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PRIMARY SOIL FORMING PROCESSES AS INFLUENCED BY THE COMPOSITION OF PARENT MATERIAL AND ENVIRONMENTAL CONDITIONS[1]

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I. Introduction

During February and March 1943 a careful sampling of the chief soil types of Puerto Rico was undertaken under the auspices of the Institute of Tropical Agriculture of the University of Puerto Rico.

The purpose of this work was to collect material for a study of the fundamental processes involved in the formation of tropical soils as influenced by the mineral composition of the parent material and varying environmental conditions. Samples of various important soil horizons and parent rock were taken with regard to the previous geological survey by Meyerhoff (14) and soil survey by Roberts (18). The areas sampled were carefully located according to their latitude and longitude so that additional material could be readily obtained if necessary.

In the course of this work a sample of Jácana clay and its parent rock was taken near the Cabo Rojo-Boquerón road at longitude 67° 8.5'W, latitude 18°-3.5'N and rock samples representing the parent material of the Los Guineos clay on the Mameyes Yunque road at longitude 65° 47'W and latitude 18°-18.5'N. The rock samples as identified in the field were classified in the case of those of the Jácana clay as andesitic in nature and those of the Los Guineos clay as quartz diorite.

In view of the fact that these two classes of rocks are chemically equivalent but structurally different and occurred in areas of extremely different climatic conditions, the idea occurred that it might be of interest to compare their weathering characteristics as influenced by these conditions. The following report is a consideration of the chemical and mineralogical variations of these rocks as brought about by these varying conditions.

II. Review of Literature

The literature regarding weathering and the processes of soil formation is very extensive, but practically no work has been done in relation to the

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mode of weathering of minerals in the different soil types and in the various horizons of the soil profile.

The type of weathering prevailing in Puerto Rico is chemical weathering, or decomposition.

The island has no frosts, and the dry sections of the south coast always receive moderate amounts of rainfall during part of the year; sudden changes in temperature never occur. As a result disintegration is of little importance as a soil forming process.

Chemical weathering involves a complicated series of mineralogic and chemical changes. These are brought about through the action of five principal processes: oxidation, hydration, carbonation, solution and deposition.

A. OXIDATION

The oxygen of the air enters into chemical combination with certain elements in the minerals and various oxidation products result. In order for oxidation to be effective, water must be present. Iron minerals are the more common ones to undergo oxidation. Van Hise (22) considers magnetite the most important iron oxide which can be oxidized without hydration into hematite. The lower oxides of manganese and of chromium are other minerals subject to oxidation.

B. HYDRATION

The union of water with soil minerals is considered by some geologists as the dominant reaction in weathering. Not only does the iron oxide become hydrated, thus increasing in size and softness but also many other compounds like silicates, oxides, and carbonates form hydrous compounds.

Spheroidal weathering of rocks or exfoliation is common in the humid regions of Puerto Rico. Water seeps through the pores and cracks of rocks and leaches the soluble constituents and hydrates the insoluble. The phenomenon of increase in volume by hydration is well known, hence the strain produced by the expansion of this hydrated compound causes the rock to peel off in layers.

Merrill (13) working with granitic rocks of the District of Columbia found that the hydrated rock on exposure to the atmosphere was shortly reduced to the condition of sand. The term "slaking" is applied to this fast breaking-up of hydrated rocks.

C. CARBONATION

In regions of high rainfall the action of CO_2 on the decomposition of rocks is of considerable importance. Although there is only 0.03 per cent of CO_2 in the atmosphere, rainwater may contain as much as 0.45 per cent. The largest quantity of carbon dioxide comes from the decomposition of organic matter in the soil. The carbonic acid reacts with bases such as calcium and magnesium producing carbonates or bicarbonates.

Merrill (13) refers to the work of Muller who determined experimentally the dissolving action of carbonic acid on various minerals. A relative resistance of the minerals to the action of carbonated water was ascertained. Thus, hornblende was found to be more easily attacked than the feldspars. Microcline proved to be more resistant than oligoclase and apatite as soluble as the silicates.

D. SOLUTION

Since pure water is a very weak solvent for most minerals, the process of solution is brought about largely through the joint action of carbon dioxide and water, or by water containing traces of mineral acids, or by salt solutions. Among the materials most readily removed in solution are compounds of calcium, sodium, potassium and magnesium. The rocks which are more easily dissolved by water are limestone, gypsum and rocks cemented by calcium carbonate. The presence of water is of utmost importance in the other processes of chemical weathering.

E. DEPOSITION

The deposition reactions can be illustrated by the decomposition of silicates and separation of silica, and the precipitation of iron and aluminum by electrolytes encountered during their movements as colloids. These reactions are more active in the belt of cementation, but they also may occur in the zone of weathering.

Chemical rock decay has been repeatedly imitated in vitro. Jenny (8) discusses Daikuhara's method of leaching powdered rocks with carbonated water. It was found that the most resistant to decomposition was hornblende-andesite, while basalt was the most easily attacked. Granite and gneiss showed medium resistance.

Denison, Fry, and Gile (6) studied the weathering of muscovite and biotite from different horizons of soils of the Piedmont region. Although the climate influences the type of weathering of the minerals, the authors consider that the differences in the form of the minerals also determine the mode of weathering. They found out that weathered biotite contains higher percentages of alumina, silica and water and lower percentages of magnesia, potash, and iron, and the weathered muscovite is lower in potash and high in water.

Merrill (13) compared the mode of weathering of the rocks of two regions of similar moisture conditions but differing in temperature relations. He explained the variations obtained in these regions on the basis of difference in temperature, disregarding the mineralogical composition of the rocks.

Robinson and Holmes (19) in their studies of the climatic influences on the formation of colloids in the process of weathering found that the silicon dioxide-aluminum oxide ratio is broader in the humid temperate regions than in the humid tropical regions. Such a low ratio is an index of laterization, but it has been found that it does not occur always in the tropics.

Seki (20) worked with volcanic ash loams of Japan, which are the ashes of pyroxene andesites admixed with some biotite. This material is subject half of the year to a tropical to subtropical climate and another half year to a cold winter. The weathering of these soils shows a tendency towards laterization, as shown by low silicon dioxide-aluminum oxide ratio. He also describes them as being highly leached from alkaline bases.

Cobb (4) analyzed igneous rocks and the soils derived from them and found that the silicon dioxide-aluminum oxide ratio in acid igneous rocks was higher than in basic rocks.

Roberts (18) and Bennett (1) classify the Nipe clay found in Puerto Rico and Cuba respectively as a typical laterite, but there are several soils which are developed under similar environmental conditions and yet show podsolization.

Bonnett (2) working with a profile of Catalina clay, a lateritic soil type of Puerto Rico, found an accumulation of iron oxide and aluminum oxide in the surface horizon, as expected in the laterization process, but he did not find any evidence of the leaching of free silica to lower levels. The high moisture conditions were very favorable for the leaching of bases and soluble silica. Quoting Bonnet, "The silica of the parent rocks of the lateritic soils investigated is more subject to solution and leaching than is the silica of a parent rock (quartz diorite) of a non lateritic soil."

III. FACTORS INFLUENCING THE FORMATION OF PUERTO RICAN SOILS

A. INTRODUCTION

Puerto Rico is the smallest island and lies farther east in the Greater Antilles group, of which Cuba, Jamaica, and Haiti are the largest insular elements. It is bounded on the north and east by the Atlantic Ocean, on the south by the Caribbean Sea, and on the west by the Mona Passage. The island is about 450 miles east of Cuba, and about 1,400 nautical miles southeast of New York City.

Puerto Rico is nearly rectangular in shape. It is approximately 100 miles long and 35 miles wide and its area is 3,393 square miles. The population in 1940 was 1,869,245 or 549.8 people to the square mile. It has always been an agricultural island and its economy is based on three main cash crops: sugar cane, tobacco, and coffee. The best soils are devoted to sugar cane, which occupies 235,000 acres or 34.5 per cent of the land from which crops were harvested in 1935.

B. CLIMATE

Puerto Rico has a tropical, oceanic climate. The average winter temperature is about 73°F. and the summer average is about 78°F. The uniformity of the climate makes it nearly ideal for a 12-month growing season.

The average annual precipitation fluctuates from 26 inches on the southwest coast to nearly 200 inches on the highest peaks of the Sierra de Luquillo. The rainfall distribution does not show definite seasons, but rather a rainy period from May to November with torrential rains during the summer. The other six months are relatively dry, but many showers occur.

C. PARENT MATERIAL

Puerto Rico contains representatives of all the three types of rocks: igneous, sedimentary and metamorphic. The parent material has been produced through the process of weathering on rocks such as Tertiary limestone, Cretaceous limestone, shales, tuff and volcanic ash, igneous intrusions, such as granites and andesites, and metamorphic rocks, such as serpentine. These rocks are found in different rainfall belts and varying slope gradients which account for an amazing pattern of soils within short distances. On this account Puerto Rico is a very interesting place for studying the formation and morphology of soils. In such a small area there are classified 115 soil series with 352 soil types.

D. TOPOGRAPHY

Puerto Rico has a rough topography. A chain of mountains extending from the east to the west divides the island in two regions: a wet north and a dry south. This is surrounded by coastal plains which vary in width and origin along the entire coast. The northern section is characterized by deposits of limestone to the west and alluvial deposits to the east. Sugar cane fields flourish in the rich alluvial soils of the southern section.

On the north eastern section of the island there is an independent range of mountains called the Sierra de Luquillo. The highest peak rises to a height of 3,500 feet and is called el Yunque.

E. LIVING ORGANISMS

The native vegetation ranges from the desert shrub type in the arid sections to the typical rain-forest type in the wet tropical rain forests of Sierra de Luquillo. Under the latter conditions chemical changes are going on continually and the formation of soils is more rapid.

All the soils show visible effects of the microfauna activity. In the humid sections earthworms are active feeding on the soil organic matter and mixing the soil on which they live. On irrigated soils they have established themselves and assist in promoting crop production although they are not so numerous as in the upland soils in the humid sections. Other common inhabitants of Puerto Rican soils are white grubs, ants, termites, and nematodes, all of which assist in mixing plant residues and supplying a certain amount of fresh parent material to upper levels.

F. TIME

The soils of Puerto Rico are relatively recent. In places of heavy rainfall and on steep slopes the soils are young as a result of rapid weathering processes.

IV. Description of Areas Studied

A. LOS GUINEOS SOIL SERIES

The Los Guineos soil series is located in the tropical rain forest area of Puerto Rico. The region is mountainous and has an average rainfall of 200 inches. The area is covered by a dense growth of vegetation which is of a deciduous nature. The parent soil material is chiefly deep seated igneous rock, of which the quartz diorite included in this study is probably the most typical.

In the great soil groups it is classified in the zonal order, which includes those great groups of soils having well developed soil characteristics, products of the active influence of climate and vegetation on the parent material. It belongs to the Red and Yellow Podzolic group of the zonal order, which is described as a group of soils developed under forest vegetation in humid or subhumid warm climates. Usually the soil profile shows a thin organic-mineral layer over a highly leached grayish-brown, light-brown or brownish-gray horizon resting on a compact or plastic acid red (Red Podzolic soil) or yellow (Yellow Podzolic soil) layer and this over a red, gray, and brown mottled horizon (18).

Los Guineos clay is found on steep or very steep slopes and its profile is characterized by a 6 or 8-inch grayish brown surface soil which is a strongly acid and medium plastic clay. The subsurface soil is 3 to 6-inch brownish-yellow clay which rapidly changes to red plastic but permeable strongly acid clay. At a depth of about 3 to 4 feet a lighter red more friable acid clay is found. Rocks are found distributed throughout the whole profile and on the surface of the soil.

This soil is of very low productivity. The steepness of the slopes and the presence of rocks and stones do not allow the use of farm machinery to cultivate the land. Inadequate surface drainage also limits the production of crops in this land. About 50 per cent of the land is planted with coffee and in other less productive areas are raised grasses of low feeding value and trees of low value. In general the vegetation is dense and erosion is kept to a minimum.

B. JÁCANA SOIL SERIES

The Jácana soil series is located in the south western part of Puerto Rico in a region of low rainfall, approximately 25 inches annually. The typical parent material is andesitic in nature, such rocks being extrusive in origin. The soils in this arid south west coast occur at low elevations and have a slight to strongly alkaline reaction.

The Jácana clay belongs to the Reddish Brown soils, which is a zonal group of soils having a light brown slightly alkaline to strongly alkaline surface horizon, which grades through a light reddish-brown horizon into lighter colored calcareous soil and rests at a slight depth on a thick layer of accumulated lime.

The Jácana clay occurs in areas having less than 30 per cent slope. The surface soil consists of an 8-inch layer of friable alkaline slightly plastic clay or silty clay. This layer gradually changes to dense medium-plastic alkaline yellowish brown or light brown clay 8 to 10 inches thick, which grades through disintegrated volcanic rock and rests on hard bedrock at a depth ranging from 15 to 40 inches. The natural drainage of this soil is good. Due to excessive dryness, shallowness, and unfavorable relief, it is used almost exclusively for pasture. The grass is of excellent quality and during favorable rainfall conditions minor crops are produced.

V. EXPERIMENTAL

A. DESCRIPTION OF MATERIALS STUDIED

1. Los Guineos clay

The material selected for this study consisted of samples from a large exfoliated boulder approximately six feet in diameter, the central part of which consisted of slightly weathered quartz diorite, sample no. 174, encircled by a second layer of highly weathered rock, sample no. 175. Adjacent to this was a layer of buff colored clay-like material, sample no. 176. In the immediate neighborhood was found a sample of apparently fresh unweathered quartz diorite similar to that which made up the original boulder.

A second series of samples were taken from another exfoliated boulder, the center of which appeared to be quite fresh, sample no. 179. This was enclosed in a layer of clay, sample no. 178, about which was a dense shell of hard ferruginous material, sample no. 177.

The location of these samples was 65° 47′W., 18° 18.5′N.

2. Jácana clay

The samples for this study consisted of the apparent unweathered andesite, sample no. 1, weathered andesite, sample no. 2, and subsoil and surface soil which occurred in direct contact with the weathered andesite, samples no. 3 and 4. The soil was very shallow, about 18 to 20 inches was the depth of the total profile and there was very little vegetation. The location of these samples was 67° 8.5′W., 18° 3.5′N.

B. PREPARATION OF SAMPLES

The rock samples were crushed in a mill to a fine powder. After thorough mixing a portion was taken and passed through an 80 mesh screen.

A representative portion of each soil sample was finely ground in an agate mortar and passed through an 80 mesh screen.

The thin sections of the rocks for petrographic study were prepared by standard methods and were .03 mm. in thickness.

C. METHODS OF ANALYSIS

The various constituents of the rocks and soils were determined by standard methods of analysis.

The moisture content was determined by drying to constant weight in an oven at 110°C.

Ignition of the sample to constant weight at 475°C. was performed and the loss in weight calculated as percentage loss on ignition.

The samples were decomposed by fusion with sodium carbonate. The fused material was taken up in 5 N-HCl.

The silica was dehydrated, ignited and determined by difference after treatment with hydrofluoric acid (10).

The Fe, Al, Ti, and P were precipitated with ammonia at a pH of 6.7 and converted to oxides on ignition.

The mixed R_2O_3 precipitate was fused with potassium pyrosulphate and Fe_2O_3-TiO_2 were determined by means of the Jones Reductor (7) by titration with N/10 $KMnO_4$.

Calcium was determined by titration with N/10$KMnO_4$ of the calcium oxalate (7).

Magnesium and manganese were precipitated together according to the method of Dean and Truog (5). Manganese was then determined by the bismuthate method (7) and magnesium determined by difference.

Separate samples were used for the determination of potassium and sodium. These were decomposed by treatment with hydrofluoric acid, taken up with perchloric acid and evaporated to dryness. The perchlorates were dissolved in water. Aliquots were taken for the potassium determination by the sodium cobalt-nitrite method of Truog and Volk (23). Sodium was determined on another aliquot by the uranyl zinc acetate method as described by Liebig, Vanselow, and Chapman (11).

Phosphorus was determined colorimetrically by fusion of a sample with sodium carbonate, leaching the fused material with water and developing a blue color with ammonium molybdate and stannous chloride (21).

All analyses are reported on a dry basis.

VI. General Discussion

The results of the chemical analysis of the materials studied are set forth in Tables 1, 2, and 3, which include the amounts of the various oxides determined ordinarily in rock analysis and the silicon dioxide aluminum oxide ratios. In Table 4, the chemical compositions of the andesite and quartz diorite included in this study are compared. It will be observed that by comparing the analyses of samples no. 1 and no. 173, andesite and quartz diorite respectively, from a standpoint of chemical composition these two rock types are quite similar even though their physical and mineralogical characteristics are quite different. The quartz diorite is a deep seated plutonic rock, and the andesite is its volcanic equivalent. In other words, the origin of these two types of rock is similar, but the manner in which the molten magma crystallized to form the rock brought about a difference in physical and mineralogical characteristics; these differences will be discussed later.

The chemical similarity of these two rock types is best brought out by a comparison of their silicon dioxide aluminum oxide ratios. This comparison is in agreement with the findings of others. Clarke (3) describes the analyses of many rocks, and in Table 4 samples A and B are analyses of typical andesites and quartz diorites. It will be noticed that the silicon dioxide aluminum oxide ratios of these typical examples are quite similar to those of the samples studied. The ratio of sample no. 179 is somewhat narrower than in the other samples. This may be explained on the grounds that this rock being the core of an exfoliated boulder, as previously described, had been weathered somewhat as was revealed by petrographic study.

The calcium, sodium, iron, and magnesium content of these different rocks, although not exactly the same, show the same general trends. Variations in these may be due to differences in the feldspar content, in the case of the calcium and sodium, the type and variability of the ferromagnesium minerals influence the variations of iron and magnesium.

The variation in potassium is easily understood by the fact that no potash bearing minerals were observed in the petrographic study of the rocks included in this study. In some cases such potash bearing minerals as sanidine and muscovite have been reported in andesites and quartz diorites, but no such minerals were observed in the samples included in this work.

Manganese and titanium are normally present combined with iron in the ferromagnesium minerals and there is not much variation in these constituents. The phosphorus in the fresh rocks is in most cases due to small inclusions of apatite in the ferromagnesium minerals, which is quite typical of all igneous rocks.

The petrographic study of these rocks brings out in detail their physical and mineralogical differences. The quartz diorite is a coarse grained rock, the chief constituents of which are plagioclase feldspar of a composition approaching andesine, green hornblende, magnetite, brown biotite with inclusions of apatite and a small amount of quartz.

In the fresh rock, sample no. 173, these minerals show a minimum amount of decomposition products. In samples 174 and 175, strong evidences of weathering are apparent, the mineral most rigorously attacked being the feldspar. It must be recalled that these rocks occurred in a region of heavy rainfall and as a consequence have been subjected to considerable action by water containing considerable quantities of carbon dioxide. The weathering of these feldspars appears to have occurred first to form varying amounts of secondary zeolitic material. The feldspar crystals are being broken up by a network of zeolitic material, probably nontronite, which due to its expansion during formation has broken up the crystals to a marked degree. Such a reaction would be accompanied by a loss of calcium and very little if any loss of silicon, alumina or sodium. That such is the case can be observed by comparing the chemical analyses in Table 2. On the other hand, when such decomposition products are further broken down to form soils, (or clay in this case) large quantities of calcium and sodium would be lost due to the relatively unstable nature of zeolites and the residue left would consist largely of silica and alumina. This can be observed by comparing the analyses in Table 2, samples 173, 174, 175, and 176, and in Table 3, samples 178 and 179.

The manner in which the ferromagnesium minerals hornblende and biotite are decomposed in the weathered rock shows that here decomposition is of a hydrothermal nature, the same as in the case of the feldspars. The ferromagnesium minerals are undergoing a change to chlorite, particularly in the case of the biotite, which would liberate quantities of magnesium and iron. When the rock had become sufficiently weathered, then large quantities of magnesium and iron were removed. The magnesium is carried away in solution, and some of the iron may accumulate. This is the case as shown in Table 3, sample 177. Here the iron has accumulated in a dense shell which includes the clay and partially weathered core or rock. Due to the fact that the iron in quartz diorite occurs in the ferrous state, this change is relatively rapid. The process is analogous to podsolization.

In the case of the andesine the physical and mineralogical characteristics are quite different from the quartz diorite. The rock is fine grained and dense, consisting of two generations of feldspar; i.e. phenocrysts of feldspar approaching andesine in composition and much smaller crystals of the same feldspar. These are all inclosed in a ground mass of very finely divided magnetite and secondary products of the weathered feldspar. No primary ferromagnesium minerals are present, but a few pseudomorphs of chlorite, possibly after hypersthene or bronzite, were noted.

The minerals in the apparently fresh rock appeared to be quite weathered but not to the degree of that in the rock adjacent to the soil. In this sample the feldspars were weathered highly showing the presence of a zeolite probably scolecite. The formation of this zeolite would be accompanied by a slight loss of silica and very little, if any, loss of calcium or sodium. This is apparent in Table 1, samples 1 and 2.

The climatic conditions are here again an important factor. The low rainfall does not introduce enough moisture to break down these zeolites readily, hence, their preservation in the rock; even in the subsoil this relationship appears to hold. The relationships of iron, alumina, and silica appear to remain about constant for the rock, subsoil, and surface soil. The only constituents which are low in the surface soil are calcium and magnesium; all others remain constant or even tend to accumulate as in the case of iron and potassium.

VII. Summary and Conclusions

Two rock types, a quartz diorite and andesite, differing physically and mineralogically, but being similar chemically and occurring under different climatic conditions were studied chemically and petrographically and the results compared with the chemical characteristics of their residual clays and soils.

It was found that under different climatic conditions the feldspar of the rock weathered in about the same manner, but in one case the products of weathering were carried away due to excess in moisture; in the other case accumulations occurred. The products of weathering in the case of the quartz diorite, under extreme rainfall conditions, were practically all removed with the exception of the silica and alumina which combined to form a residual clay. Even in this case under extreme conditions the clay minerals forming the residue might be eventually broken down. In the case of the andesite, occurring under low rainfall conditions, the only constituents removed were calcium and magnesium; the other constituents remained about the same. The ferromagnesium minerals in the quartz diorite were also broken down by hydration, and iron was lost. In the case of the andesite, however, the iron being chiefly as magnetite was attacked very little in the process of weathering and very little change was observed.

In all cases the study of the silicon dioxide-aluminum oxide ratio is of material assistance in tracing the progress of these various weathering processes.

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X. APPENDIX

TABLE 1

*Chemical Composition of Andesitic Rock and Adjacent Soil. Climate, arid. Jácana Soil Series**

Sample No.	1	2	3	4
	%	%	%	%
SiO_2	61.61	51.15	52.70	54.81
Al_2O_3	17.50	20.40	16.98	16.43
Fe_2O_3	6.84	9.11	10.82	11.26
TiO_2	0.60	1.36	1.10	0.92
CaO	3.26	3.60	2.43	0.68
MgO	1.51	3.55	1.11	0.57
Na_2O	2.29	2.72	2.02	2.19
K_2O	0.45	0.45	1.31	1.57
MnO_2	0.27	1.34	1.38	0.89
P_2O_5	0.10	0.18	0.12	0.08
Loss on ignition	1.70	3.19	6.70	7.57
Total	96.13	97.05	96.67	96.97
$SiO_2 : Al_2O_3$	5.8:1	4.2:1	5.2:1	5.6:1

*1 Fresh andesitic rock
2 Weathered andesitic rock
3 Subsoil, 7″–19″
4 Surface soil, 0″–7″

TABLE 2

*Chemical Composition of Quartz Diorite and its Residual Clay. Climate, humid. Los Guineos Soil Series**

Sample No.	173	174	175	176
	%	%	%	%
SiO_2	60.37	60.84	54.14	74.65
Al_2O_3	17.37	17.83	18.24	13.98
Fe_2O_3	7.88	6.96	9.10	4.83
TiO_2	0.48	0.43	0.64	0.54
CaO	7.24	6.34	5.90	0.03
MgO	2.76	1.93	3.38	0.08
Na_2O	1.86	2.38	1.77	0.77
K_2O	0.73	1.16	0.74	0.20
MnO_2	0.12	0.75	0.28	0.00
P_2O_5	0.07	0.07	0.04	0.01
Loss on ignition	0.05	0.54	2.75	6.29
Total	98.93	99.23	96.98	101.38
SiO_2: Al_2O_3	5.9:1	6.2:1	5.0:1	9.0:1

* 173 Fresh rock
174 Slightly weathered quartz diorite
175 Weathered rock, quartz diorite
176 Buff colored clay

TABLE 3

*Chemical Composition of Quartz Diorite and its Residual Clay. Climate, humid. Los Guineos Soil Series**

Sample No.	179	178	177
	%	%	%
SiO_2	54.13	70.17	58.55
Al_2O_3	19.90	16.14	12.61
Fe_2O_3	8.17	5.96	20.60
TiO_2	0.53	0.59	0.55
CaO	4.66	0.03	0.03
MgO	2.74	0.09	0.15
Na_2O	1.20	0.76	0.49
K_2O	0.85	0.21	0.04
MnO_2	0.44	0.00	0.00
P_2O_5	0.03	0.01	0.01
Loss on ignition	4.89	7.45	8.07
Total	97.54	101.41	101.10
SiO_2: Al_2O_3	4.6:1	7.3:1	7.9:1

* 179 Core of exfoliated quartz diorite
178 Clay, between samples 179 and 177
177 Outer shell of rock

TABLE 4

*Comparison of the Composition of Andesite and Quartz Diorite and Other Typical Examples**

Sample No.	179	1	173	A	B
	%	%	%	%	%
SiO_2	54.13	61.61	60.37	62.64	58.57
Al_2O_3	19.90	17.50	17.37	17.82	16.10
Fe_2O_3	8.17	6.84	7.88	4.10	8.59
TiO_2	0.53	0.60	0.48	0.59	1.41
CaO	4.66	3.26	7.24	3.22	7.39
MgO	2.74	1.51	2.76	0.47	2.33
Na_2O	1.20	2.29	1.86	4.47	2.11
K_2O	0.85	0.45	0.73	4.99	1.01
MnO_2	0.44	0.27	0.12	0.04	0.18
P_2O_5	0.03	0.10	0.07	0.25	0.37
Loss on ignition	4.89	1.70	0.05	0.65	1.27
Total	97.54	96.13	98.93	99.24	99.33
SiO_2: Al_2O_3	4.6:1	5.8:1	5.9:1	5.7:1	6.1:1

* 179 Core of exfoliated quartz diorite weathered
1 Unweathered andesitic rock
173 Unweathered quartz diorite
A Typical andesite (Clarke)
B Typical quartz diorite (Clarke)