties of the main root zone can, in most cases, only be vaguely inferred from the taxonomic classification.

FAO/UNESCO Legend

The FAO/UNESCO Legend for the Soil Map of the World constitutes, in essence, a collection of the soil units used for the preparation of this map. The units are defined in the World Soil Resources Report No. 33 (FAO, 1968); the key to these units was published in 1970 (FAO, 1970).

The correlation of taxa of Soil Taxonomy (Soil Survey Staff, 1970) with units of the FAO Legend is facilitated by the fact that the differentiating criteria of the FAO Legend were largely drawn from

Soil Taxonomy. The definitions and nomenclature for diagnostic horizons in particular are virtually the same in both schemes. However, the way the differentia are employed in the keys is based on divergent rationales.

The soils selected for this study represent three of the 26 main units recognized in the FAO Legend, namely Ferralsols, Acrisols and Cambisols.

Ferralsols. This group comprises soils with oxic horizons and is subdivided into six units. Following the key to Ferralsols, the Nipe, Coto, Bayamon and Catalina series must be classed as Humic Ferralsols, since they have no plinthite but have more than 1.35 percent organic matter to a depth of 100 cm, and a base saturation of less than 35 percent. Although the unit Acric Ferralsols is recognized in the FAO Legend for soils similar to Acrorthox, the Nipe series has to be included with the Humic Ferralsols because these take precedence over the Acric Ferralsols in the key

The Matanzas and Piña series do not qualify for Humic Ferralsols since they have a base saturation of more than 35 percent and contain too little organic matter, respectively. These series have re than 1 meq CEC/ 100 g clay, precluding their classification as Acric Ferralsols, and do not meet the color requirements for

Rhodic and Xanthic Ferralsols. The Matanzas and Piña series are, therefore, Orthic Ferralsols. However, both are integrading to Rhodic Ferralsols on account of their red B horizons.

Acrisols. This unit is the identically defined equivalent of the Ultisols of Soil Taxonomy. None of the Acrisols studied has a plinthic or gleyic horizon, but three have more than 1.5 percent organic matter in the upper part of the B horizon. Thus not qualifying for Plinthic or Gleyic Acrisols, the Los Guineos, Carreras and Daguey series key out as Humic Acrisols.

The Torres series does not meet the organic matter requirement for Humic Acrisols nor the criteria for Ferric Acrisols and must therefore be classed as Orthic Acrisols.

Cambisols. In the FAO Legend, soils with cambic horizons are either Gleysols or Cambisols. The Picacho series lacks a gleyic horizon and thus belongs to the Cambisols. Within this unit, it qualifies for Ferralic Cambisols, as the exchange capacity of the cambic horizon is less than 24 meq / 100 g clay. The Picacho series, a Humitropept in Soil Taxonomy, cannot be identified as a Humic Cambisol because it has no umbric epipedon.

French Soil Classification

A positive and objective placement of the soils studied in the French classification system developed by the Commission de Pedologie

et de la Cartographie des Sols (1967) could not be achieved due to the inherent inadequacies of the scheme. In the French system the classification of tropical soils is difficult because (1) there are few well defined differentiating criteria, (2) there exists no key, and (3) because the underlying principles of classification are genetic concepts leaving a considerable margin for subjective conjecture. However, the Commission has pointed out the provisional character of the system and is presently working on a new set of definitions.

The highest category includes twelve classes which are separated mainly on the basis of development of genetic horizons and the kind of weathering process of primary minerals taking place in the upper part of the solum. The latter criterion indicates the type of process rather than its degree or intensity. Thus a soil at the beginning of a presumably "ferrallitic" evolution is classified directly into the "sols ferrallitiques", even though the manifestations of the process are incipient. Its juvenile stage is then indicated at the subgroup level, e.g. as "faiblement rajeuni".

In the French system, two kinds of weathering processes are considered important in the tropics: the formation of ferrallitic material normally taking place under warm humid conditions and leading to "sols ferrallitiques", and the formation of "fersiallitic" material occurring mainly in areas with prolonged dry seasons and

resulting in "sols a sesquioxydes de fer".

All of the eleven Puerto Rican soils studied were placed in the class of "sols ferrallitiques". The central concept of this class is one of soils showing a high degree of alteration of the primary minerals and having abundant 1:1 lattice clays and/or hydroxides of iron and aluminium. This class is subdivided into three subclasses according to levels of base saturation. These are the weakly, moderately and strongly desaturated "sols ferrallitiques", characterized by base saturation values of 40 to 80, 20 to 40, and less than 20 percent, respectively, and corresponding amounts of exchangeable bases of 2 to 8, 1 to 3, and less than 1 meq/100 g soil.

Following these criteria, the Matanzas series is "faiblement désaturé", the Coto, Bayamon, Catalina, Los Guineos, Carreras, Daguey, Torres, and Picacho series are "moyennement desaturés", and the Nipe and Piña series are "fortement desaturés". The placements into groups and subgroups of "sols ferrallitiques" are listed in Table II. The descriptive terms used to characterize soil units at these levels have not been defined and are of qualitative connotation only. In the absence of a key and precise definitions, these placements necessarily reflect personal judgement.

Soil Formation

A concept of soil genesis has been outlined by Simonson (1959) as consisting of two overlapping stages: (1) the accumulation of parent material, and (2) the differentiation of horizons. The latter is ascribed to additions, removals, transfer, and transformations of materials and energy within the soil system. The rate and direction of these internal physico-chemical processes is controlled largely by the formative factors advanced by Jenny (1941). On the rationale that the understanding of soil variability in terms of soil-forming factors is likely to remain a unifying phylosophy in pedology, these factors were described in detail above.

In the discussion that follows it is intended to evaluate the effect of the formative conditions on the process and result of soil formation at selected sites in Puerto Rico. In light of the fact that the mineralogy is elucidated in detail by Jones et al. in part II, no effort is made here to cover these aspects in depth. Similarly, the micromorphology is not discussed because it is currently under investigation and will be the topic of a later publication. The objective of the following discussion is to consider in the main the alterations postulated by Simonson (1959) in a qualitative way with emphasis on the impact of geomorphology on soil formation.

Oxisols

Nipe Series. The Nipe series (site 1) was first described and investigated by Bennet and Allison (1928) in Cuba where it occurs extensively over the northwestern part of the Nipe Mountains in the Province of Oriente. On account of its value as an ore, the Nipe clay of Cuba has been studied in considerable detail by, among others, Cox (1911), Leith and Mead (1911), and Little (1911). Following Bennett's description of the Nipe series, it was recognized by Roberts et al. (1942) in the course of the original soil survey of Puerto Rico. More recently, Sivarajasingham (1961) dedicated a comprehensive thesis to the study of the genesis of the Nipe clay of Puerto Rico, and the Soil Survey Staff (1967, p. 155) provided further analytical data.

In Cuba, Leith and Mead (1911) observed a practical identity in the areal distribution of Nipe clay and that of serpentinite. While in Puerto Rico the occurrence of the Nipe series is also restricted to serpentinite, it is not found ubiquitously on this rock. In the main serpentinite mass southeast of Mayaguez, this is attributed to strong dissection. In another minor outcrop close to the southwestern coast, the semiarid climate presumably averted Oxisols as none were identified in a recent detailed soil survey of the area (Carter et al., 1965). While serpentinite underlies some 80 km^2 in southwestern

Puerto Rico, the Nipe series is, therefore, of minor extent. Roberts et al. (1942) mapped roughly 1,000 ha of Nipe clay, but this figure is definitely too high as it includes soils now correlated as Haplorthox. A more realistic estimate of the acreage of the Nipe series would be between 500 and 700 ha.

The Nipe soil is a product of the process customarily referred to as laterization. Mohr and Van Baren (1954, p. 353) present a generally satisfactory definition of laterization as "... the leaching out and elimination of SiO_2 , alkali and alkaline earths and the concentration, in their hydrated form, of iron and aluminum oxide, the latter compound being partly combined with silica ... " Based on studies in Puerto Rico, Briggs (1960, p. 118) considered laterization to be "... that weathering process which results in residuum whose Al_2O_3 and total iron oxide content by weight percentage is greater than the Al_2O_3 and total iron contents by weight percentage of the parent rock. It is also characterized by decreases in the content by weight percentage of SiO_2 , CaO, MgO, Na_2O and possibly K_2O with increased weathering, and by increases in the content by weight percentage of free and combined water ... The apparent concentration of iron and aluminum ... is the result of replacement of silicon, calcium and other cations by light hydrogen cations , thus effectively

increasing the relative weight of aluminum and iron present, but not their volume." Laterization further results in the residual concentration of elements with ion potentials (ion charge : ion radius) between 3.0 and 9.5, such as Ti, Ni, Cr, Zr, and a suite of other rare elements (Goldschmidt, 1937). In most cases, the formation of lateritic material requires humid conditions, free internal drainage, geomorphic stability over prolonged times, and the increased weathering intensities caused by continually high temperatures.

The chemical analyses of Nipe profiles from Cuba and Puerto Rico presented in Table III are a clear reflection of the process of laterization as defined above. However, a distinction must be made between geochemical weathering and pedogenetic alterations. The data in Table III indicate that desilication and removal of bases occur largely in the first stage of decomposition near or at the rock surface, and the changes of chemical composition in the transition from saprolite to the solum are not marked. Laterization in this case is, therefore, considered mainly a geochemical process affecting the initial rock rather than a pedogenetic process altering the soil parent material.

TABLE III

Chemical composition of Nipe clays and serpentinites from Cuba and Puerto Rico

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The losses of original constituents during rock weathering are striking. As the data in Table III indicate, about 90 percent of both the SiO_2 and MgO originally present are lost in the transition from fresh rock to saprolite. This is atttributable to conditions of intense leaching and the peculiar mineralogy of the serpentinite which consists mainly of magnesium and ferrous-iron silicates, largely antigorite. These minerals decompose faster than aluminosilicates, and silica is removed more completely because the amount of sesquioxides which could combine with silica is small (Sivarajasingham, 1961). Also, practically no silica is present in the serpentinite in the form of quartz, which would tend to accumulate as a resistant mineral. These conditions are also reflected in the predominance of gibbsite over kaolinite in the saprolite, indicating a low concentration of silica due to intense leaching. The residual formation of gibbsite in such a micro-environment was also observed by Nakamura and Sherman (1965) in the weathering of a basic rock, mugearite. in Hawaii.

As pointed out in the chapter on geomorphology, the Nipe soil at site 1 is not considered residual from the underlying serpentinite. Weaver (1962) presented conclusive evidence of the sedimentary nature of the parent material, and Sivarajasingham (1961) also described a discontinuity at a nearby profile. Hence, the pedogenetic interpretation of the vertical variability of soil parameters would be

prone to speculation. However, because the regolith is undoubtedly derived from serpentinite and considering the data provided by Sivarajasingham (1961) reproduced in Table III for a profile of established residual origin, some general conclusions can be drawn.

The chemical similarity of the saprolite and the overlying subsoil as shown in Table III suggests that no major removal of constituents occurs in the transition from parent material to soil. Apparently geologic weathering has produced a material which is in quasi-equilibrium with the environmental conditions so that no major further alterations can take place in the pedologic weathering zone. The high contents of organic matter of up to 10 percent in the A horizon (Soil Survey Staff, 1967, p. 154) mark the only main chemical difference between the soil and its parent material. Organic carbon and nitrogen are therefore the only chief additions of material to the soil system.

As regards transfers, there is no field evidence of lessivage. The shiny ped surfaces observed are considered the result of pressure orientation and are believed to be stress cutans rather than argillans. Such coatings are particularly conspicous in the ~~B24~~ C1 horizon which also has a fine polyhedral structure. Identical morphologic features are also typical for the Kraznozems developed on basalts in Australia,

where the coatings were proved to be stress cutans (R. Isbell personal communication, 1973). In the absence of conclusive evidence of faunal pedoturbation, biocycling is considered the only active process causing translocations. The higher concentration of silica as plant opal and phosphorus and bases in the surface soil relative to the subsoil is ascribed to this process.

The main transformation of material is evidenced by the physical changes occurring from saprolite to surface soil. According to Sivarajasingham (1961), the saprolite is very porous and the collapsed saprolite porous. With decreasing depth the matrix becomes increasingly denser and more crystalline. — On the basis of slight increases in the amount of kaolinite, Sivarajasingham (1961) suggested a hypothesis of resilication of gibbsite as a slow process sustained by a low but consistent concentration of silica. However, in the Nipe soil selected for this study, the contents of kaolinite and gibbsite showed virtually no variation in the horizons analysed. Apart from the chemical changes affecting the organic matter, pedologic organization is, therefore, considered the main transformation process of importance to the genesis of Nipe soil.

The discussion above indicates that no strong pedogenetic processes have been excerted upon the soil material. As a consequence, horizonation is weakly expressed and the solum below the A

horizon is essentially uniform in all respects. As has been shown this is, however, in large measure due to the peculiar parent material weathered from an unusual rock. As pointed out by Vine (1966) it is therefore a mistaken notion to regard this soil "... as the end-product of decomposition and leaching, to which other soils tended to develop in hot, humid conditions." It should further be mentioned that the Nipe series is not a very old soil in a chronological sense. Despite the fact that it is considered to be in the senile to final stage of Mohr and Van Baren's development sequence (1954) and that it represents advanced stages of weathering according to the sequence of Jackson et al. (1948), the Nipe soils occur on a comparatively young surface of Pliocene age. In Puerto Rico, the soils on geomorphic surfaces of similar age but underlain by andesitic rocks are mostly Ultisols. This clearly indicates that, other conditions being equal, ultrabasic rocks are laterized more rapidly than andesitic rocks.

Matanzas, Coto, Bayamon and Piña Series. These soils at sites 2, 3, 4, and 5 are discussed jointly because they are all developed in blanket deposits which constitute their parent material. It is of importance to the understanding of the genesis of these soils to consider the accumulation of their parent materials in more detail.

Earlier investigat~~ions~~ors believed the blanket deposits to be residual from Tertiary limestones (Briggs, 1972). In particular, Roberts et al. (1942) postulated the Matanzas, Coto and Bayamon series to be derived from limestone. However, the hypothesis that the blanket deposits are unreworked residue from the limestone they overlie does not stand close scrutiny. First, the Aymamon limestone is exceptionally pure commonly exceeding 98 percent calcium carbonate with its insoluble residue being almost wholly clay; quartz grains are very rare. Second, the presence of recognizable crystals of high-temperature quartz is a strong indication that most, if not all, of the quartz was initially derived from igneous or metamorphic rocks (Briggs, 1962). Common minor constituents of these sediments are anatase, oligoclase, sanidine and unidentified feldspars (Hildebrand, 1960). These facts effectively rule out the possibility that the blanket deposits are in total residual from limestone. Although an appreciable addition must have been made by residuum from limestone, the original provenance of the bulk of the blanket deposits is the volcanic-plutonic central highland of the Puerto Rican landmass. Prior to its erosion and subsequent sedimentation, this material had presumably undergone intensive lateritic weathering on Miocene surfaces in the interior. This is borne out by the distinct

resemblance between the blanket deposits and lateritic soils of the uplands as regards their chemical composition (Briggs, 1962). The parent materials for the Coto, Matanzas, Bayamon and Piña soils are, therefore, sediments that were subjected to profound alterations during a previous lateritic weathering cycle.

The chemical data reproduced in Table IV substantiate this fact. The analyses of the blanket deposits near Isabela are typical for the parent material of the Coto series, whereas the data for the sandier sample from near Manati approximate the composition of the subsoil of the Bayamon and Piña series. The analysis of a saprolite derived from andesitic rock is included in Table IV to demonstrate the similarity between this material and the clayey blanket deposits.

TABLE IV
Chemical composition of blanket deposits from northern Puerto Rico and saprolite from east-central Puerto Rico

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Reflecting their lithologic provenance from plutonic and /or volcanic areas, the blanket deposits display considerable variation in the amount of quartz. In the soils studied the sand content varied from 3.3 percent in the Matanzas series to 89.3 percent in the Piña series; the sand fraction consisting almost entirely of quartz. Owing to these textural variations and differences in geomorphic position as well as soil moisture, the pedogenetic conditions are not uniform over

the area of blanket deposits. As a result, the soils of this group exhibit some dissimilar features.

The Matanzas series (site 2) was first described by Bennett and Allison (1928) in Cuba and later recognized in Puerto Rico by Roberts et al. (1942). In Cuba, the Matanzas series is one of the most extensive soils and occurs on the great plains of the Matanzas, Havana and other Provinces, but in Puerto Rico it is of minor extent and confined to the base of cone-shaped limestone hills. It is of shallow depth and overlies with sharp contact karsted limestone with a highly irregular microrelief. In view of the mineralogical composition of the Matanzas soils, characterized by kaolinite, gibbsite, hematite and quartz, their exclusive residual origin from very pure limestone would be difficult to establish despite their position. Whilst it cannot be claimed that the mineralogic data support an allochthonous origin, at least they are more consistent with the view that the parent material of the Matanzas soil is not completely residual. The influence of limestone is, however, clearly reflected in the high base saturation maintained by the continuous addition of calcium carbonate as rock debries from upslope and probably by capillary rise in the shallow solum.

From a pedogenetic point of view, an exceedingly weathered soil material and a high base saturation appear to be mutually exclusive.

While in other Eutrorthox this may be attributed to drastic climatic changes, it seems more logical in this case to assume that a strongly weathered sediment had been mixed with limestone residuum and recharged in situ. The Matanzas series further differs from the other soils in this group in that boehmite predominates over gibbsite. This might, in part, be due to drier conditions in the shallow and highly permeable soil promoting dehydration to monohydrate.

The Coto series (site 3) occupies the central parts of the area of blanket deposits on the plains of northwestern Puerto Rico. It is distinguished by its yellowish red colors (5YR 5/6) and its usually considerable depth. The Soil Survey Staff (1969, p. 174) sampled and analysed a profile close to the pedon selected for this study and identified oxic horizons to a depth of 365 cm. This conforms with the postulated presence of a laterized sediment, as in-situ- laterization to that extent would appear unlikely on a largely Pleistocene surface. Profile depth is, however, subject to great variation and limestone may be encountered at depths of 1 m or less. Moreover, depth variance is erratic and merely reflects the relief of the karsted surface which the blanket sediments overlie.

In the Coto profile examined, oxic horizons (B21, B22, B23) with nearly massive structure are found above an oxic horizon (B24) with "tropeptic" structure starting at 90 cm. ~~Although not positively~~

identified ~~in the field~~, some coatings on ped faces in this horizon ~~may be~~ clay skins. It is therefore conjectured that the B21, B22 and B23 horizons have suffered slight eluviation of dispersable clay. The particle size distribution reported by the Soil Survey Staff (1969, p. 174) also indicates a clay bulge at about 1 m depth. The gradual transition from the nearly massive to the more structured horizon tends to support the pedogenetic rather than sedimentary origin of this clay increase.

The profile of the Bayamon series (site 4) exhibits similar features. An almost massive oxic horizon (B21) is underlain by a transitional horizon (B22) in which ~~some~~ some clay ~~bridges~~ fi Cms were observed. The horizon below (B3) shows quite distinct ~~clay films~~ cutans and has, in fact, the appearance of an old textural B horizon.

In the sandy Piña series (site 5) no evidence of clay migration could be ~~seen~~ in the field within a depth of 125 cm. This soil has the structure of typical ~~for Acrorthox~~ oxic horizons. Below the plow layer, the soil material however has a stronger consistence and is also more compact, which is typical for many cultivated Oxisols with similar texture (A. Van Wambeke, personal communication, 1973). This material has a tendency to become hard on drying and then impedes root growth. This is considered a fabric - related transformation induced by man. Below 90 cm depth the consistence becomes more "fluffy" which is typical for well

developed oxic horizons (Eswaran, 1972). It is probable that some evidence of clay illuviation may be found at greater depth. Since the sandy Piña soils in their natural state likely had a higher permeability than the clayey Coto and Bayamon soils, eluviation would be expected to extend to greater depth.

Mineralogically, the Coto, Bayamon and Piña series are rather similar as regards the mineral assemblage but the relative amounts of mineral types present vary. As determined by ~~Johns~~ Jones et al. and discussed in detail in part II, kaolinite is the dominant silicate mineral accompanied by lesser amounts of hydrated halloysite and chlorite; the oxide minerals identified comprise quartz, gibbsite, goethite, hematite and magnetite. In a given profile there is very little vertical variation in the relative amounts of these minerals. It is therefore concluded that no major mineral transformation occur in the transition from parent material to solum.

The Matanzas, Bayamon, and Piña soils exhibit strikingly low silt contents between 1.2 and 5.4 percent; in the Coto series these values vary between 5.3 percent (Soil Survey Staff, 1969, p. 174) and 12.0 percent. According to Van Wambeke (1962), low silt : clay ratios are an indication of old soils. Similarily, these soils must be considered to be in a "senile stage" of development in Mohr and Van Baren's scheme (1954) and represent advanced weathering

stages in the sequence of Jackson et al. (1948). Yet these soils are young as regards absolute age since they formed on largely Pleistocene surfaces. The fact that Oxisols could developed there in relatively short time must be attributed to the highly weathered parent material which achieved its oxic properties in a previous weathering cycle.

The Catalina series (site 6) was established by Roberts et al. (1942) in the original soil survey of Puerto Rico and mapped over some 50,000 ha. However, it is estimated that less than half of the soils identified as Catalina clay by Roberts conform to the present definition of this series as Tropeptic Haplorthox. In the modern soil survey of the island now in progress, a considerable part of the original Catalina soils have been correlated with Ultisols. References to the Catalina clay of the former concept (e.g. Bonnet, 1939; Mohr and Van Baren, 1954 ; Vine, 1966) are, therefore, ambiguous.

The Catalina soil selected for this study is located near the type location of this series in the so-called Barranquitas Soil Study Area in east-central Puerto Rico. The Soil Survey Staff (1967) described and analysed thirteen pedons from this small area, and a geomorphic study to elucidate soil - landscape relations has recently been completed (Daniels et al., 1973). In addition to a detailed geologic map (Briggs and Gelabert, 1962), there also exists an excellent treatise on laterization in this area by Briggs (1960).

The genesis of the Catalina soil can be conveniently considered in terms of two phases : rock weathering and soil formation. Regarding the former, Briggs' research (1960) provided detailed information on the chemical and mineralogical changes occurring in the transition from fresh rock to saprolite. The losses and alterations of original constituents can be visualized from Briggs' data (1960) reproduced in Tables V and VI.

TABLE V
Chemical composition of lava breccia and saprolite from east-central Puerto Rico (after Briggs, 1960, p. 107)

TABLE VI
Normative mineral assemblages, by percent volume, of lava breccia and saprolite from east-central Puerto Rico (after Briggs, 1960, p. 111)

It is evident that most of the bases notably calcium, but only minor amounts of total silica are lost during original rock weathering. Table VI indicates the following changes in the content of the principal normative minerals during weathering : Pyroxene (augite) has disappeared, anorthite has been destroyed, most of the albite has been removed, orthoclase has been reduced slightly, but quartz remained almost constant ; while chlorite was significantly reduced, there is a very marked increase in kaolinite from 6.1 to 39.0 percent and also a gain in limonite (Briggs, 1960).

Although quartz amounts to less than 5 percent, there is only

a slight decrease in the total silica content. The mineralogical data suggest that most of the silica liberated in the breakdown of plagioclase recombines with aluminum to form kaolinite. This would indicate less intensive leaching near the rock surface ensuing a higher silica concentration which is also suggested by the absence of gibbsite. The amount of potassium is relatively constant, in spite of the usually mobile character of this cation. Briggs (1960) presumed that much of the potassium may really occur in sericite, a mineral more stable than K-feldspars. However, because no sericite was positively identified, all K was included in K-feldspars in the norm calculations.

The saprolite constitutes the parent material of the Catalina soil and must be considered a strongly weathered lateritic material although not as profoundly altered as the saprolite derived from serpentinite. In both cases the saprolites are the result of geochemical rather than pedologic weathering. The types of changes affecting this parent material in the process of the formation of the Catalina soil are mainly transformations and, to a minor degree, additions, transfers, and removals.

Judging from the mineralogical data presented by Briggs (1960) and the results obtained by Jones et al. (see part II), it appears that in the transition from saprolite to soil the iron oxide minerals achieve a higher degree of crystallinity. Whereas limonite predominates in the

saprolite, goethite and hematite are the main iron oxide species throughout the solum. The gradual increase of gibbsite with decreasing depth is difficult to explain. It cannot be ascertained without further studies whether this is due to desilication of kaolinite or to synthesis from aluminum released in the weathering of K-feldspars and sericite. The latter would further ensue the removal of minor amounts of silica and potassium. Fabric-related transformations are exhibited in the pedological organization of the material with increasingly denser packing in the upper horizons.

The presence of a few illuviation cutans in the lower part of the solum (Soil Survey Staff, 1967, p. 167) may be taken as an indication for transfers of silicate clay. In the upper profile, however, there is no conclusive evidence for active lessivage. The consistently higher concentration of bases in the A horizons of all of the Haplorthox of the Barranquitas Soil Study Area (Soil Survey Staff, 1967) is attributed to transfers caused by re-cycling of nutrient by vegetation. As in the case of the Nipe series, the incorporation of organic matter accounts for the main addition of material to the soil system.

The geomorphic studies have shown that the Catalina soils in the Barranquitas Study area occupy surfaces of Miocene age. Yet the soils found on these surfaces have properties such as "tropeptic" structure and some argillans which are normally associated with

younger Oxisols. While no conclusive explanation for this inconsistency can be offered, some conjectures may be made. First, the Catalina pedon studied occurs on the footslope of a geomorphic surface which grades into a backslope where fresh rock is exposed near or at the surface. It is thus in a position where it could have recurrently received unweathered material from upslope. Second, the possibility of occasional accretion of volcanic ash blown in from the still active volcanoes in the Lesser Antilles cannot be dismissed. The effect of this would be a sporadic colluvial and/or aeolian rejuvenation which would tend to retard soil development to more advanced stages. The notably higher quartz content of the topsoil as compared with the subsoil may also be interpreted as the result of admixture of the residual soil material with minor quantities of more recently supplied materials.

In the Barranquitas Study Area, there clearly exists a causative relationship between the occurrence of Miocene surfaces and the formation of Oxisols. The Soil Survey Staff (1967) analyzed nine pedons from Tertiary surfaces in this area and found all to be Tropeptic Haplorthox, while Ultisols and Inceptisols were identified on younger surfaces. These Tertiary surfaces had attained their present configuration essentially in Miocene and were presumably not subjected to major subsequent alluviation (Daniels et al., 1973). It follows that

time zero of soil formation for the soils on these surfaces should also be in Miocene. While therefore old as regards absolute age, the soils on these surfaces display features indicative of younger Oxisols. This may be ascribed to recurrent rejuvenation and probably to periods of less intense soil formation during glacials in Pleistocene.

Soils similar to the Catalina series are believed to have been extensive in Puerto Rico during the fullest development of the St John Peneplain (Briggs, 1960). Oxisols in the interior of Puerto Rico are now confined mainly to the rare remnants of old surfaces which have escaped erosion. The lateritic material that was eroded during the dissection of the St. John Peneplain was transported mainly to the north coast and deposited there to form the blanket deposits discussed above.

Ultisols

Next to the Inceptisols, Ultisols are the most extensive soils in Puerto Rico and occupy some 220,000 ha or about one fourth of the total land area of the island. The Los Guineos, Carreras, Daguey and Torres series (sites 7,8,9 and 10) are considered representative for the range of Ultisols found in the humid uplands of Puerto Rico.

No detailed chemical or mineralogical data are available to assess the changes occurring in the weathering of the original rock to

the parent material of these soils. However, all are derived from volcanic rocks of andesitic to basaltic composition and it is presumed that the trend of weathering is similar to the one described above for the Barranquitas area. While similar in kind, there are differences in degree and the saprolites at sites 7 to 10 are less completely weathered. Thus, amphibole and a dioctahedral smectite (beidellite) was detected in the C2 horizon of the Carreras soil indicating less intense weathering. The saprolite underlying the sola of the Los Guineos and Daguey series is moderately weathered as suggested by the presence of small amounts of vermiculite. The parent material of the Torres series is transported rather than residual. It is more intensely weathered and mineralogically resembles the parent material of Catalina clay.

The less strongly weathered character of the parent material allows pedogenetic processes to induce more noticeable alterations than in the case of the Oxisols discussed above. Transfers and transformations are the dominant types of changes within the soil system, but additions and removals are also of importance. All of the four Ultisols show evidence for translocation of clay in the form of illuviation cutans in the argillic horizon. As seen from the data in Table VII, the clay increase with depth is marked in the Daguey and Torres series though less pronounced in the Los Guineos and Carreras

soils. In the latter case this is ascribed to truncation of the eluviated horizon. In the Los Guineos series the clay maximum is in the B22t horizon below the B21 reported in Table VII.

TABLE VII
Particle size distribution of selected horizons of eleven soils from Puerto Rico

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The mineralogical analyses carried out by Jones et al. and discussed in part II indicate that the mineral assemblage in the solum is largely inherited from the parent material. All soils are dominated by kaolinite and contain lesser amounts of goethite and hematite. Gibbsite was determined in the Los Guineos and Torres soils where it increased from less than 1 percent in the parent material to 5 to 10 percent in the A horizons. Gibbsite is therefore considered to be the result of mineralogic transformations in the solum. The pedogenic synthesis of gibbsite is intriguing but subject to speculation in this case. From the data compiled in Table VIII there appears to exist a relationship between the presence of gibbsite and the concentrations of Al and Si in the soil solution. Although the data are not conclusive, there is a tendency for gibbsite to be present when both the Al and Si concentrations are low (Los Guineos, Torres), while it is absent when both are high (Carreras). The increase of aluminum with depth and particularly in the parent material also suggests a

relation to the amount of weatherable aluminosilicates in the soil and parent material. Thus, the more weathered Orthoxic subgroups (Daguey, Los Guineos, Torres) have relatively low levels of KCℓ-extractable Al in the solum, whereas it is high in the less weathered Typic subgroup (Carreras). In ten Ultisol pedons analyzed by the Soil Survey Staff (1967), this correlation also holds true. The high levels of extractable aluminum in the Typic subgroups of Ultisols of Puerto Rico is the chief chemical constraint and main management problem of these soils. By contrast, extractable aluminum is low in the Oxisols of Puerto Rico. It is conjectured that this is due to the near absence of weatherable minerals in the sola of these soils and to the polymerization of the monomeric aluminum to gibbsite.

TABLE VIII
Relations between aluminum and silicon concentrations and gibbsite content in four Ultisols from Puerto Rico

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The spacial arrangement of the soil mass into discrete structural units, particularly evident in the argillic horizons, constitute a further transformation of material. The main addition to the soil system is that of organic matter amounting to more than 15 kg per surface cubic meter. Minor removals occur through the leaching out of very small amounts of bases liberated in the weathering of primary minerals and probably silica. The Los

Guineos series displays a morphologic peculiarity in that yellowish B horizons overlie reddish horizons. In Puerto Rico, soils with such horizonation are confined to areas of more than 200 cm annual rainfall and sloping topography. Epiaquic subgroups were established in Soil Taxonomy to characterize soils having these features. The conditions causing this morphology are not well understood but are thought to be related to lateral water movement.

The Ultisols of Puerto Rico occur on younger and less stable geomorphic surfaces than the residual Oxisols. An indication of the geomorphic instability is, for example, seen in the upper solum of the Daguey soil where shear planes roughly parallel to the slope were observed. Similar features have also been found in Ultisols on Kauai, Hawaii (Beinroth et al., 1973). There is a distinct possibility that in Puerto Rico soil creep on sloping surfaces may be triggered by seismic activity. The more juvenile character of the Ultisols studied is also indicated by the silt clay ratios reported in Table VII. These values average 0.31 for the Ultisols as opposed to 0.12 for the Oxisols which according to Van Wambeke (1962) suggests a younger age for the Ultisols.

Inceptisols

Inceptisols are the most extensive soils of Puerto Rico and occupy approximately 370,000 ha or about 42 percent of the island.

For the most part these are shallow Eutropepts and Ustropepts or Tropaquepts. The Picacho series (site 11) included in the present study is a deeper and more weathered Inceptisol intergrading to Ultisols. This and similar Humitropepts are of limited extent in Puerto Rico and are confined to the perhumid areas on the highest mountains.

The parent material of the Picacho series is a saprolite derived in situ from quartzdiorite. Jones et al. (see part II) determined its mineralogic composition as consisting of moderate amounts (10-25%) of quartz, kaolinite and goethite; small quantities (1-10%) of mica, dehydrated halloysite, magnetite, lepidocrocite, and gibbsite; and detected amounts of amphibole, hydrated halloysite, and montmorillonite. While the presence of mica and amphibole indicates that the saprolite is not exceedingly weathered, the mineral assemblage of the original rock has nevertheless been profoundly altered.

The relative abundance of oxide and silicate minerals in the solum does not greatly vary from that in the parent material. The main mineralogic transformations in the transition from parent material to soil are the destruction of mica and a slight increase in hydrated halloysite and montmorillonite. The latter is likely an alteration product of mica since it has a similar structure but

interlayer water instead of K ions between the layers. However, the authigenic formation in an environment of leaching would be unusual. For a detailed discussion of the mineralogy of the Picacho series, reference is made to the paper by Jones et al. in part II.

There was no field evidence for transfers of silicate clays through lessivage. Yet this is to be expected in a soil of an area with a perhumid climate where water percolates through the profile at all seasons (Soil Survey Staff, 1970). In spite of significantly higher clay contents, the subsurface horizons do, therefore, not qualify for argillic horizons and are considered cambic horizons. The presence of original rock structure in the B22 horizon also precludes its designation as argillic. The ensuing classification of the Picacho series as an Inceptisols agrees with its occurrence on a youthful and very unstable geomorphic surface as well as with its relatively high silt : clay ratio (see Table VII).

The morphology of the Picacho profile is similar to that of the Los Guineos series in that soil colors are yellowish in the upper solum but attain more reddish hues with depth. It was also observed that the subsoil was considerably less moist than the topsoil. This may be due to the fact that the dense tropical rainforest vegetation with its very high consumptive water use extracts a significant portion of the soil moisture before it reaches the subsoil. Lateral

seepage is further believed to be an important factor regarding the water movement in these soils. However, the chemical analysis suggest that the Picacho soils are leached throughout the profile. Removal of small amounts of bases released in the weathering of primary minerals is , therefore, considered an ongoing pedogenetic process.

The Picacho soil studied developed under virgin rain forest vegetation and was never cultivated. Under such conditions the additions of organic material to the soil system are large. Nye and Greenland (1960) estimated that the biomass production in a tropical forest is about 17 tons per hectare per annum. Yet the organic carbon content of the A horizon of the Picacho soil is only 2.60 percent. If this value represents the equilibrium level, it must be concluded that the rate of decomposition and turnover of organic material is rapid under the prevailing conditions. As a consequence a considerable amount of nutrients is liberated in the process of mineralization (Nye and Greenland, 1960). The bases thus released are recycled by vegetation to a large extent rather than lost to leaching. Went and Stark (1968) describe mycorrhizal patterns at Manaus, Brazil, as mineral cycling mechanisms and assume that the organic matter for the fungi is drawn from litter. In a detailed study of microorganisms and mineral cycling in the

El Verde rain forest of Puerto Rico, it was concluded from budget estimates of soil metabolism that large organic flows also occur down to roots within the trunk (Odum, 1970). F.H. Wadsworth (personal communication, 1973) indicated that once a rain forest is established it becomes essentially a self-sustaining system which is largely independent of the nutrient status of the soil.

Occurrence of Similar Soils in Other Tropical Areas

The geology, geomorphology and climate of Puerto Rico and the resulting nature and distribution of soils (Beinroth, 1971) is far from being typical for the humid tropics as a whole. While the eleven soils selected for this study characterize the range of highly weathered soils found on the island, they are not necessarily representative for soils that are extensive in intertropical region. Yet the correspondence of the Puerto Rican soils studied with those of other areas is difficult to assess and can only be discussed in general terms.

Although the recent publication of the FAO/UNESCO Soil Map of South America (FAO, 1972) and the Soil Map of the Tropics (Aubert and Tavernier, 1972) are major achievements and important contributions to soil geography, their high degree of generalization precludes reliable correlations at low taxonomic levels.

Though not suited for detailed comparisons, these maps are nontheless valuable for locating soil areas of probable coincidence. Thus, an analysis of Aubert and Tavernier's map (1972) indicates that Orthox occur over roughly 750 million hectares in Africa and Latin America; Udults comprise some 410 million hectares in Asia, Africa and Latin America; but Humults are only depicted in extra-tropical Brazil.

It can be concluded that soils similar but not necessarily identical to the Bayamón, Catalina, Coto, Matanzas, Nipe, and Piña series of Puerto Rico, which are all Orthox, must be encountered in the areas mapped as Orthox. However, the similarity may be restricted to those soil properties used to differentiate the Orthox at the suborder level. By the same token, the Torres series should be similar in a general way to the soils delineated as Udults on Aubert and Tavernier's map, but it cannot be ascertained if it has correlatives at the great group, subgroup or family levels, respectively. According to the same map, no extensive counterparts for the Carreras, Daguey and Los Guineos series are to be expected elsewhere in the tropics as Humults are not recognized in the intertropical area. Equivalents for the Picacho series are probably included in the map unit "Soils in Areas with Mountains" of Aubert and Tavernier (1972). — On the FAO/UNESCO Soil Map of the World, all sheets of which are scheduled to be published in the near

future, the Catalina, Coto, Bayamon, and Nipe series approximately correspond with Humic Ferralsols, while the Matanzas and Piña series should be similar to Orthic Ferralsols. The Carreras, Daguey and Los Guineos series have equivalents in the areas delineated as Humic Acrisols on the FAO/UNESCO maps, while the Torres series is similar to Orthic Acrisols. The map unit of Ferralic Cambisols provides a rough correlative for the Picacho series.

More specifically, the Nipe series is known to occur in the Dominican Republic and in Cuba (Bennett and Allison, 1928). It is also rather similar to the Terra Roxa Legitima which is extensive on basalts in Brazil (A. Van Wambeke, personal communication, 1973), and approximates the Kraznozems which are common but not wide-spread on basalts in Australia (R. Isbell, personal communication, 1973). The Soil Survey Staff (1970) thought Acrorthox also to be extensive in other parts of the tropics.

The Matanzas and Coto series have almost identical counterparts in the Dominican Republic and are the most extensive soils of Cuba according to Bennett and Allison (1928). The geomorphic studies of Briggs (1966) strongly suggest, that soils very similar to the Matanzas, Coto and Piña series also occur in Jamaica. The Puhi series of Hawaii is an excact taxonomic equivalent of the

Matanzas series of Puerto Rico but a much deeper soil. On a world-wide scale, the extent of Eutrorthox is probably not large.

Haplorthox like the Catalina, Bayamon, Coto and Piña series of Puerto Rico are wide-spread soils of the evergreen forests of the tropics (Soil Survey Staff, 1970). However, in the case of the Bayamon, Coto and Piña series, the similarity is a morphological, chemical and mineralogical rather than a genetic one. According to Vine (1960), the extensive Kikuyu Red Loam derived from sub-acid lavas in the highlands between Nairobi and Mount Kenya in East Africa appears to be very similar to the Catalina series, which is in agreement with the author's observations.

CONCLUSIONS

The conclusions to be drawn from the preceeding discussion may be summarized as follows :

Soil Classification

(1) A re-definition of the Acrorthox is suggested and the establishment of a Tropeptic subgroup proposed. It should further be considered to introduce a Dystropeptic subgroup for shallow Tropohumults in analogy with the Tropudults.

(2) Uncertainty in the positive field identification of illuviation cutans in some tropical soils adds to the difficulty to differentiate

between Oxisols and Ultisols, and Ultisols and Inceptisols in borderline cases.

(3) The classification of most tropical soils primarily on the basis of subsoil properties is not beyond criticism from an agronomic point of view.

(4) In the absence of a key and precise quantitative definitions, the placement of soils in the Frech system of soil classification is, in the present state, unavoidably opiniated.

Soil Formation

(1) Laterization in Puerto Rico is largely a geochemical rather than pedologic weathering process and proceeds significantly faster on ultrabasic than on andesitic - basaltic rocks.

(2) Oxisols are of minor extent in Puerto Rico and their occurrence is mainly controlled by geomorphic and lithologic factors. Residual Oxisols, developed from andesitic-basaltic volcanic rocks on Miocene surfaces, are only preserved under particular geomorphic conditions. On Pliocene surfaces, Oxisols are only known to occur where serpentinite is the parent rock; other conditions being equal, Ultisols predominate on Pliocene surfaces underlain by andesitic volcaniclastics. The Oxisols on the essentially Pleistocene surfaces along the north coast of Puerto Rico are developed in sediments laterized in a previous weathering cycle and are not residual from

the underlying pure limestone.

(3) Reference to the Oxisols of Puerto Rico in terms of "young", "mature", and "old" is ambiguous. It appears preferable to characterize these soils by the absolute age of the geomorphic surface and/or by stages of soil development.

(4) Soil-forming conditions in Puerto Rico are not representative for major parts of the tropics. Taxonomic equivalents of the soils studied occur elsewhere in intertropical areas, but the extent cannot be assessed with accuracy due to the lack of detailed modern soil maps.

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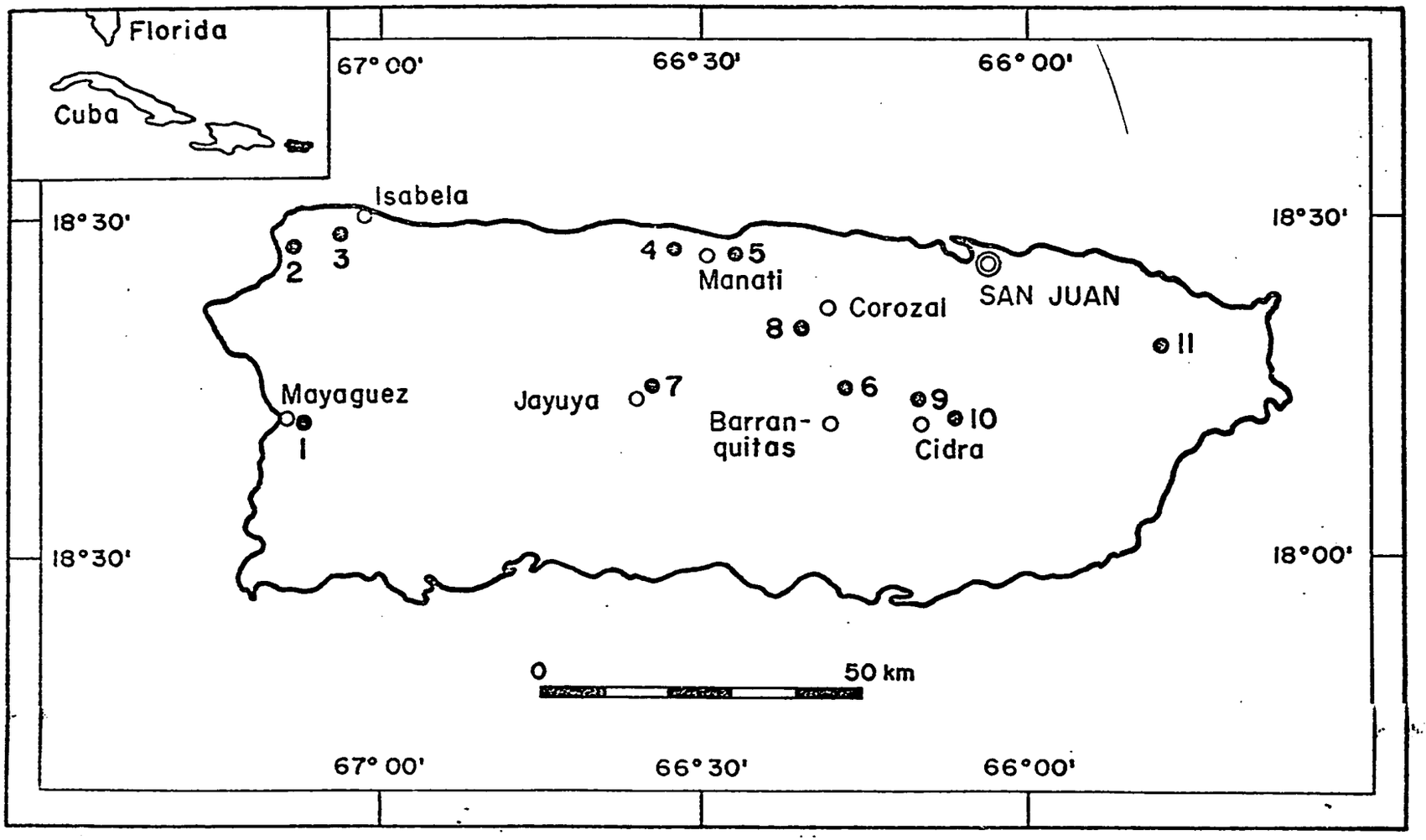
Florida
Cuba
67° 00'
66° 30'
66° 00'
18° 30'
18° 30'
18° 30'
18° 00'
Isabela
2
3
4
5
Manati
Corozal
SAN JUAN
8
11
Mayaguez
1
Jayuya
7
6
9
10
Barran-
quitas
Cidra
0
50 km
67° 00'
66° 30'
66° 00'

LEGEND

Site	Soil Series	Soil Classification	Latitude	Longitude	Elevation (m)
1	Nipe	Typic Acrorthox	18° 11' 2" N	67° 6' 10" W	350
2	Matanzas	Tropeptic Eutrorthox	18° 26' 40" N	67° 8' 32" W	160
3	Coto	Tropeptic Haplorthox	18° 28' 2" N	67° 3' 25" W	131
4	Bayamon	Tropeptic Haplorthox	18° 26' 5" N	66° 33' 19" W	50
5	Piña	Typic Haplorthox	18° 25' 45" N	66° 26' 56" W	83
6	Catalina	Tropeptic Haplorthox	18° 14' 31" N	66° 16' 40" W	607
7	Los Guineos	Epiaquic Orthoxic Tropohumult	18° 14' 45" N	66° 34' 24" W	740
8	Carreras	Typic Tropohumult	18° 19' 14" N	66° 21' 32" W	250
9	Daguey	Orthoxic Tropohumult	18° 13' 50" N	66° 10' 2" W	500
10	Torres	Orthoxic Tropudult	18° 12' 3" N	66° 7' 5" W	450
11	Picacho	Udoxic Humitropept	18° 17' 45" N	65° 47' 30" W	750

Fig. ~~2~~ 1. Location of sample sites in Puerto Rico.

TABLE I

Climatic data for selected stations in Puerto Rico

Station	Typical for site (s)	J	F	M	A	M	J	J	A	S	O	N	D	Annual
						Mean Precipitation (cm)								
Mayaguez	1	5.08	5.16	9.35	12.50	20.93	22.38	26.52	27.91	27.41	23.52	14.88	6.55	202.18
Isabela	2,3	8.59	7.59	7.24	9.22	16.74	12.37	10.13	14.25	14.68	14.68	17.12	11.20	143.81
Barceloneta	4,5	14.07	9.88	7.65	9.07	15.32	9.63	12.62	13.64	13.56	13.21	17.83	13.44	149.91
Barranquitas	6	9.30	8.41	6.20	8.76	14.55	12.83	10.08	14.50	15.27	22.73	12.34	15.60	150.57
Toro Negro	7	10.24	11.86	11.07	18.60	32.66	17.93	17.20	25.40	34.14	38.51	22.96	11.94	252.53
Corozal	8	13.11	10.29	10.26	14.91	20.62	14.00	19.05	21.23	18.87	18.42	22.05	17.07	199.87
Cidra	9,10	10.59	7.87	5.54	11.71	17.91	15.52	18.42	18.59	20.68	17.96	14.25	11.10	170.13
Rio Grande Upper	11	27.97	24.43	18.95	24.43	39.65	36.30	32.94	37.11	38.81	36.47	38.61	31.88	385.55
						Mean Temperature (°C)								
Mayaguez	1	23.7	23.7	23.9	24.6	25.5	26.2	26.1	26.3	26.4	26.2	25.3	24.4	25.2
Isabela	2,3	23.6	23.9	24.0	24.6	25.6	26.1	26.6	26.6	26.5	26.2	25.5	24.3	25.5
Barranquitas	6	19.6	19.7	20.4	21.5	22.1	22.9	23.2	23.2	23.0	22.8	21.6	20.3	21.7
Corozal	8	22.5	22.4	23.0	23.9	25.1	25.6	25.7	25.8	25.7	25.5	24.6	23.3	24.4

Source : Decenial census of United States climate, Puerto Rico and Virgin Islands.
U.S. Dept. Commerce, Weather Bureau, Climatography of U.S. 81-45, Washington, D.C., 1962

TABLE II
Placement of selected Puerto Rican soils in different classification systems.

Site	Series	US Soil Taxonomy	FAO/UNESCO Legend	French System (CPCS)
1	Nipe	Typic Acrorthox clayey, oxidic, isohyperthermic	Humic Ferralsols	Sols Ferrallitiques, fortement désaturés en (B). humifere, modal
2	Matanzas	Tropeptic Eutrorthox clayey, kaolinitic, isohyperthermic	Orthic Ferralsols	Sols Ferrallitiques, faiblement désaturés en (B). remanié, faiblement rajeuni
3	Coto	Tropeptic Haplorthox clayey, kaolinitic, isohyperthermic	Humic Ferralsols	Sols Ferrallitiques, moyennement désaturés en (B). typiques, faiblement rajeuni
4	Bayamon	Tropeptic Haplorthox clayey, kaolinitic, isohyperthermic	Humic Ferralsols	Sols Ferrallitiques, moyennement désaturés en (B). typiques, faiblement rajeuni
5	Piña	Typic Haplorthox fine-loamy, oxidic, isohyperthermic	Orthic Ferralsols	Sols Ferrallitiques, fortement désaturés en (B). remaniés, modal
6	Catalina	Tropeptic Haplorthox clayey, kaolinitic, isohyperthermic	Humic Ferralsols	Sols Ferrallitiques, moyennement désaturés en (B). typiques, humique
7	Los Guineos	Epiaquic Orthoxic Tropohumults clayey, kaolinitic, isothermic	Humic Acrisols	Sols Ferrallitiques, moyennement désaturés en (B). typiques, humique
8	Carreras	Typic Tropohumults clayey, mixed, isohyperthermic	Humic Acrisols	Sols Ferrallitiques, moyennement désaturés en (B). Rajeunis, avec erosion
9	Daguey	Orthoxic Tropohumults clayey, kaolinitic, isohyperthermic	Humic Acrisols	Sols Ferrallitiques, moyennement désaturés en (B). typiques, humique
10	Torres	Orthoxic Tropudults clayey, mixed, isohyperthermic	Orthic Acrisols	Sols Ferrallitiques, moyennement désaturés en (B). typiques, humique
11	Picacho	Udoxic Humitropepts clayey, mixed, isothermic	Ferralic Cambisols	Sols Ferrallitiques, moyennement désaturés en (B). rajeunis, avec erosion

TABLE III

Chemical composition of Nipe clays and serpentinites from Cuba and Puerto Rico

Horizon	Depth cm	SiO_2 %	Al_2O_3 %	Fe_2O_3 %	TiO_2 %	Cr_2O_3 %	MgO %	CaO %	K_2O %	P_2O_5 %	MnO %	$SiO_2:Al_2O_3$
Cuba[1]												
1	0-66	3.28	18.46	63.04	.80		.33	.12	.06	.03	.42	.18
2	66-100	2.25	11.13	69.56	.26		.48	tr	.08	tr	.28	.20
3	100-400	1.83	12.36	71.12	.80		.64	.01	.02	tr	.38	.15
4	400-500	1.55	14.66	68.10	.80		.60	.15	.05	tr	.47	.11
Serpentine	500 +	41.93	2.00	7.84	.05		34.02	1.50	.08	tr	.12	20.97
Puerto Rico[2]												
A	0-13	12.52	15.34	48.54	.72	3.86	.19	.12	.09	.14	.26	.82
B1	13-38	8.78	16.43	57.61	.57	3.30	tr	.10	.02	.05	.22	.53
B2	38-127	3.00	18.69	57.79	.42	3.54	.09	.06	tr	.07	.31	.16
C1	155	2.56	15.21	64.90	.43	3.18	.11	.16	tr	.08	.23	.17
C2	365	2.29	12.62	63.48	.39	5.23	tr	.20	tr	.08	.22	.18
Weathered rock	400	16.89	10.45	49.57	.34	4.67	6.02	.37	tr	.04	.22	1.62
Puerto Rico[3]												
A1	0-5	6.48	19.15	62.61	.57	1.04	.41	.90	.17	.32	.62	.34
A3	8-13	6.58	18.70	62.69	.44	1.23	.50	1.05	.16	.37	.51	.35
B1	23-28	6.36	20.60	60.50	.36	.71	.41	.59	.14	.33	.47	.31
B2	56-61	6.10	21.82	61.23	.37	.92	.21	.54	.13	.32	.40	.28
C1	91-96	5.67	23.80	58.14	.30	.92	.33	.90	.14	.33	1.09	.24
Saprolite	120-125	3.62	20.22	60.69	.34	1.10	.94	.43	.08	.31	1.10	.18
Partially weath. rock	132-137	21.10	14.15	42.71	.30	1.15	4.15	.02	.03	.21	1.21	1.49
Fresh rock	152 +	38.43	1.25	8.86	.10	.44	34.45	.99	.03	.15	.17	30.74

1) Adapted from Bennett and Allison (1928, p. 73)
2) Adapted from Roberts et al. (1942, p. 475)
3) Adapted from Sivarajasingham (1961, p. 40)

TABLE IV

Chemical composition of blanket deposits from northern Puerto Rico and saprolite from east-central Puerto Rico

Sample	Depth cm	SiO_2 %	Al_2O_3 %	Fe_2O_3 %	TiO_2 %	MgO %	CaO %	K_2O %	P_2O_5 %	MnO %	$SiO_2:Al_2O_3$
Blanket deposits[1]	175	35.25	30.91	19.73	.85	.46	.18	.21	.24	.05	1.14
Blanket deposits[2]	100-180	38.26	27.58	19.37	1.22	.34	.12	.19	.45	.11	1.39
Blanket deposits[3]	215-255	61.49	19.73	9.55	.88	.02	.12	.16	.01	.05	3.12
Saprolite[4]	200	38.12	22.59	17.20	1.04	.36	.00	1.81	.16		1.69

1) Near Isabela; C horizon, Matanzas clay (Roberts et al., 1942, p. 449)

2) Near Isabela; C horizon, Coto clay (Roberts et al., 1942, p. 447)

3) Near Manatí; C horizon, Vega Alta fine sandy loam (Roberts et al., 1942, p. 463)

4) Near Barranquitas (Briggs, 960, p. 107)

TABLE V
Chemical composition of lava breccia and saprolite from east-central Puerto Rico (after Briggs, 1960, p. 107)

Oxide Determined	Sample A[1]	Sample B[2]	Sample C[3]	Sample D[4]
SiO_2	42.48[5]	49.07	44.91	38.12
Al_2O_3	12.56	14.21	16.56	22.59
Fe_2O_3	4.75	9.23	11.99	17.20
FeO	3.92	1.78	.00	.36
TiO_2	.58	.68	.77	1.04
MgO	5.44	5.70	3.47	1.18
CaO	15.26	6.47	1.07	.00
Na_2O	2.95	2.75	1.98	.08
K_2O	1.50	1.86	2.34	1.81
H_2O (comb.)	2.46	3.49	5.47	9.81
H_2O (free)	.85	3.88	8.62	7.24
CO_2	6.58	.03	.16	.04
P_2O_5	.30	.36	.09	.16
MnO	.16	.24	.32	.04
Total	99.79	99.75	99.75	99.67

1) Greenish-black basaltic andesite flow breccia

2) Olive -gray to grayish-red weathered flow breccia

3) Pale olive-gray to pale reddish-brown weathered flow breccia

4) Reddish-brown flow breccia saprolite

5) Percent by weight

TABLE VI

Normative mineral assemblages, by percent of volume, of lava breccia and saprolite from east-central Puerto Rico (after Briggs, 1960, p. 111)

Normative minerals	Sample A[1]	Apparent destruction	Apparent accretion	Sample D[2]
Quartz: SiO_2	4.5			4.6
K-feldspar: $KAlSi_3O_8$	10.3	3.8		6.5
Plagioclase: Albite, $NaAlSi_3O_8$	31.0	30.6		.4
Anorthite, $CaAl_2Si_2O_8$	5.1	5.1		0
Pyroxene: $(Ca, Fe, Mg)SiO_3$	15.3	15.3		0
Magnetite: $FeO.Fe_2O_3$	4.8	4.0		.8
Ilmenite: $FeTiO_3$	.9	.9		0
Apatite: $Ca_5P_3O_{12}(Cl, F)$	1.4	1.4		0
Free water: H_2O	1.9		34.1	36.0
Chlorite group: $H_8Mg_5Al_2Si_3O_{18}$	18.7	16.4		2.3
Kaolinite group: $Al_2O_3.SiO_2.2H_2O$	6.1		32.9	39.0
Rutile: TiO_2	0		.6	.6
Limonite: $Fe_2O_3.nH_2O$	0		8.9	8.9
Maghemite: Fe_2O_3	0		.9	.9
Total	100.0	77.5	77.5	100.0

1) Greenish-black basaltic andesite flow breccia

2) Reddish-brown flow breccia saprolite

TABLE VII

Particle size distribution of selected horizons of eleven soils from Puerto Rico[1]

Series	Horizon	Depth cm	Sand %	Silt %	Clay %	Silt : Clay
			Oxisols			
Bayamon	A1	0-20	56.2	4.1	39.[illegible]	.10
	B21	20-40	43.2	2.5	54.[illegible]	.05
Catalina	Ap	0-16	1.5	15.5	83.[illegible]	.18
	B21	16-35	.1	11.8	88.1	.13
Coto	Ap	0-13	27.8	9.8	62.[illegible]	.16
	B21	24-45	22.0	12.0	66.0	.18
Matanzas	A1	0-35	8.1	7.4	84.6	.09
	B21	35-70	3.3	5.4	91.3	.06
Nipe	A1	0-25	9.8	35.2	55.0	.64
	B21	40-70	3.0	13.0	84.0	.16
Piña	Ap	0-20	89.3	1.6	9.1	.18
	B21	34.60	70.9	1.2	27.9	.04
			Ultisols			
Carreras	Ap	0-14	15.2	23.0	61.8	.38
	B21t	14-28	12.0	23.1	64.9	.36
Daguey	A	0-10	6.4	27.5	66.1	.42
	B21t	10-30	3.0	20.0	77.0	.26
Los Guineos	A1	0-8	6.3	20.7	73.0	.28
	B21	8-25	3.9	16.7	79.4	.21
Torres	Ap	0-10	11.0	23.8	65.2	.37
	B21t	10-30	6.5	15.8	78.2	.20
			Inceptisols			
Picacho	A	0-18	51.0	16.7	32.3	.52
	B21	18-35	36.0	18.9	45.1	.42

1) Analyses by Department of Agronomy and Soil Science, University of Hawaii

TABLE VIII

Relations between aluminum and silicon concentrations and gibbsite content in four ultisols from Puerto Rico

Series	Horizon	Depth cm	Al meq/100g soil	Si[1] ppm. solution	Gibbsite[2] %
Carreras	B2lt	14-28	8.22	5.11	-
	B22	28-55	11.42	3.84	-
	C 2	110-125	12.73	5.28	-
Daguey	B21	10-30	1.18	1.25	-
	B22	30-60	3.89	1.26	-
	C 1	95-140	6.73	2.06	-
Los Guineos	B21	8-25	2.22	.48	1-10
	B32	65-90	2.96	.22	1-10
	C 3	200-250	8.49	1.60	0-1
Torres	B21	10-30	1.69	1.38	1-10
	B22	30-50	3.20	.96	0-1
	B3	90-125	5.31	1.01	0-1

1) Saturation extract; data by R. L. Fox, University of Hawaii

2) Data by R. C. Jones, University of Hawaii