United States Department of the Interior

Geological Survey

Clay Mineralogy of Sediments from the Rio Cibuco System and the Adjacent Rivers and Insular Shelf of North-Central Puerto Rico

by

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Open-File Report 91-628

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ABSTRACT

The prolonged rainfall and intermittent dry seasons in the highlands of north-central Puerto Rico are conducive to lateritic weathering. This laterization has resulted in a fluvial and insular shelf clay mineral assemblage that is dominated by kaolinite-group minerals and smectite. Minor amounts of illite, mixed layer illite-smectite, gibbsite, and trace amounts of chlorite and vermiculite are also present. Small amounts of hematite, goethite, quartz, and feldspar occur along with the layer silicates in the clay fraction.

Variations in the clay-mineral assemblage are related to changes in the intensity and duration of the chemical weathering and in the composition of the underlying source rocks.

INTRODUCTION

This paper semiquantitatively assesses clay mineral abundances in the Rio Cibuco, Rio Grande de Manati, and Rio de la Plata river systems and on the adjacent shelf off northern Puerto Rico (Fig. 1). These results are used to comment on the weathering mechanisms and environment affecting soil development in the source areas and to examine the shelf processes controlling offshore sediment distribution.

Earlier work on fluvial (Ehlmann, 1968) and shelf (Breyer and Ehlmann, 1981) clay-mineral distributions along the northern coast of Puerto Rico was qualitative and limited to sediments associated with the Rio Grande de Manati system. However, these papers documented the relationship between conditions in the source area and clay mineralogy of the streams and insular shelf.

Puerto Rico, which is the smallest and easternmost island of the Greater Antilles, can be readily divided into an Early Cretaceous-Eocene volcanic-plutonic province, a carbonate province primarily of Oligocene and Miocene age, and Holocene coastal lowlands (Weaver, 1964). The volcanic-plutonic province forms an east-west mountain range (the Central Cordillera) that is composed mainly of marine volcanics (lava tuffs and lava breccias) and reworked pyroclastic rocks (Cox and Briggs, 1973). Associated with these volcaniclastic strata are intrusive igneous rocks. The bulk of these intrusives are granodiorite, but diorite, quartz diorite, gabbro, quartz monzonite, and serpentinites are locally common. The carbonate province rests on the flanks of the volcanic-plutonic province and is composed mainly of limestones with smaller amounts of marl, dolomite, and calcareous quartz sandstones (Monroe, 1973). Along the northern coast, this province dips to the north and displays a spectacular karst topography (Monroe, 1968; Monroe, 1976).

The island's rainfall is controlled by moisture-laden cloud systems that are driven by northeast trade winds and encounter the higher elevations of the Central Cordillera (Ehlmann, 1968; Bush and others, 1988). Inasmuch as the resultant precipitation falls mainly on the northern side of the mountains, most of the major rivers on the island have their headwaters in the Central Cordillera and drain to the north. The Rio Cibuco, which has a maximum discharge of about 27,400 cfs (776 m^3/s), is one of these rivers (Fig. 1).

The upstream portions of the Rio Cibuco, Rio de la Plata, and Rio Grande de Manati, like many of the northward-flowing rivers (Weaver, 1958), are actively downcutting into the Central Cordillera. Rapids and waterfalls are common. Terrigenous sediment eroded from the island is transported by these rivers to the northern insular shelf.

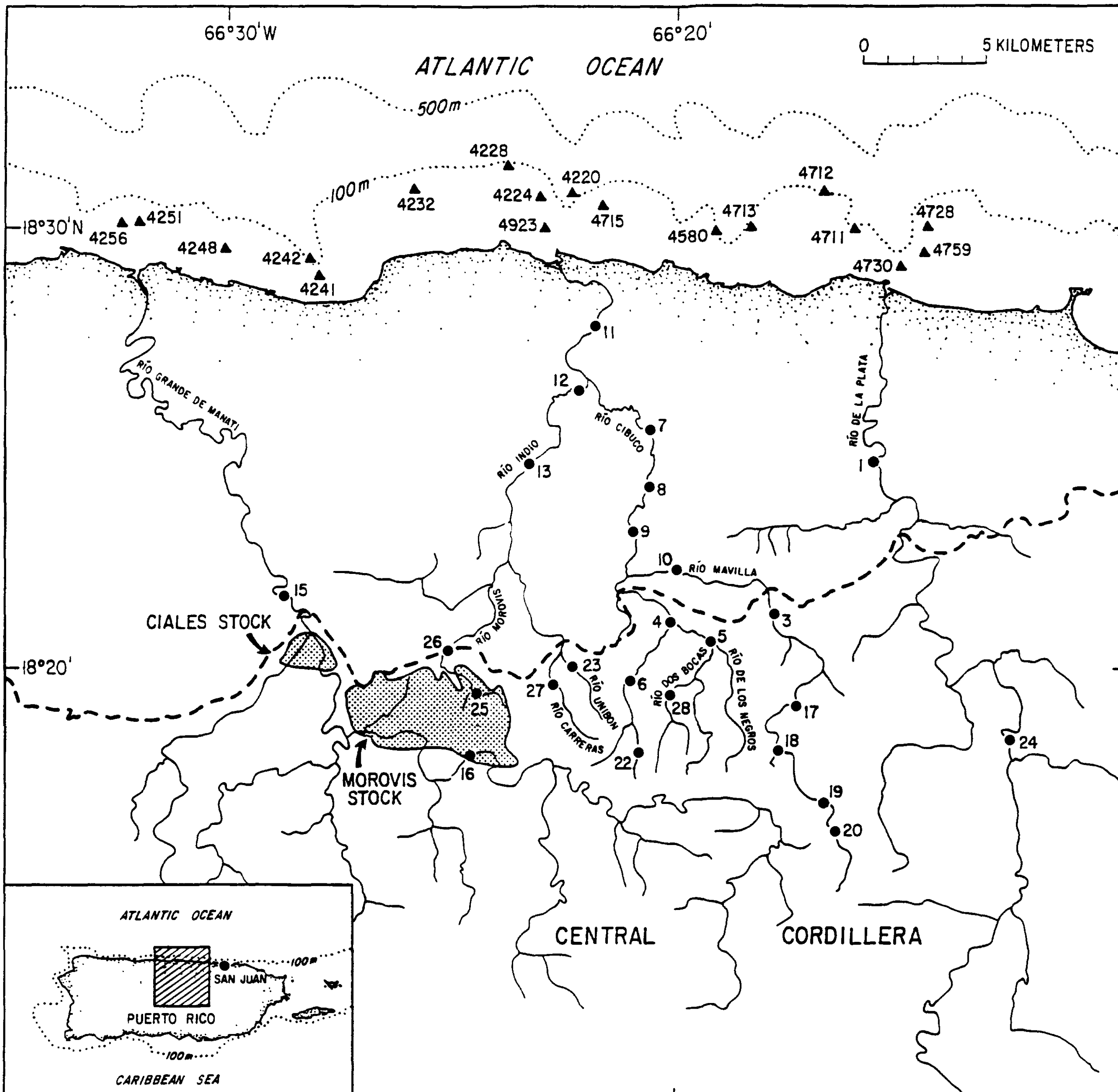

Figure 1. Map showing the locations of river (solid circles) and shelf (solid triangles) samples from north-central Puerto Rico. The dashed line separates rocks of the volcanic-plutonic province (south) from the limestone province (north). Inset shows location of study area on the island of Puerto Rico.

The shelf off northern Puerto Rico is an extremely high energy, wave-dominated environment (Schneidermann and others, 1976). This shelf ranges in width from 2-5 km and has a shelf break at a depth of 70-80 m. The dominant bottom-current direction on the northern shelf is to the west (Wood and others, 1975; Grossman, 1978); sediment distributions on the shelf are probably in equilibrium with the present-day oceanographic processes (Schneidermann and others, 1976).

METHODS

X-ray powder diffraction analyses were performed on 25 river bed samples and 18 shelf samples (Fig. 1). Particular care was taken to collect the river-bed samples at sites of recent deposition, such as the upstream ends of point bars and from channel bars at the base of rapids. The shelf samples, which were obtained from the Duke University sample repository, were collected as grab samples aboard the R/V Jean A.

The clay fraction (<2 μm) from each sample was separated by centrifuge and mounted as an oriented aggregate on a glass slide by a filter-membrane peel technique (Pollastro, 1982). Each oriented clay mineral sample was subjected to four treatments (air-drying, glycolation with ethylene glycol, heating to 400 °C, and heating to 550 °C) to determine which clay minerals were present.

Clay-mineral abundances were estimated by a method described by Biscaye (1965). Those minerals not included in this method (i.e. gibbsite) were estimated by comparing the sample diffraction peak areas and intensities with those from a collection of external standards. The semiquantitative estimates are reported in relative weight percent and are generally considered to be accurate to within 10 percent of their actual values; however, if only due to rounding errors, the lower values (<10 percent) may vary considerably more than this.

A scanning electron microscope (SEM) equipped with an energy-dispersive X-ray spectrometer was used to examine the composition and morphology of the individual clay mineral particles.

RESULTS

The results of the X-ray diffraction studies are presented in Table 1. Kaolinite-group minerals dominate most of the samples from both the rivers and the northern insular shelf. A strong asymmetric peak at 4.44 angstroms that is of greater intensity than a broad basal 001 peak at 7.3 angstroms, and broad plateau peaks between 2.56 and 2.31 angstroms in the unoriented aggregate analyses (Ehlmann, 1968) suggest that halloysite, rather than kaolinite, is the dominant kaolinite-group mineral present. Halloysite is of similar composition to kaolinite, but with additional water, and is one of the first weathering products of igneous glass and feldspar during hydrolysis (Kirkman, 1981).

Although X-ray diffraction results suggest that halloysite is more common than kaolinite, SEM observation of the crystal morphology of individual clay-mineral grains from the Rio Cibuco does not reveal any particles with the tubular habit commonly characteristic of halloysite nor does the squat ellipsoidal form of halloysite (Kirkman, 1981) ever exceed twenty percent. However, the pseudohexagonal plates and blocky morphologies more typical of kaolinite (Welton, 1984) are always present. In any case, a slight increase in the peak sharpness and intensity of the 7 angstrom 001 kaolinite-group diffraction peak in the downstream and shelf samples may suggest a greater contribution of kaolinite from

Table 1. Estimated mineral modes, in relative weight percent, determined from X-ray powder diffraction. A blank indicates that the mineral was not detected; T = trace (<1 percent).

SAMPLE NUMBER	LOCATION	SMECTITE	CHLORITE	MIXED LAYER ILLITE-SMECTITE	VERMICULITE	ILLITE	KAOLINITE-GROUP	GIBBSITE
Rio de la Plata System								
1	Rio de la Plata	32		1	T	6	60	T
24	Rio de la Plata	32		6	T	8	53	T
Rio Cibuco System								
11	Rio Cibuco	44		T		2	53	T
7	Rio Cibuco	31		1		4	63	T
8	Rio Cibuco	27		1	T	3	68	T
9	Rio Cibuco	23		2	T	5	69	
4	Rio Cibuco	34		2		T	63	
6	Rio Cibuco	17		4	T	2	77	
22	Rio Cibuco	14		4	T	6	75	T
10	Rio Mavilla	19		4	T	9	65	2
3	Rio Mavilla	8		10	T	11	67	3
17	Rio Mavilla	26	T	4		1	66	2
18	Rio Mavilla	27		4		5	63	1
19	Rio Mavilla	32		10	T	6	51	T
20	Rio Mavilla	15		11		3	69	2
5	Rio de los Negros	51		T		1	47	
28	Rio Dos Bocas	25		6		3	66	
12	Rio Indio	66		T		2	32	T
13	Rio Indio	77		1		1	20	
23	Rio Unibon	48	T	1		2	48	
27	Rio Carreras	45		T		T	53	1
26	Rio Morovis	49	T	T		3	46	1
25	Rio Morovis	65		T		1	33	T
Rio Grande de Manati System								
15	Rio Manati	14	T	6	T	4	75	T
16	Rio Manati	18		4		2	74	2
Northern Insular Shelf Samples								
4728		23		8	T	2	66	
4759		27		8	T	4	60	
4736		40		9	T	9	41	
4711		18		8	T	2	70	1
4712		20		9	T	1	69	
4713		22		8		2	67	T
4580		17		8	T	5	67	2
4715		19	T	9		3	67	1
4220		13	T	12		3	71	
4923		20		5	T	6	68	
4224		14	T	10		6	68	1
4228		16		5	T	3	75	
4232		16	T	10		4	69	
4241		15	T	8		4	72	
4242		15	T	11		4	69	T
4248		11	T	8		7	73	T
4251		2	T	5		4	88	T
4256		5		8	T	6	79	1

the areas underlain by Tertiary carbonates.

In river and shelf sediments associated with the Rio de la Plata and Rio Cibuco River systems, smectite occurs in greater amounts than in river and shelf sediments associated with the Rio Manati. It is commonly the most abundant clay in the western tributaries of the Rio Cibuco system. The 001 smectite peaks on the X-ray diffraction profiles are usually broad suggesting poor crystallinity or the presence of some mixed layering.

Although they are present in small amounts throughout the rivers studied, gibbsite, mixed-layer illite-smectite, and illite are slightly more common in the Rio Mavilla sediments. The gibbsite, a hydrate of aluminum, is produced by desilication of the kaolinite-group minerals. No other form of uncombined aluminum, besides gibbsite, was identified in any of the X-ray diffraction patterns. Greater quantities of mixed-layer illite-smectite in the shelf sediments may reflect contributions from another source or interparticle diffraction effects caused by geochemical changes as these clays entered the marine environment (Sawhney and Reynolds, 1985). The broad nature and small size of the illite 001 peaks at 10 angstroms made differentiation of this mineral group from "hydrated halloysite", which also has 10 angstrom 001 spacing, more complicated. Therefore, the abundance of illite may be slightly overestimated and the abundance of kaolinite-group minerals slightly underestimated. Vermiculite occurs in trace amounts more commonly in the rivers and on the shelf of eastern portion of the study area; chlorite is more common to the west. No vermiculite-smectite or chlorite-smectite mixed-layer clays were identified in the river or shelf samples.

Small amounts of clay-sized goethite, hematite, and quartz are ubiquitously present in the X-ray diffraction patterns of the river and shelf sediments. The goethite diffraction peaks are broad suggesting that the crystallites are of small size or are poorly crystalline, and perhaps grade into amorphous iron oxide. Goethite is generally more abundant than hematite, possibly indicating high water activity and high organic matter concentrations in the eroding soils (Milnes and others, 1987). The peak areas, and presumably therefore the concentrations, of the iron oxides generally decrease downstream and onto the shelf.

Small amounts of feldspar are also present in most of the samples. Plagioclase is the dominant feldspar, especially in sediments from the Rio de la Plata, the Rio Mavilla, Rio de los Negros, and Rio Dos Bocas tributaries of the eastern Rio Cibuco system, and the shelf samples. Although probably never more abundant than plagioclase, potassium feldspar is usually more common in the Rio Grande de Manati and in the Rio Unibon, Rio Carreras, Rio Morovis and Rio Indio tributaries of the western Rio Cibuco system than in the Rio de la Plata or in the eastern part of the Rio Cibuco system. Quartz is also generally more abundant in the clay fractions of samples from the western portion of the study area.

DISCUSSION

Prolonged rainfall and intermittent dry seasons under the tropical conditions present in north-central Puerto Rico are conducive to lateritic weathering of the igneous intrusive and volcaniclastic sedimentary source rocks underlying the highland areas near the island divide. Exposed bedrock in the study area and elsewhere along the northern slope of the Central Cordillera (Weaver, 1958) is weathered to a yellowish brown. Many of these rocks are speckled with weathered feldspars and with rusty patches representing the remains of iron- and manganese-bearing minerals. The weathered highland areas of the Central Cordillera are eroded by the seasonally high rainfall and the sediments are fluvially transported to the shelf. The clay minerals present in the Rio Cibuco system, in the adjacent rivers, and on the insular shelf clearly reflect this intense lateritic weathering. The presence of gibbsite (an aluminum oxide) is an indicator of the intensity of this weathering and signals the onset of bauxitization.

The subtle changes in the smectite/kaolinite-group abundances across the study area are probably the result of two main factors. First, because smectite is often an early weathering product of igneous rocks in saprolites, lateritic soil development may be incomplete in areas where more equal mixes of kaolinite-group minerals and smectite occur (Breyer and Ehlmann, 1981). The Late Cretaceous tuffs, volcanic breccias, tuffaceous sandstones and siltstones, and lavas that underlie most of the igneous portion of the study area are extensively, but not deeply weathered (Briggs and Akers, 1965). Together, soil and saprolite are typically less than 2 m thick and only locally exceed 4 m in depth (Berryhill, 1965). The general lack of a deep weathering profile, including soil and saprolite, in a tropical area where formation of deep residual material would be expected is the result of rapid erosion. High relief and heavy rainfall are factors in the rapid sediment removal (Berryhill, 1965). Local areas that are blanketed by thicker lateritic profiles and, therefore, contain sediments that have been subjected to more prolonged weathering coincide with plutonic rocks (i.e. the granodioritic Ciales and Morovis Stocks). These deposits are more common in the western portion of the study area where kaolinite-group minerals are more dominant.

Second, the clay mineralogy of the weathering products is related to the original composition of the source rocks. The rivers in the study area drain a variety of rock types, some of which are discussed above. Basaltic and andesitic rocks, which contain olivine, hornblende, and pyroxenes, are more abundant in the eastern portion of the study area. These minerals commonly alter to smectite under alkaline lateritic conditions. Granodiorites, which contain about 15% quartz (Berryhill, 1961, 1965), are more abundant in the western portion of the study area. Inasmuch as rocks that alter to the kaolinite-group minerals are usually the more acid types (Deer and others, 1966), the kaolinite-group distribution also suggests that source rock composition may be a factor in controlling the changes in clay mineralogy. The greater abundance of quartz and potassium feldspar in the western portion of the study area is also clearly related to the presence of the Morovis and Ciales Stocks (>14% quartz; >20% orthoclase) and numerous smaller potassium-rich intrusive bodies (alkali syenites; >40% orthoclase), associated with faults, that are widely distributed in this area (Berryhill, 1965). These intrusives contribute the orthoclase to the streams and rivers that cross them. Hydrothermal alteration of the source rocks, which is locally present throughout the study area (Hildebrand, 1961; Cox and Briggs, 1973), may also affect the result of the lateritic weathering process.

Comparisons of Rio Manati sediments with those from other rivers on the east, south, and west coasts of Puerto Rico (Ehlmann, 1968; Norton, 1974) demonstrate that areas characterized by more arid conditions and less intense chemical weathering contain major smectite and lesser amounts of kaolinite-group minerals. Although differences in annual rainfall could result in variations in the rate and intensity of weathering, hydrologic studies in the Rio de la Plata, Rio Cibuco, and Rio Manati drainage basins show no appreciable difference in annual precipitation (Bush and others, 1988).

An earlier study (Schneidermann and others, 1976) has shown that the presence or absence of a fluvial contribution is a significant factor affecting the areal distribution of sediment textural characteristics on the insular shelf of Puerto Rico. The inverse relationship that exists between smectite and kaolinite-group mineral concentrations on the northern insular shelf is probably primarily the result of differences in the clay-mineral assemblages of the fluvial sources. Smectite is more common in the eastern portion of the study area and progressively decreases toward the west; kaolinite-group minerals are more common in the west and decrease toward the east. Although much of the fluvial sediment is eventually transported across the narrow insular shelf and down slope toward the Puerto Rico Trench (Fuerst, 1979), elevated concentrations of smectite extend far to the west of the shelf off the Rio Cibuco showing that clay mineral distributions on the shelf are controlled by the westerly-flowing bottom currents (Wood and others, 1975; Grossman, 1978). Kaolinite-group minerals are more abundant relative to the other clay minerals in these marine sediments than they are in the rivers, perhaps reflecting input from beach erosion or small streams that drain only the Holocene coastal lowlands, input from relict Pleistocene strata that underlie the thin patchy cover of recent sediments on the shelf, or differential transport.

ACKNOWLEDGMENTS

We thank R. Circe', C. DeLorey, and W. Schwab for their assistance in the field and S. Carter and J. Hathaway for critically reviewing this report.

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