Silt heavy-mineral distributions in the Rio Cibuco
system and adjacent rivers of north-central Puerto Rico
by

Poppe, L.J.[1], Commeau, J.A.[1], and Luepke, G.[2]

[1]U.S. Geological Survey, Woods Hole, MA 02543

[2]U.S. Geological Survey, Menlo Park, CA 94025

ABSTRACT

Mineralogical studies of the silt-sized fraction of sediment samples from the Rio de la Plata, Rio Grande de Manati, and rivers of the Rio Cibuco system in north-central Puerto Rico have examined the effects of lateritic weathering and explored the silt for possible economic heavy minerals. This fraction, which is slightly enriched in heavy minerals relative to the sand fraction, is predominantly detrital, but contains a strong authigenic component. The detrital silt heavy-mineral fraction is dominated by an amphibole-garnet-pyroxene-epidote assemblage. The authigenic silt heavy-mineral fraction, which is largely an artifact of the lateritic weathering, is dominated by iron oxides and altered grains. This laterization has dramatically altered the relative percentages of the minerals originally present in the source rocks.

Lateral variability within the Rio Cibuco system is considerable and related to the changing composition of the underlying source rocks along the course of the river and its tributaries. Important differences between the silt heavy-mineral assemblages present in the Rio de la Plata, Rio Grande de Manati, and rivers of the Rio Cibuco system and between the heavy-mineral assemblages in the silt- and sand-sized fractions are also apparent.

We detected no minerals containing significant amounts of Cu, Ni, Sn, or Zn in any of the river-sediment samples. However, elevated concentrations of titanium-bearing minerals and small amounts of cerargyrite, chromite, gold, and manganese oxides occur.

INTRODUCTION

This paper describes the results of a reconnaissance study on the silt-sized heavy and light-mineral fractions of the Rio Cibuco system and the adjacent rivers of north-central Puerto Rico. Earlier studies of heavy-mineral distributions in Puerto Rico (Guillou and Glass, 1957; Grossman, 1978; Lincoln, 1981; Pilkey and Lincoln, 1984; Bush et al., 1988) were limited to the sand fraction. These studies concentrated on the sand fraction for several reasons that include: (1) the surface tension of organic heavy liquids used in the separatory process made it difficult to achieve complete submergence of the finer-grained particles; (2) petrographic analyses were difficult to perform on the finer grain sizes due to the physical limits on the resolution of optical microscopes; (3) X-ray powder diffraction (XRD) is too crude to detect many of the mineral species that occur in trace amounts; and (4) most commercial placer deposits exploit the sand fraction. These problems have dissuaded researchers from studying the scientifically- and, possibly, commercially-important silt-sized fraction. However, the recent introduction of the heavy liquid sodium polytungstate separation method (Callahan, 1987; Gregory and Johnston, 1987) and the availability of automated image analyzers (AIA) for scanning electron microscopes (SEM) equipped with energy-dispersive X-ray spectrometers (EDS) now facilitates the study of silt-sized heavy minerals (Commeau et al., 1992).

The purpose of this report is to describe the diagnostic characteristics of the silt heavy- and light-mineral fractions. These descriptions are used to determine whether this assemblage is controlled by source, weathering, or diagenetic processes, to compare the silt fraction mineralogy with that of the sand fraction, to evaluate the potential for placer and concentrated lode deposits within the Rio Cibuco system, and to discuss what the silt fraction tells us about the sedimentary processes operating in the rivers of north-central Puerto Rico.

REGIONAL GEOLOGY

Puerto Rico, which is the smallest and easternmost island of the Greater Antilles, can be readily divided into an Early Cretaceous-Eocene volcanic-plutonic terrane, a carbonate terrane primarily of Oligocene and Miocene age, and Holocene coastal lowlands (Weaver, 1964; Fig. 1). The volcanic-plutonic terrane forms an east-west mountain range (the Central Cordillera) that is composed mainly of volcanic tuffs, volcanic breccias, and andesitic and basaltic lavas mainly of the Los Negros, Avispa, Pozas, and Perchas Formations (Berryhill, 1965; Nelson, 1967; Cox and Briggs, 1973). Occurring with these volcanics are marine, reworked pyroclastic rocks of the Magueyes, Cibuco, and Palmarejo Formations and a few light gray-reddish limestones and limestone breccias of the Corozal Limestone. Associated with these volcanic strata are intrusive igneous rocks. The bulk of these intrusives are granodiorites and quartz diorites, but diorites, gabbros, and quartz monzonites are locally common in dikes and sills. Secondary mineralization associated with vein deposits of hydrothermal origin is also common.

The carbonate terrane rests on the flanks of the volcanic-plutonic terrane and is composed mainly of limestones with smaller amounts of marl, dolomite, and calcareous quartz sandstones of the Cibao Formation, Lares Limestone, and Mucarabones Sand (Nelson, 1967; 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 et al., 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. One of these rivers, the Rio Cibuco, has a 175 km^2 drainage basin and a maximum discharge of about 27,400 cfs (776 m^3/s; Lopez and Colon-Dieppa, 1973; 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 cutting into the Central Cordillera. Rapids and waterfalls are common in these upstream areas, suggesting highly oxygenated conditions. Meandering downstream sections of these rivers have a lower gradient and appear to have lower flow velocities. Terrigenous sediment eroded from the island is transported by these rivers to the northern insular shelf.

FIELD AND LABORATORY METHODS

The river samples were collected during 1990-1991 by driving along the banks of the Rio de la Plata, Rio Grand de Manati, and rivers of the Rio Cibuco system and sampling at conveniently accessible points (Figs. 1,2). As in a previous study of the sand fraction of the Rio de la Plata (Bush et al., 1988), particular emphasis was placed on taking samples at points where accumulations of placer mineral were likely to occur; for example at the upstream ends of point bars and at channel bars located just downstream from rapids. The samples are texturally representative of the fluvial bedload at these sites; no field processing, such as the removal of gravel by sieving or concentration of the heavy fraction with standard gold pans, was attempted.

The silt-sized sediments (particles of 62-µm decreasing to those hydraulically greater than or equivalent to quartz spheres of 4-µm) were isolated from the sand and gravel fractions by wet-sieving and from the clay fraction by decantation prior to the heavy-liquid separations. A random subsample of the remaining silt fraction was suspended in a small amount of distilled water, added to a solution of sodium polytungstate, and disaggregated by sonification. The suspension was then rapidly evaporated at 60ºC in a convection oven to the proper specific gravity (S.G. 2.85) and centrifuged to separate the light and heavy minerals. The bottoms of the centrifuge tubes were then frozen in liquid nitrogen to trap the heavy minerals. The unfrozen supernatant containing the light mineral fraction was then washed from the tube. The light- and heavy-mineral fractions were independently suction-mounted onto pre-weighed 0.45 µm Millipore filters. These filters were rinsed, dried, and weighed to determine the relative weight percents of the heavy- and light-mineral fractions.

Splits of both the heavy and light silt fractions were analyzed by XRD; additional splits of the heavy-mineral fraction were analyzed by SEM/AIA/EDS. The splits for XRD analysis were ground, mounted on glass slides, and X-rayed as randomly oriented aggregates. Semiquantitative estimates of the minerals present were made by comparing the diffraction peak areas and intensities of each sample with the areas and intensities recorded from a collection of external standards (Goehner, 1982).

The splits for the SEM/AIA/EDS analysis were dispersed on carbon mounts (Fig. 3A). In the SEM, the computer-driven electron beam automatically scanned the field of particles, the AIA system measured their sizes, shapes, and grayness (an indirect measure of atomic weight), and the EDS system acquired an X-ray spectrum from each particle. SEM/AIA/EDS analyses of the heavy-mineral grains continued until at least 300 grains were analyzed for each sample.

Most heavy-mineral species or groups can be readily identified during the SEM/AIA/EDS analyses by their distinctive composition and morphology. Polymorphs and minerals with overlapping compositions were combined into "macrogroups" and, if possible, differentiated by XRD analysis. For example, XRD analyses of the heavy-mineral fractions were specifically checked for the presence of individual minerals or groups in the amphiboles+pyroxenes+tourmaline+olivine macrogroup that could not be differentiated by the SEM/AIA/EDS system or spodumene, kyanite, andalusite, and sillimanite that would appear chemically to be part of the beryl+topaz macrogroup. If no diffraction maxima characteristic of a given mineral were observed in any of the XRD patterns, then this mineral was assumed to be absent.

As with other heavy-mineral separatory techniques, the separation of phyllosilicates is difficult because the specific gravities of the layer silicates may straddle that of the heavy liquid (S.G. 2.85) and not all of the grains are removed in the heavy-mineral residue. Therefore, SEM/AIA/EDS and XRD analyses were used to determine the concentrations of the layer silicates present in the heavy and light mineral fractions. These concentrations have been subtracted and reported separately (Poppe et al., 1991b). See Poppe et al. (1991a, 1992) and Commeau et al. (1992) for a more complete discussion of the techniques employed during this study.

The sand fraction (2.0-0.062 mm) from some of the river sediment samples was analyzed for comparison with the silt fraction. The sand heavy- and light-mineral fractions were separated with tetrabromoethane (S.G. 2.96) and a Franz magnetic separator using standard procedures. The minerals were identified with both binocular and petrographic microscopes. Selected grains were examined with a SEM to check the optical identifications.

RESULTS

The concentrations of silt- and sand-sized heavy minerals in the river samples are given in Table 1. These concentrations average 14.6% and 11.9% for the silt and sand fractions, respectively. Although no downstream trends in the total concentration of the heavy-mineral fraction are apparent, the concentrations vary greatly from river to river. For example, concentrations of sand and silt heavy minerals are usually lower in the Rio Indio and Rio Morovis samples. Conversely the concentrations for both the silt- and sand-fraction heavy minerals are consistently greater in the Rio Mavilla sediments.

The individual silt-fraction heavy-mineral species and groups identified in the river sediment samples and their population percents are listed in Table 2. The titanium-bearing minerals, which are common accessory minerals in igneous, hydrothermal, and plutonic rocks, are present in every sample from the study area. Ilmenite (ilmenite and ilmenomagnetite) usually dominates the titanium-bearing minerals, but smaller amounts of the TiO_2 group, which is composed of rutile, anatase, brookite, and leucoxene, and sphene are almost always present. Many of the grains in the TiO_2 group are small (<8 μm), bladed, sometimes twinned, euhedral crystals of rutile; most of the ilmenite grains have corroded surfaces covered with lattices of diagenetic rutile prisms (Fig. 3B,C). Ilmenite is more common in the Rio Grande de Manati than in any of the Rio Cibuco system tributaries (Fig. 4A).

Because the EDS system can not detect oxygen or carbon, the iron oxides and iron carbonates are combined into the hematite+goethite+magnetite+maghemite+ siderite group. XRD analyses show that hematite dominates this group in most of the samples from the Rio Cibuco system. Goethite, which is present in minor amounts in every sample, is the most abundant mineral from this group in the sample from the Rio Las Carreras. Small amounts of aluminum present within the iron oxide and iron carbonate group suggest that some of the goethite may be Al-bearing (Mendelovici et al., 1979). Magnetite (Fig. 3D) is also present in every sample and is the most abundant iron oxide in the Rio de la Plata, Rio Morovis, and Rio Grand de Manati sediments. However, broadened shoulders on the higher two-theta-angle side of the magnetite XRD peaks suggests that at least some maghemite may also be present. Siderite occurs only in small amounts (<2%) and only in the downstream samples collected from over the Tertiary carbonate terrane. Mineral grains of the manganese oxide+manganosiderite+ferromanganese group occur in trace amounts in almost half of the river sediment samples. All of the Mn-bearing grains contain at least some iron.

Pyrite, which occurs in the bedrock as vein fillings and along faults (Berryhill, 1965), was the only silt-fraction sulfide mineral detected in any of the samples. This mineral is most common in the samples from the carbonate terrane, where it often occurs in its authigenic framboidal form (Fig. 3E). Pyrite grains from the more oxygenated mountain streams over the igneous terrane are occasionally euhedral (Fig. 3F), but usually rounded, partly altered detrital fragments that exhibit greater Fe/S ratios than normal pyrite suggesting that some conversion to iron oxide has occurred. Although small barium deposits have been described just west of the Rio Grande de Manati (Cox and Briggs, 1973), only one sample from the Rio Cibuco contained traces of barite.

Zircon, corundum, and beryl+topaz, which are common igneous accessory minerals, occur in the silt fraction of most samples from the study area (Fig.5A). Although not positively identified, occasional small peaks in the XRD patterns at 5.54 angstroms suggest that traces of anadalusite, prehaps formed by contact metamorphism, may occur in the beryl+topaz group of some samples. Minor amounts of apatite+vivianite group minerals occur in the silt sediments of the Rio Cibuco, Rio Morovis, and Rio Grande de Manati, but no monazite was detected in any of the river sediment samples.

The silt detrital heavy-mineral suite is dominated by an amphibole-garnet-pyroxene-epidote assemblage (Fig. 5B,C). Together, these minerals range in concentration between 45.4% and 76.6% of the samples. The abundances of the minerals in this assemblage, and some of the other silt heavy-mineral species and groups, vary spatially in the study area. The amphiboles and garnets are usually more abundant in the Rio Cibuco system; the pyroxenes and epidote are usually more common in the Rio de la Plata and Rio Grande de Manati (Fig. 4B). Chemical composition of the mineral grains suggests that the main garnet group mineral present is probably almandine.

The Rio Cibuco and Rio Mavilla are the only two rivers with enough sample locations to examine along-stream trends in the silt fraction. Although the data contain substantial variability, some along-stream trends are readily apparent. For example, garnet increases in abundance upstream in the Rio Cibuco (Fig. 4C). Conversely, the highest epidote and amphibole abundances occur downstream and decrease upstream to the south.

Most of the detrital mineral grains have corroded surface textures (Fig. 5B). This corrosion has progressed on many of the mineral grains to the degree where they could not be identified because of their extensive alteration. These altered grains, which range in concentration from 0.88% to 9.12% of the silt heavy fraction, are somewhat rounded and resemble microconcretions that are usually composed of cemented mixtures of Fe, Al, Si, and Ti oxides.

Minerals of obvious commercial importance were specifically targeted during the SEM/AIA/EDS analyses. Chromite, an oxide of iron and chromium, occurs in trace amounts in most of the river sediment samples from the study area (Fig. 5D). Chromite exceeds 1% of the silt heavy-mineral fraction in one sample from the Rio Mavilla and in the sample from Rio Dos Bocas. Most of the samples in this study contained at least a trace of gold. However, flakes of relatively pure gold were found in only two samples. Both samples were from the weathered igneous terrane, one from the Rio Cibuco and one from the Rio Mavilla. These gold particles are 0.6-7.0 μm in diameter. The remaining gold occurred as minute (<0.3 μm) particles intimately associated with much greater amounts of iron oxide and, as such, were sorted into the hematite+goethite+magnetite+maghemite+siderite group during the SEM/AIA/EDS analysis. Silver occurs in the form of cerargyrite and ranges in population percent (relative to numbers of particles rather than weight) up to 2.0% of the heavy-mineral fraction (Fig. 5E). The cerargyrite grains, which are present in 19 of the 25 samples from both the igneous and carbonate terranes, are small, averaging only 0.34 μm in diameter. The high specific gravity of gold and silver makes these finer-grained particles hydraulically equivalent to silt. Because of the small particle size in which they occur, the weight percent of the gold and silver actually present is only about 10% of the value reported as population percent. No mineral grains containing significant concentrations (>1%) of Cu, Ni, Sn, or Zn were detected in any of the samples.

The silt light-mineral fraction in the Rio Cibuco system is dominated by quartz. Most of this quartz undoubtedly originated from the erosion of granodiorites and quartz diorites (Nelson, 1967), but some probably came from the alteration products of weathered glass shards in the tuffs (Berryhill, 1961) and hydrothermally emplaced linings in open fractures (Pease, 1960). Plagioclase, which is always more common than K-feldspar, occurs in amounts greater than, or relatively equal to quartz in the Rio de la Plata and Rio Grand de Manati. The feldspar grains are extensively corroded (Fig. 5F) and, based on XRD analyses, partly replaced by smectite and halloysite (Poppe et al., 1991b). The results of this study are presented on a calcium carbonate-free (calcite+aragonite) basis. Although XRD analyses of the silt light mineral fraction showed that most samples from the Rio Cibuco system, Rio de la Plata, and Rio Grande de Manati contained very little or no calcium carbonate, the samples from the Rio Indio contained about 3-7% calcite, perhaps suggesting some active down-cutting of the stream bed of that river into the underlying Tertiary limestones.

DISCUSSION

Prolonged rainfall and intermittent dry seasons under the tropical conditions present in north-central Puerto Rico are conducive to lateritic weathering of the mafic source terrane underlying the highland areas near the island divide. Because of these lateritic conditions, the exposed bedrock in the study area and elsewhere along the Central Cordillera (Weaver, 1958) is weathered to a yellowish brown. The silt-fraction minerals present in the Rio Cibuco system and adjacent rivers, like those in the clay (Ehlmann, 1968; Poppe et al., 1991b) and sand fractions, clearly reflect this intense lateritic weathering and several examples are readily apparent. First, the abundance of bladed authigenic rutile crystals and presence of chemically leached ilmenite grains covered with trellis structures of rutile suggest that at least some of the individual rutile grains were probably formed diagenetically during the chemical leaching of Fe from the ilmenite and released transport-related abrasion (Valentine and Commeau, 1990; Poppe et al., 1991a). Second, laterization concentrates Si, Fe, Al, and Ti (Allen, 1948). Altered grains composed almost entirely of the oxides of these elements are common in the silt heavy-mineral fraction. Third, free quartz is only present in small or trace amounts in the source rocks except in the granodiorites of the Morovis and Ciales stocks and the quartz diorites and monzonites where quartz may make up as much as 20-25% of the source rocks (Weaver, 1958; Lidiak, 1965; Fig. 1), and in a few scattered hydrothermally altered zones. The dominance of quartz in the detrital, silt light-mineral fraction and the corroded, altered condition of the remaining feldspars suggests that most of the feldspars are destroyed during the weathering process.

Because of the short, steep nature of the rivers, the along-stream trends observed in the Rio Cibuco (Fig. 4C) are probably not related to preferential sorting. Inasmuch as the Rio Cibuco and its tributaries are rapidly eroding the rocks from at least ten formations, numerous intrusives, and undivided units (Berryhill, 1965; Nelson, 1967), the along-stream trends and the variability within these trends are probably related to dilution due to the increasing distance from an individual source rock and the diversity of the contributing rock types. For example, the silt heavy-mineral fractions from samples 4, 6, and 22 in the Rio Cibuco and sample 20 in the Rio Mavilla have low amphibole/pyroxene ratios due to the underlying clinopyroxene-rich basaltic tuffs of the Los Negros Formation (Nelson, 1967). Sediment samples from just downstream in these rivers contain much higher concentrations of amphiboles due to input from a large, hornblende-rich, quartz diorite intrusive (Nelson, 1967; Fig. 1). Contact metamorphism of the basaltic tuffs during emplacement of the intrusive may also be responsible for the elevated garnet concentrations in these four upstream samples.

Comparisons of the silt-fraction mineralogy with the sand-fraction mineralogies from previously conducted studies and from some preliminary results on the samples collected during this study (Table 3; Fig. 6) suggest that the compositions of these fractions differ markedly. For example, work near the mouth of the Rio de la Plata (Pilkey et al., 1987; Bush et al., 1988) and in beach sands along the northern coast (Guillou and Glass, 1957) found that magnetite makes up 30-40% of the carbonate-free, sand-sized heavy-mineral fraction, but the entire iron oxide+iron carbonate group comprises less than 10% of the Rio de la Plata silt heavy-mineral fraction. Similarly, magnetite comprises 77.4% of the sand heavy-mineral fraction in sample 26 from the Rio Morovis (Table 3), but the silt iron-oxide+iron-carbonate group averages only about 9.3% in this river. Garnet, which averages 24% of the silt heavy-mineral fraction in the river sediment samples, is present only as trace to small amounts (1-15%) in the sand heavy-mineral fraction of the river and beach sediments. Bush et al. (1988) reported that rutile and leucoxene do not constitute any significant percentage of the sand heavy-mineral fraction and analyses of the sand heavy mineral fraction of the river sediments samples from this study revealed similar values. However, the TiO_2 group averages 2.0% of the silt heavy-mineral fraction in the rivers. Ilmenite and altered grains are usually more common in the sand fraction; tourmaline and olivine are more common in the silt fraction.

Minor deposits of gold, silver, copper, manganese, and monazite have been previously reported in the study area (Berryhill, 1965; Nelson, 1967; Meyerhoff, 1933; Cox and Briggs, 1973; Pilkey and Lincoln, 1984; Bush et al., 1988). Most of these deposits are associated with veins and, in the case of some of the gold and all of the monazite, placers.

Most of the gold detected during the SEM/AIA/EDS analyses occurred as very small crystals encrusted with iron oxides. This close association of gold with iron oxides in lateritic environments, which has been previously discussed by Mann (1984), Bhaskara Rao (1987), and Nair et al. (1987), occurs when the gold is dissolved from the parent rocks and is reprecipitated in the weathering crusts. Because of the small, unconcentrated nature of the river sediment samples, the limited quantities of gold detected during this study does not preclude the possibility that deposits of economic value exist. Sample size averaged about 642 g. More complete, accurate numbers could have been generated for gold if the heavy fractions were magnetically concentrated (gold should be found in the least magnetic fraction) and if more grains were analyzed during the SEM/AIA/EDS analysis.

The cerargyrite (AgCl or horn silver), which is found in small amounts throughout the study area, was probably formed by the oxidation of argentite (Ag_2S). The universal presence of chlorine in hydrothermal waters, especially in the marine-reworked volcanic sandstones present in the study area, and the insolubility of AgCl make the occurrence of cerargyrite common in the oxidized zones above silver-bearing ore deposits (Lindgren, 1933). However, silver solubility increases under conditions of low Ph, high Eh, and increasing chloride concentration, despite the limited solubility of AgCl, because silver also forms the soluble chloride complexes of $AgCl_2^-$ and $AgCl_3^{-2}$ (Sillen and Martell, 1964; Mann, 1984). Inasmuch as earlier work has shown that the conditions in the highlands are acidic (Norton, 1974) and because the abundance of hematite is evidence for a strongly oxidizing environment, at least the first two conditions are clearly present in the weathered igneous terranes of Puerto Rico. Therefore, much of the silver originally present as secondary mineralization in the eroding hydrothermal vein deposits within the igneous terrane (Hildebrand, 1961) may be mobilized and removed from the source rocks in the dissolved state and not represented in the fluvial sediments. If this is the case, then unweathered veins with commercially significant concentrations of silver may exist at relatively shallow depths in the study area.

Small deposits of copper, which are associated with secondary sulfide mineralization in veins lining fractures, have been reported at thirteen locations in the area drained by the rivers in this study (Cox and Briggs, 1973). Interestingly, no Cu-bearing mineral grains (Cu >1%) were detected in the silt heavy-mineral fraction. Explanations for this absence may include: (1) copper precipitates under surface conditions (higher Eh and pH) as a very minor constituent in the hydrous iron oxides in such small quantities that it is not separately identified, (2) the copper is dissolved during weathering and erosion and not transported in the particulate state, (3) the copper is confined to a different size class (i.e. colloidal or sand), or (4) the sample sites were too far from the sources. However, no copper minerals have been detected in the sand fraction. Because the silver is usually associated with copper (Cox and Briggs, 1973) and because silver was also detected in many of the river sediment samples, one of the first two explanations is most likely correct.

Monazite has been reported in concentrations of as much as 9% of the sand heavy-mineral fraction in samples from the Rio de La Plata, Rio Cibuco, and northern insular shelf of Puerto Rico (Pilkey and Lincoln, 1984; Bush et al., 1988). However, the absence of monazite in both the sand- and silt-sized river sediment samples from this study and chemical analyses of the sand fraction (D. Bush, Duke University, oral communication, 1991) makes these earlier results highly suspect.

Possible commercial concentrations of the minerals found in the river sediments during this study may occur upstream in eroding veins and shear zones or downstream in placer deposits on the insular shelf. Earlier work has shown that the sand heavy-mineral fraction on northern Puerto Rico's narrow, high-energy shelf is in equilibrium and exhibits strong seaward sorting (Schneidermann et al., 1976; Pilkey and Lincoln, 1984). This sorting is based on the seaward decrease in the energy of wave-driven bottom currents and the specific gravities and characteristic sizes of the heavy-mineral grains. Inasmuch as individual silt-sized heavy-mineral species are also concentrated in narrow zones within shelf environments because of their hydraulic equivalence (Poppe et al., 1991a), a likelihood exists for the occurrence of silt-fraction placers at the mouths of rivers and in ancient shorelines off rivers with upstream fluvial placer and concentrated lode deposits.

SUMMARY

We offer the following conclusions about silt-sized mineral distributions in the rivers of north-central Puerto Rico.

(1) Heavy-mineral concentrations are high in the river sediments and average 14.6% and 11.9 % in the silt and sand fractions, respectively. Comparisons of individual heavy-mineral species and group abundances between the silt and sand fractions reveal marked differences.

(2) The unaltered, detrital silt heavy-mineral fraction in the Rio Cibuco system is dominated by an amphibole-garnet-pyroxene-epidote assemblage. Pyroxenes are more common than amphiboles in the Rio de la Plata and Rio Grande de Manati sediments; ilmenite is most common in the Rio Manati. Along-stream changes in the detrital, silt heavy-mineral fraction are probably related to the underlying, rapidly-eroding source rocks, rather than to sorting.

(3) Lateritic weathering has dramatically altered the silt mineralogy and produced a significant authigenic component. This authigenic component is dominated by iron oxides and altered grains; grains of bladed rutile and leached ilmenite are common. Altered, corroded feldspar grains are a major part of every light-mineral fraction.

(4) Small amounts of silver, chromium, and gold and elevated concentrations of the titanium-bearing minerals occur in the river sediments. However, the potential for fluvial and, presumably, offshore placer mineral resources of other elements is probably limited.

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REFERENCES

Allen, V.T., 1948, Formation of bauxite from basaltic rocks of Oregon: Econ. Geol., v. 43, 619-625.

Bhaskara Rao, A., 1987, Laterized gravel bed: a new guide horizon for lateritic gold: Chem. Geol., v. 60, p. 287-291.

Berryhill, H.I., 1961, Ash-flow deposits, Ciales Quadrangle, Puerto Rico and their significance: U.S. Geol. Sur. Prof. Paper 424, p. B224-B226.

Berryhill. H.I., 1965, Geology of the Ciales Quadrangle, Puerto Rico: U.S. Geol. Sur. Prof. Bull. 1184, 116 p.

Briggs, R.P. and Akers, J.P., 1965, Hydrologic map of Puerto Rico and adjacent islands: U.S. Geol. Sur. Hydrol. Invest. Atlas HA-197, 1 sheet.

Bush, D.M., Hyman, L., and Priddy, R., 1988, Heavy mineral resource potential - Rio De La Plata, Puerto Rico: Rept. to the Puerto Rico Dept. Nat. Res., Duke University, Durham, NC, 128 p.

Callahan, J., 1987, A nontoxic heavy liquid and inexpensive filters for separation of mineral grains: Jour. Sediment. Pet., v. 57, p. 765-766.

Commeau, J.A., Poppe, L.J., and Commeau, R.F., 1992, Separation and identification of the silt-sized heavy-mineral fraction in sediments: U.S. Geol. Sur. Circ. (in press).

Cox, D.P., and Briggs, R.P., 1973, Metalogenic map of Puerto Rico: U.S. Geol. Sur. Misc. Geol.

Invest. Ser. Map I-721, 7 p.

Ehlmann, A.J., 1968, Clay mineralogy of weathered products and of river sediments, Puerto Rico:
Jour. Sediment. Petrol., v. 38, p. 885-894.

Gregory, M.R., and Johnston, K.A., 1987, 1987, A nontoxic substitute for hazardous heavy liquids –
aqueous sodium polytungstate solution: New Zealand Jour. Geol. Geophy., v. 30, p. 317-320.

Grossman, Z.N., 1978, Distribution and dispersal of Manati river sediments: Puerto Rico north
insular shelf: unpublished Master's thesis, Dept. of Geology, Duke Univ., Durham, NC.

Guillou, R.B. and Glass, J.J., 1957, A reconnaissance study of the beach sands of Puerto Rico: U.S.
Geol. Sur. Bull. 1042 I, p. 272-305.

Lidiak, E.G., 1965, Petrology of andesitic, spilitic, and keratophyric flow rock, north-central Puerto
Rico: Geol. Soc. Amer. Bull., v. 76, p. 57-88.

Lincoln, R.B., 1981, Heavy mineral distribution in fluvial and marine environments - north coast of
Puerto Rico: unpublished Master's thesis, Dept. of Geology, Duke Univ., Durham, NC, 101 p.

Lindgren, W., 1933, Mineral Deposits: McGraw Hill, New York, 930 p.

Lopez, M.A. and Colon-Dieppa, E, 1973, Magnitude and frequency of floods in Puerto Rico: Puerto
Rico Coop. Water Res. Investig., Data Release PR-9, 63 p.

Mann, A.W., 1984, Mobility of gold and silver in lateritic weathering profiles: some observations
from western Australia: Econ. Geol., v. 79, p. 38-49.

Mendelovici, E., Yariv, S., and Villaba, R., 1979, Aluminum-bearing goethite in Venezuelan
laterites: Clays and Clay Min., v. 27, p. 368-372.

Meyerhoff, H.A., 1933, Manganese in Puerto Rico: Revista Obras Publicas Puerto Rico, 12, p. 489-

491.
Monroe, W.H., 1973, Stratigraphy and petroleum possibilities of middle Tertiary rocks in Puerto Rico: Amer. Assoc. Petrol. Geol. Bull., v. 57, p. 1086-1099.
Monroe, W.H., 1976, The karst landform of Puerto Rico: U.S. Geol. Sur. Prof. Paper 899, 69 p.
Nair, N.G.K., Santosh, M., and Mahadevan, R., 1987, Laterization as a possible contributor to gold placers in Nilambur Valley, southwest India: Chem. Geol., v. 60, p. 309-315.
Nelson, A.E., 1967, Geologic map of the Corozal quadrangle, Puerto Rico: U.S. Geol. Sur. Misc. Invest. Ser. Map I-473.
Pease, M.H., 1960, Structural control of hydrothermal alteration in some volcanic rocks in Puerto Rico: U.S. Geol. Sur. Prof. Paper 400-B, p. B360-363.
Pilkey, O.H. and Lincoln, R.B., 1984, Insular shelf heavy mineral partitioning: northern Puerto Rico: Jour. Mar. Mining, v. 4, p. 403-414.
Pilkey, O.H., Bush, D.M., and Rodriguez, R.W., 1987, Bottom sediment types of the northern insular shelf of Puerto Rioc; Punta Penon to Punta Salinas: U.S. Geol. Sur. Misc. Invest. Ser. Map I-1861.
Poppe, L.J., Commeau, J.A., and Valentine, P.C., 1991a, Mineralogy of the silt fraction in surficial sediments from the outer continental shelf off southeastern New England: Jour. Sediment. Petrol., v. 61, p. 54-64.
Poppe, L.J., Commeau, J.A., and Luepke, G., 1991b, Clay mineralogy of sediments from the Rio Cibuco system and the adjacent rivers and insular shelf of North-Central Puerto Rico: U.S. Geol. Sur. Open-File Rept. 91-628, 14 p.

Poppe, L.J. and Commeau, J.A., 1992, Mineralogy of the silt fraction in surficial sediments from the
United States mid-Atlantic shelf, slope, and rise: Mar. Geol., v. 104, in press.

Schneidermann, N., Pilkey, O.H., and Saunders, C., 1976, Sedimentation on the Puerto Rico insular
shelf: Jour. Sediment. Pet., v. 46, p. 167-173.

Sillen, L.G. and Martell, A.E., 1964, Stability constants of metal ion complexes: London Chem. Soc.
Spec. Pub. 17, 754 p.

Valentine, P.C. and Commeau, J.A., 1990, Fine-grained rutile in the Gulf of Maine – diagenetic
origin, source rocks, and sedimentary environment of deposition: Econ. Geol., v. 85, p. 862-
876.

Weaver, J.D., 1958, Utado Pluton, Puerto Rico: Geol. Soc. Amer. Bull., v. 60, p. 1125-1141.

Weaver, J.D., 1964, Guidebook for a field trip in Puerto Rico, 22-24 Novenber 1964: Mayaguez,
Univ. Puerto Rico, 40 p.