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# Geochemical evidence for African dust and volcanic ash inputs to terra rossa soils on carbonate reef terraces, northern Jamaica, West Indies

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## Abstract

The origin of red or reddish-brown, clay-rich, “terra rossa” soils on limestone has been debated for decades. A traditional qualitative explanation for their formation has been the accumulation of insoluble residues as the limestone is progressively dissolved over time. However, this mode of formation often requires unrealistic or impossible amounts of carbonate dissolution. Therefore, where this mechanism is not viable and where local fluvial or colluvial inputs can be ruled out, an external source or sources must be involved in soil formation. On the north coast of the Caribbean island of Jamaica, we studied a sequence of terra rossa soils developed on emergent limestones thought to be of Quaternary age. The soils become progressively thicker, redder, more Fe- and Al-rich and Si-poor with elevation. Furthermore, although kaolinite is found in all the soils, the highest and oldest soils also contain boehmite. Major and trace element geochemistry shows that the host limestones and local igneous rocks are not likely source materials for the soils. Other trace elements, including the rare earth elements (REE), show that tephra from Central American volcanoes is not a likely source either. However, trace element geochemistry shows that airborne dust from Africa plus tephra from the Lesser Antilles island arc are possible source materials for the clay-rich soils. A third, as yet unidentified, source may also contribute to the soils. We hypothesize that older, more chemically mature Jamaican bauxites may have had a similar origin. The results add to the growing body of evidence of the importance of multiple parent materials, including far-traveled dust, to soil genesis.

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## 1. Introduction

Red or reddish-brown, clay-rich soils (“terra rossa”) and bauxites (Al-rich soils) on carbonate substrates are found on several continents and numerous islands in the Caribbean and western Atlantic, the Mediterranean, and the Pacific. The origin of these visually striking soils has been the subject of debate for decades. [Schaetzl and Anderson \(2005\)](#) review the possible modes of origin that have been proposed for terra rossa soils. In some cases, an in situ origin of the soils is not difficult to ascertain because there is abundant non-carbonate material in the host sediment, and weathering of these primary minerals can explain the clay-rich nature of the soils. Problems arise, however, when attempts are made to determine the origin of clay-rich soils on carbonate rocks of high purity. For example, [Tracey et al. \(1964\)](#) and [Birkeland \(1999\)](#) showed

that unreasonable amounts of carbonate would be required to produce soils by this process on carbonate terrains in the Marianas Islands (Guam and Rota) of the Pacific. In the case of Rota Island, the entire island would have to have been dissolved in order to produce the observed soil profiles, a physical impossibility ([Birkeland, 1999](#)).

[Muhs et al. \(1987\)](#) summarize four possible modes of origin that have been described by previous workers who have studied soils and bauxites on Caribbean and western Atlantic carbonate islands, or islands with significant carbonate terrains. One is the traditional residual hypothesis, with accumulation of insoluble residues from dissolution of the host carbonate rock. A second mechanism is transportation of fluviially entrained clays from topographically higher positions (local, external sources) to lower carbonate surfaces. Two other processes require sediment inputs from distant, external sources. One of these is weathering of volcanic ash that has fallen on the carbonate surfaces and the other is weathering of fine-grained eolian sediments (dust) that have origins in distant regions.

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In the Caribbean basin and western Atlantic Ocean region, there are many carbonate islands, or at least islands with significant carbonate terrains, including the Florida Keys, Bermuda, Bahamas, Barbados, and parts of Jamaica (Fig. 1). Approximately two-thirds of Jamaica (Fig. 2) is underlain by limestone bedrock of Tertiary or Quaternary

age (McFarlane, 1977). The limestones of Jamaica host widespread, thick, red, and clay-rich terra rossa soils and bauxites (Fig. 2). Indeed, Jamaica is one of the world’s leading producers of bauxite mined for aluminum (Patterson et al., 1986). In this paper, we examine the properties of terra rossa soils on some of the younger carbonate substrates of Jamaica. A recent study reports varying degrees of influence of volcanic ash and African dust on the genesis of soils on other carbonate islands of the Caribbean and western Atlantic (Muhs et al., 2007a). Here, we test the hypothesis that Jamaican soils may have been similarly affected by long-range transport of African dust.

## 2. Previous studies of soil and bauxite genesis on Jamaica

### 2.1. Residual accumulation from limestone impurities

Scholten and Andriess (1986) invoked a residual origin for reddish-brown, clay-rich soils developed on Tertiary limestone in the western part of Jamaica. Many previous investigators have appealed to the same process to explain the origin of Jamaican bauxite (Schmedeman, 1948, 1950; Hartman, 1955; Hill, 1955; Hose, 1963; Clarke, 1966; Sinclair, 1967, 1976). The main arguments against a residual origin are that there are simply too few impurities in most island carbonates to account for the amount of observed soil. Hartman (1955) reports that much of the White Limestone Group (Tertiary) and Coastal Limestone Group (Tertiary and Quaternary) rocks are composed of carbonates of exceptional purity, with CaO-plus-loss-on-ignition contents exceeding 99%. Thus, formation of a meter-thick terra rossa soil could require complete dissolution of 100 m of limestone.

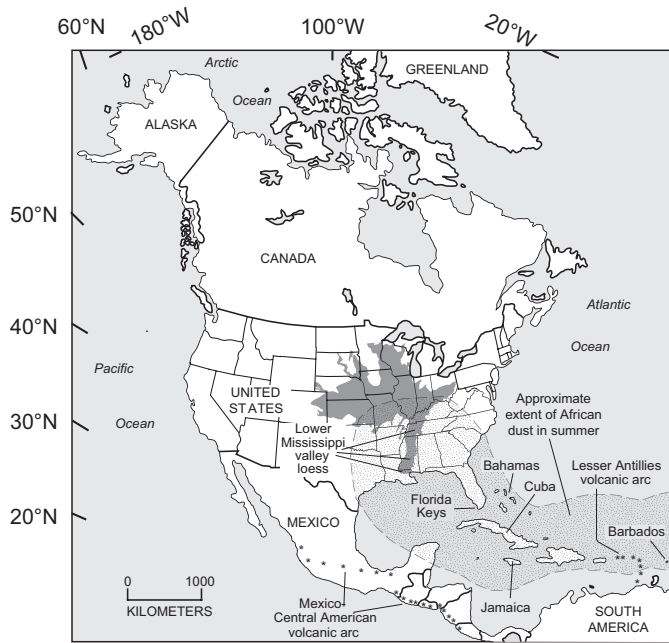


Fig. 1. Map of North America, the Caribbean basin, Jamaica and other islands referred to in text. Also shown are the distribution of loess (from compilations of Bettis et al., 2003; Muhs and Bettis, 2003) and approximate extent of African dust in summer, based on 1983–1992 TOMS satellite data and studies by Prospero and Carlson (1972), Prospero (1999), Perry et al. (1997), and Kallos et al. (2006).

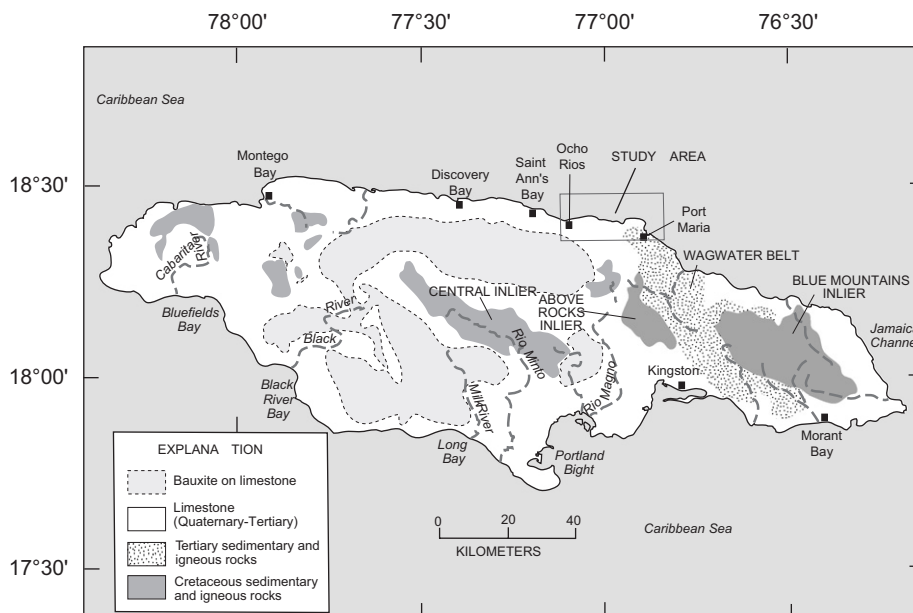


Fig. 2. Map of simplified bedrock geology of Jamaica (from McFarlane, 1977; Jackson et al., 1989) showing distribution of limestone-hosted bauxite (modified from Lyew-Ayee and Stewart, 1982) and major geographic features.

## 2.2. Fluvial origin from higher landscapes

A fluvial origin has been used to explain some occurrences of bauxite on carbonate rocks in Jamaica and Haiti (Zans, 1959; Kelly, 1961; Chubb, 1963; Boulegue et al., 1989). On Haiti, Boulegue et al. (1989) propose a mechanism whereby kaolinite develops as an alteration product of basalt weathering and is subsequently transported to, and trapped in, karst depressions in younger limestones. Following this “entrapment” in karst depressions, dissolution of silica results in the alteration of kaolinite to gibbsite and the formation of bauxite. Ahmad et al. (1966) propose that insoluble residues in limestone are the ultimate source of bauxite soils on Jamaica, but also recognize that soils are far too thick to explain accumulation by this mechanism alone. They hypothesize that the great thicknesses of bauxitic soils are a result of redistribution by erosion and sedimentation. However, because bauxite covers a significant portion of Jamaica and is present on some of the highest parts of the western half of the island (Fig. 2), it is difficult to envision this process as an explanation for many bauxite deposits.

## 2.3. Weathering of volcanic ash

Because many low-latitude carbonate islands are adjacent to active volcanic island arcs in the Caribbean, volcanic ash is a potential source of soil clays. Bauxites on pre-Quaternary limestones of Jamaica have long been considered to have developed primarily from Miocene volcanic ash falls (Burns, 1961; Waterman, 1962; Comer, 1974, 1984; Comer et al., 1980).

Jamaica is situated approximately midway between the active Lesser Antilles island arc and the active volcanic arcs of Central America and Mexico, ~1500 km from each chain (Fig. 1). Isopach maps of late Quaternary tephras from Central American and Mexican volcanoes show dispersal patterns mainly to the north, into the Gulf of Mexico and to the south, into the eastern Pacific Ocean (Drexler et al., 1980). Little ash from this volcanic chain appears to be deposited eastward in the Caribbean Sea, although Drexler et al. (1980, their Fig. 6) show a trace amount of ash recorded in a core taken in waters to the north of Cuba. Studies of the 1982 eruption of El Chichón volcano in Mexico show that ash reached altitudes as high as 17–31 km in the stratosphere (Matson, 1984). In the latitudes of El Chichón and Jamaica (17–18°N), this means that ash dispersal could have taken place either to the west, in the stratosphere, and/or to the east in the upper troposphere (Sigurdsson et al., 1980). Indeed, satellite images taken on 4 April 1982 record an ash cloud moving from El Chichón to the east, in the direction of Cuba and Jamaica (Matson, 1984).

It is also possible that ash erupted from the Lesser Antilles island arc (Fig. 1) can reach Jamaica, some 1500 km to the west of the volcanic arc. Evidence from deep-sea cores indicates that ash falls in the Caribbean

region have been common throughout the Quaternary (Sigurdsson et al., 1980; Reid et al., 1996). Clay-rich soils on Quaternary reef terraces of Barbados, east of the Lesser Antilles island arc, appear to have developed to a great extent from volcanic ash falls, based on both isotopic studies (Borg and Banner, 1996) and trace-element-geochemical data (Muhs et al., 2007a). On the other hand, Sigurdsson et al. (1980) point out that ash from Quaternary volcanic eruptions in the Lesser Antilles island arc is transported mainly to the east, due to ejection of volcanic particles into the upper troposphere, where winds are westerly. Thus, whereas this mechanism may be viable for soil genesis on Barbados (east of the island arc), it is less certain as a process for Jamaica (west of the arc). Nevertheless, Carey and Sigurdsson (1980) report ash in a marine core 1200 km to the west of the Lesser Antilles island arc. They suggest that ash dispersal to the west is possible via transport in the stratospheric upper-air easterlies, above an altitude of 17 km.

## 2.4. Derivation of soils from airborne dust

A potential source of soil parent material for Jamaica and other islands in this part of the Caribbean is African dust, carried west across the Atlantic Ocean (Fig. 1). The dust-bearing “Saharan Air Layer,” near its sources in Africa, can reach altitudes as high as 5–7 km. Farther west, dust concentrations are greatest at altitudes of 1.5–3.7 km, within the lower troposphere and the zone of the northeasterly trade winds. Dust from Saharan storms can reach the island of Barbados (Fig. 1) within about a week after departure from the western African coast (Prospero et al., 1970, 1981; Prospero and Carlson, 1972; Prospero and Lamb, 2003). Based on analyses of satellite imagery, aerosol sampling networks, and back-trajectory calculations, the sources of this eolian dust are the Sahara and Sahel regions of Africa (Prospero et al., 1970, 1981, 2002; Prospero and Nees, 1986; Goudie and Middleton, 2001; Caquineau et al., 2002). In summer, dust from Africa is transported at least as far north as Florida (Prospero and Nees, 1987; Prospero, 1999) and very likely into the central and eastern United States (Perry et al., 1997; Kallos et al., 2006).

Interestingly, almost four decades ago, Land and Epstein (1970, p. 191) hypothesized that African dust could be a parent material for terra rossa soils on emergent reefs of Jamaica. Lyew-Ayee (1984) pointed out the geochemical similarity between Cuban bauxites and dust collected in the Caribbean, when portrayed on a  $\text{TiO}_2\text{--Al}_2\text{O}_3\text{--Fe}_2\text{O}_3$  ternary diagram. Pye (1988) suggests, on the basis of work in Australia by Brimhall et al. (1988), that African dust could be the source of aluminum enrichment in Jamaican bauxites. Muhs et al. (1990) report the same possibility for younger soils on Jamaican limestones, which we re-examine in the present paper.

Another potential source of dust to Jamaica is the distal, fine-grained component of North American loess. Loess in

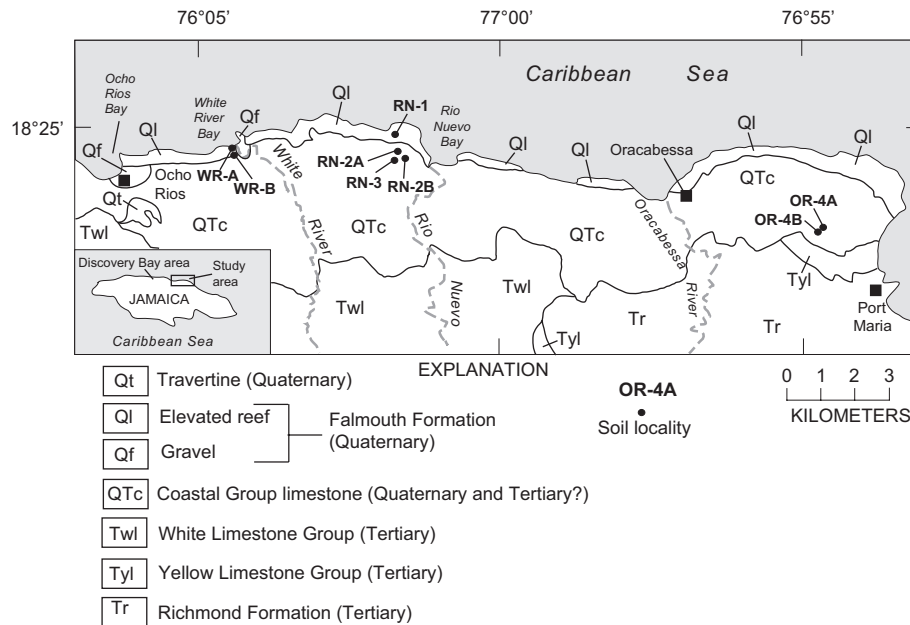


Fig. 3. Map of a portion of the northern coast of Jamaica, showing Tertiary and Quaternary geology. Redrawn from the Ocho Rios and Port Maria 1:50,000 geologic quadrangles (Henry, 1978a, b).

the lower Mississippi River valley was deposited mostly to the east of the river, indicating winds from the west or northwest, consistent with paleowinds documented elsewhere in central North America (Bettis et al., 2003; Muhs and Bettis, 2003). Because Jamaica is situated to the southeast of this major loess belt, it is possible that the fine-grained component (e.g., particles <20  $\mu\text{m}$  diameter) of this loess might have been transported southeastward and provided soil parent material for the island. Data presented by Muhs et al. (2007a) indicate that soils on the Florida Keys and the Bahamas may have been affected by both African dust and North American loess.

### 3. Study area, geology, and uncertainties in geochronology

We studied soils on the north coast of Jamaica, where flat-lying carbonate rocks of Quaternary and Tertiary age are best exposed (Zans et al., 1962; McFarlane, 1977). The most detailed studies of young carbonates on Jamaica have been conducted on the north-central coast, near Discovery Bay (Fig. 2). Land and Epstein (1970) and Land (1973, 1991) identified two emergent reef units in this area, called the Falmouth Formation and Hope Gate Formation. The two reefs form marine terrace landforms and have been mapped in the Discovery Bay area by Boss and Liddell (1987). The upper surface of the Falmouth Formation is  $\sim 5\text{ m}$  above sea level (a.s.l.) and abuts the older, topographically higher Hope Gate Formation. U-series ages of corals from the Falmouth Formation indicate that this unit dates to the last interglacial period,  $\sim 125,000\text{ yr BP}$  (Moore and Somayjulu, 1974; Szabo, 1979). Previously, the Hope Gate Formation was thought to be middle Pleistocene (Land, 1973); however, Land

(1991) reported  $^{87}\text{Sr}/^{86}\text{Sr}$  values from carbonates in the Hope Gate Formation that suggest latest Pliocene to earliest Pleistocene ages ( $\sim 2\text{ Ma}$ ). This older age estimate is consistent with the fauna of the formation, which includes a number of extinct species (Stemann et al., 2004).

A greater number of emergent reefs can be found farther east along the northern coast of Jamaica between Ocho Rios and Port Maria (Figs. 3 and 4). On the 1:50,000-scale geologic maps of this area, only the Falmouth Formation is mapped separately; older carbonate reefs are included within the Coastal Group Limestone shown in Fig. 3 (Henry, 1978a, b). Nevertheless, Zans et al. (1962), Cant (1970, 1972, 1973), and Horsfield (1973, 1975) report four prominent, emergent reef terraces between the Rio Nuevo-Oracabessa area and Port Maria (Fig. 4). Cant (1970) reports these reefs as  $\sim 1\text{--}15\text{ m a.s.l.}$  (terrace 1),  $58\text{--}70\text{ m a.s.l.}$  (terrace 2),  $94\text{--}119\text{ m a.s.l.}$  (terrace 3), and  $131\text{--}180\text{ m a.s.l.}$  (terrace 4), with perhaps three additional (minor) terraces at intermediate elevations. Cant (1970, 1972, 1973) correlates terrace 1 in the Oracabessa area with the Falmouth Formation ( $\sim 125,000\text{ yr BP}$ ), and terrace 2 with the Hope Gate Formation, which he estimates to be  $\sim 200,000\text{--}310,000\text{ yr BP}$ , based on an assumption of a constant uplift rate. Correlation of terrace 2 at Oracabessa was made before Land (1991) reported his Sr-isotope data. Thus, if Cant's (1970, 1972, 1973) uplift rate age estimate is correct, terrace 2 does not correlate with Land's (1991)  $\sim 2\text{ Ma}$  Hope Gate Formation. Cant (1970) reports that terrace 4 at Oracabessa has sediments with reversed magnetism and it is therefore older than the Brunhes-Matuyama paleomagnetic boundary at about  $780,000\text{ yr BP}$  (Spell and McDougall, 1992). When we visited Cant's (1970, 1972, 1973) terrace sequence near



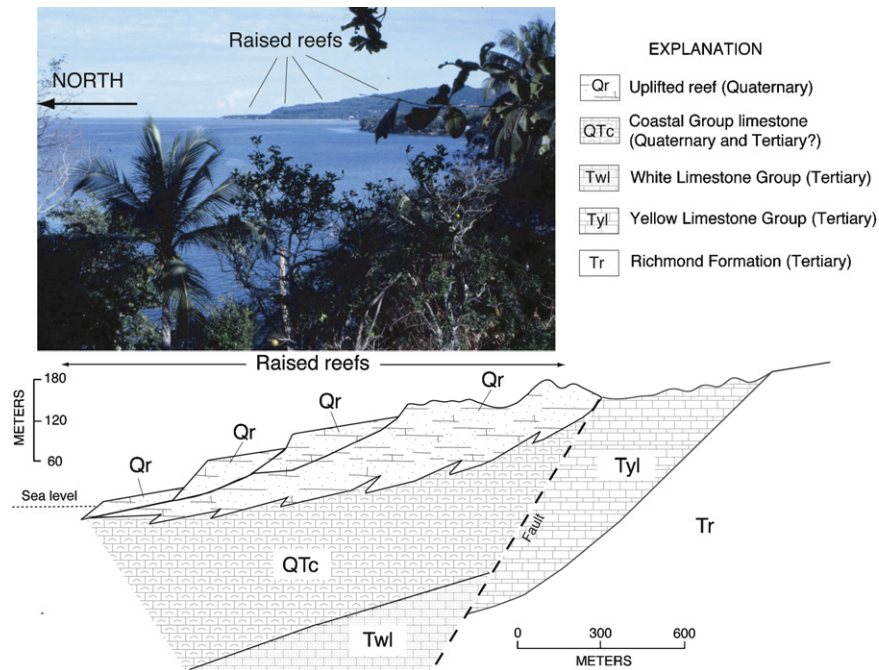


Fig. 4. Raised reefs of northern Jamaica. Photograph shows view to the east, just east of Oracabessa (see Fig. 3 for location). Drawing shows geologic cross section of raised reefs and underlying bedrock units in the area photographed above, redrawn from Cant (1970).

Oracabessa, we were unable to find undisturbed or uneroded soils on many of the lower terraces. Indeed, on the outer edge of the lowest terrace, less than a meter above sea level, soils have been completely removed by wave erosion. However, we did find two uneroded and undisturbed soils on Cant's terrace 4, at an elevation of ~150 m (OR-4A and OR-4B).

The best-exposed sequence of uneroded soils that we found is on what we interpret to be emergent reef terraces near Rio Nuevo Bay (Fig. 4). Exposures of the carbonate facies here are very shallow, so it was not possible to ascertain whether these represent true constructional reefs of Quaternary age, wave-cut platforms beveled on Quaternary reefs, or wave-cut platforms eroded on older, Tertiary carbonate rocks. All fossil material that we found was recrystallized, precluding age determinations by either U-series or Sr-isotope methods. We stress, therefore, that our interpretations are based primarily on geomorphic relations, interpretations of what we assume to be terrace inner edge elevations, and correlation to dated terraces to the east (Oracabessa) and west (Discovery Bay). Much more detailed mapping, subsurface exploration, and geochronology are needed in this area before firm conclusions can be drawn about terrace chronology.

At the Rio Nuevo Bay sequence, we measured elevations of what we interpret to be three emergent reef terraces, by hand-level and from 1:50,000 topographic maps. The lowermost terrace has an outer-edge elevation ~15 m a.s.l. and an apparent inner edge near ~30 m elevation, where the coastal road crosses it. This terrace is ~250 m wide and is mapped as the reef facies of the 125,000-yr-old Falmouth Formation by Henry (1978b). Soil profile RN-1

was collected from this surface, about 200 m seaward of the coastal road. Although this landform is mapped as the reef facies of the Falmouth Formation, we found rounded, carbonate-coated cobbles of microcrystalline quartz throughout the RN-1 profile, suggesting that this soil may have developed on the gravel facies of the formation. The next highest terrace surface has an outer edge that is ~37 m a.s.l., a width of ~400 m, and an apparent inner edge elevation of ~42 m. Soil profiles RN-2A and RN-2B were collected from this surface. Above the 42-m-high terrace, there is yet another terrace surface that has an outer edge at ~50 m a.s.l. This surface is ~270 m wide, and has an apparent inner edge elevation of at least ~64 m. The inner edge elevation measurement is only a minimum estimate, because a wedge of well-rounded, beach-derived (?) cobbles (composed of microcrystalline quartz) mantles the landward margin of the terrace. Soil profile RN-3 was collected from the midpoint of the terrace surface.

We estimate possible ages of the two higher terraces using a late Quaternary uplift rate of 0.19 m per 1000 yr from the ~30-m-high terrace and the higher terraces' shoreline angle elevations. Although we infer that these terraces formed initially as constructional reefs, they also have a geomorphic expression suggesting they may have been modified subsequently as wave-cut platforms. Speed and Cheng (2004) report that many of the marine terraces on Barbados, although partly formed by reef construction, also have a partly erosional origin, characterized by wave-cut platforms, sea cliffs, and shoreline angles that mark the platform-cliff junction. We derive an uplift rate of ~0.19 m per 1000 yr by using the ~30-m-high elevation of what appears to be the shoreline angle of the Falmouth

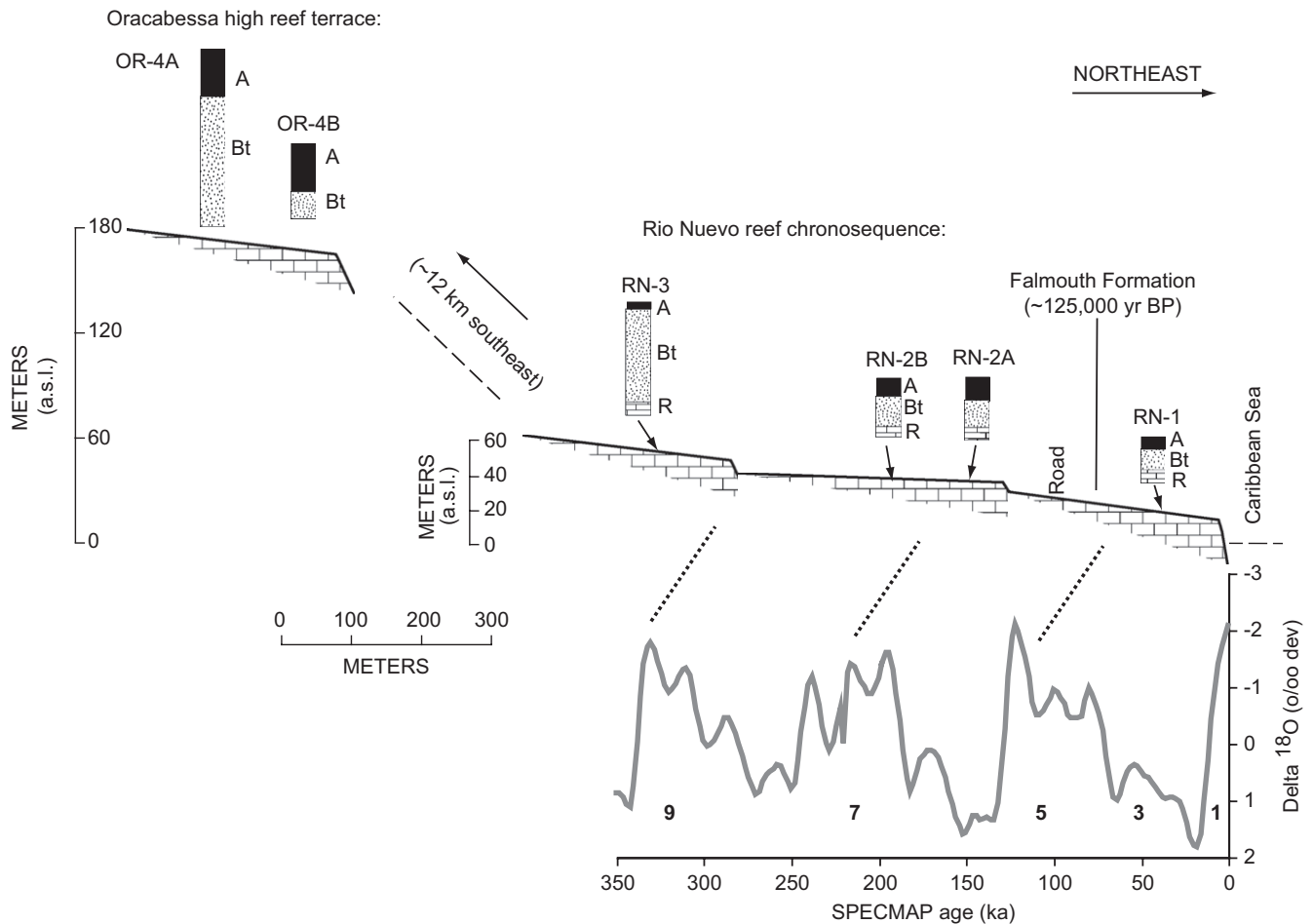


Fig. 5. Soil chronosequence on terraces near Rio Nuevo and possible correlation of interglacial reef terraces with the SPECMAP oxygen isotope record (Imbrie et al., 1984).

Formation terrace surface, an assumption that sea level was ~6 m higher than present at the time of terrace formation (see review in Muhs, 2002), and an age of ~125,000 yr. This relatively low uplift rate is consistent with the predominantly strike-slip transpressional tectonic style that has affected Jamaica during the Neogene (Burke et al., 1980). If we assume that sea levels were close to present for the two higher (~42 and ~64 m) terraces, their (assumed) shoreline-angle elevations and the calculated uplift rate yield estimated ages of ~220,000 and ~330,000 yr, which suggest possible correlation with interglacial marine isotope stages 7 and 9, respectively (Fig. 5). Nevertheless, we emphasize that these age estimates are tentative and are used here in the context of a working hypothesis rather than a firm chronology.

Near White River Bay, a carbonate reef is exposed at the junction of the coastal road and a smaller road leading to the south (Fig. 3). This road cut had, in early 1985, a lateral exposure of ~60 m, and showed a seaward-to-landward reef facies change in the sediment (Fig. 6). Henry (1978b) mapped these sediments as reef facies of the ~125,000-yr-old Falmouth Formation. The outer edge, near the coastal road, hosts at least 4 m of reef-crest facies, with

corals in growth position (although recrystallized), including what appear to be *Montastrea* sp. and *Diploria* sp. (Fig. 7). Landward of this facies, there is a narrow zone of coral rubble, and farthest landward, there is a layer, at least ~1 m thick, of carbonate sand that we interpret to be a backreef, lagoonal facies. Soil profile WR-A was collected on the reef-crest facies and profile WR-B was collected on the lagoonal facies.

#### 4. Properties of soils on the northern coast of Jamaica

##### 4.1. Methods

Soils were described in the field using standard soil terminology as practiced in the USA (see Birkeland, 1999). Samples were collected and subsequently analyzed by soil horizon. For clay mineralogy, the <2 μm fraction was separated by sedimentation after removal of carbonates with acetic acid (buffered to a pH of 5.0), removal of organic matter by H<sub>2</sub>O<sub>2</sub>, dispersion with Na-pyrophosphate, and separation of sands (>53 μm) by wet-sieving. Clays were given an oriented mount on glass slides and X-rayed three times: air-dry, with ethylene-glycol



solvation, and heat-treated (550 °C for 2 h). Identification of clay mineral species follows the techniques of Moore and Reynolds (1997). Major element chemistry was

conducted on bulk, pulverized soil samples in laboratories of the USGS using wavelength-dispersive X-ray fluorescence (Taggart et al., 1982). Trace element chemistry, including the rare earth elements (REE) was conducted on splits of bulk samples using instrumental neutron activation analysis (Budahn and Wandless, 2002). The one exception to this is Y, which was determined by energy-dispersive X-ray fluorescence; these data were previously reported by Muhs et al. (1990).

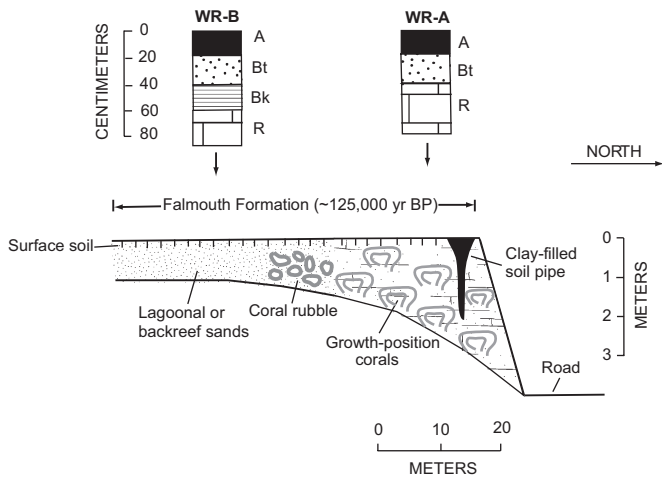


Fig. 6. Cross section of reef facies and soils sampled in road cut near White River Bay (see Fig. 3 for location).

#### 4.2. Soil morphology

The morphology of the soils we studied reflects their ages estimated from the uplift rate (Table 1). Older soils are thicker, redder, and more clay-rich than are younger soils. In the Rio Nuevo area, profile RN-1, on what we infer to be the ~125,000-yr-old last interglacial terrace, has a shallow (~26 cm) profile with mostly 10YR hues in the B horizon. The B horizon has clayey textures, but the angular-to-subangular blocky structure in this horizon is weak. Profiles RN-2A and RN-2B, on the next highest surface, have deeper profiles (37–40 cm), redder (5YR to 2.5YR)

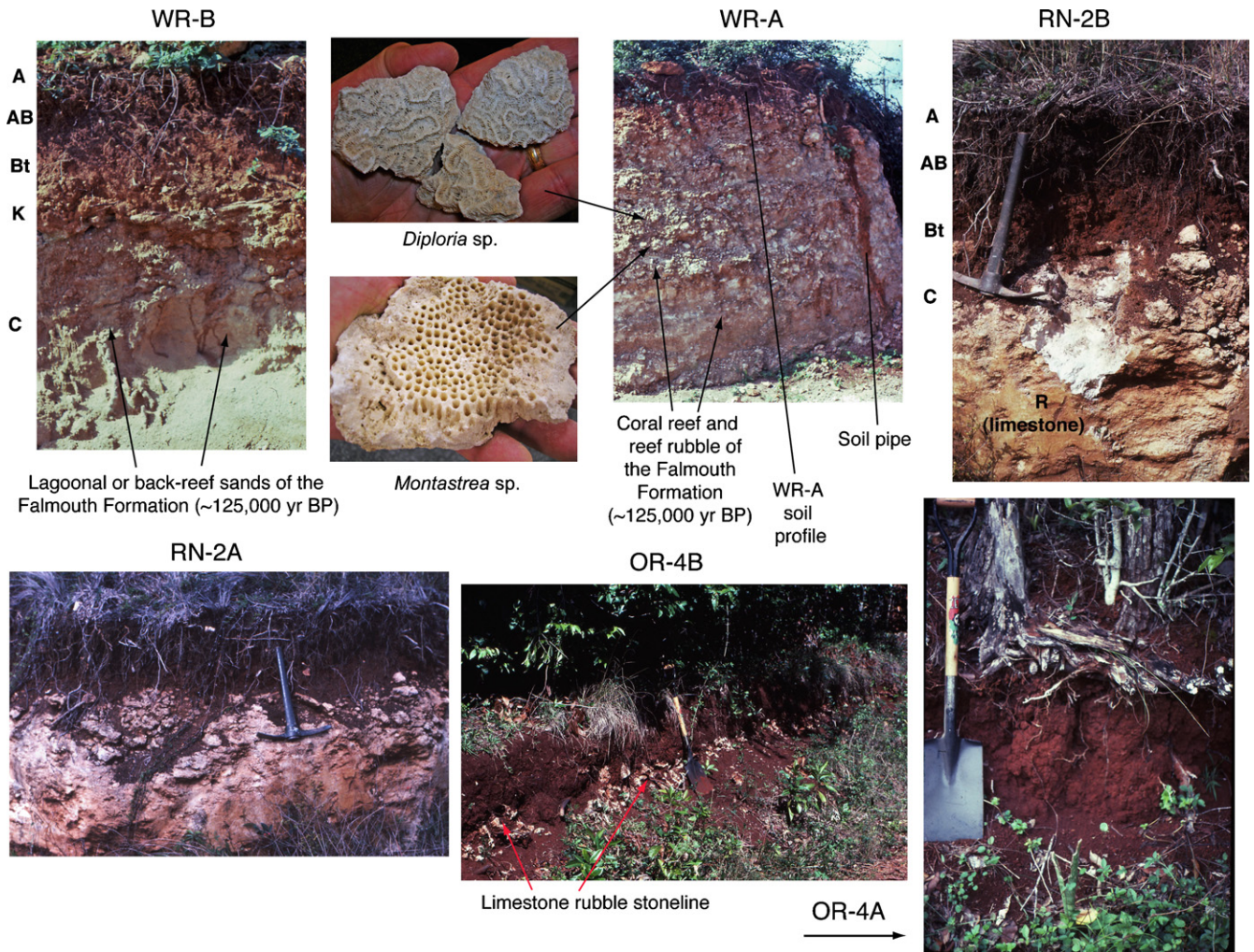


Fig. 7. Photographs showing some of the soil profiles with their master soil horizons, as well as corals collected from the Falmouth Formation reef at WR-A (see Fig. 3 for localities).





B horizons, clayey textures, and moderate-to-strong angular blocky structures. Profile RN-3, still older, has an even thicker profile (86 cm), although the B horizon is not as red. In addition, the B horizon has only weak-to-moderate angular blocky structure. We note, however, that at the time of description, this profile was moister than either RN-2A or RN-2B, which may explain the lower grade of structure. Profiles OR-4A and OR-4B, on the oldest terrace, show a much more developed soil morphology than any of the other soils. Profile OR-4B is relatively thin (~42 cm), so we suspect it has been eroded, because OR-4A, just a short distance away, has a thickness of more than 140 cm. Both soils have 10R hues, very clayey B horizons, and mostly strong, subangular blocky structure. Profile OR-4B has a stone line composed of limestone fragments in its upper part (Fig. 7). Stone lines have been described from other tropical localities and concepts on their origin are discussed in Johnson (1993).

On the reef exposed near White River Bay, soils (WR-A and WR-B) on the ~125,000-yr-old Falmouth Formation show a degree of development intermediate between RN-1 (~125,000 yr) and RN-2A/RN-2B (~220,000 yr) in the Rio Nuevo area. These soils have moderate (40–45 cm) profile thicknesses, B horizons with mostly clay loam or sandy clay loam textures, 5YR or 7.5YR hues, and moderate-to-weak angular or subangular blocky structure. WR-B, which developed on carbonate sands of the lagoonal facies of this reef, has a cemented Bk horizon below the Bt horizon.

#### 4.3. Clay mineralogy

Because all of the soils we studied have particle size distributions dominated by clay, we conducted detailed clay mineralogical analyses to see if there are changes with relative age. The A horizon of RN-1, the youngest soil with the weakest profile development, has strong peaks at 7.13 Å (12.4°2θ) and 3.56 Å (25.0°2θ). These two peaks are unaffected by glycolation, but collapse with heating to 550 °C for 2 h, behavior that is typical for kaolinite. The 7.13 Å (12.4°2θ) peak has a gradual drop-off on the low-angle side and a sharp drop-off on the high-angle side, whereas the 3.56 Å (25.0°2θ) peak has a sharp drop-off on the low angle side and a gradual drop-off on the high-angle side (Fig. 8). The asymmetry of the two kaolinite peaks may indicate that this mineral is poorly crystallized or interstratified. RN-1 also has a strong peak at 3.34 Å (26.6°2θ) which is unaffected by glycolation and heating, indicating quartz. A minor peak at 9.9 Å (8.9°2θ), also unaffected by glycolation and heat treatment, indicates possible minor amounts of mica, but the high background on this sample makes this interpretation uncertain. Profile WR-A, also young, but with better profile development, has kaolinite peaks similar in form and intensity to those of profile RN-1, consistent with what we infer to be similar ages (Fig. 8). However, both the A and B horizons of WR-A lack quartz. In addition, both

horizons have a small peak at 4.85 Å (18.3°2θ), although the peak in the B horizon is less distinct. This mineral may be gibbsite.

Both the A and B horizons of RN-2A, older than RN-1 and WR-A, show very strong and more symmetrical kaolinite peaks as well as strong quartz peaks (Fig. 8). In addition, however, both horizons, when air-dry, show broad peaks at 12.8 Å (6.9°2θ), with a gradual drop-off to the high-angle side. In the A horizon, this peak forms a broad rise from about 14.7 Å (6.0°2θ) to 10 Å (8.8°2θ) and diminishes to a small peak at ~9.6 Å (9.2°2θ) with heating. In the B horizon, the broad 12.8 Å (6.9°2θ) peak shifts to an indistinct shoulder between about 17 Å (5.2°2θ) and 11 Å (8.0°2θ) when glycolated; with heating, it forms a broad rise between 14.7 Å (6.0°2θ) and 9.8 Å (9.0°2θ). It is difficult to interpret these patterns, but one possibility is that they represent some kind of a mixed-layer, mica-chlorite species.

In the A horizon of profile RN-3, still older, there are very symmetrical and prominent kaolinite and quartz peaks. In addition, however, the A horizon of this soil shows a very strong peak at 13.4–12.3 Å (6.6–7.2°2θ) that shifts to a more symmetrical position of 14.2 Å (6.2°2θ) upon glycolation, and collapses to 9.9 Å (8.9°2θ) with heat treatment. We interpret this mineral to be chlorite. In the B horizon, kaolinite and quartz are also present, but the most abundant mineral has a broad 17–12 Å (5.2–7.3°2θ) peak when air dry and glycolated and collapses to about 9.9 Å (8.9°2θ) upon heating. This behavior suggests possible mixed-layer smectite–chlorite. The existence of smectite is supported by the observation that most of the B horizon of this soil exhibits slickensides.

In the oldest soil studied, OR-4A, a very different mineralogy appears (Fig. 9). In both the A and B horizons of this soil, very strong and symmetrical kaolinite peaks are present. In addition, however, air-dry and glycolated patterns show an even stronger peak at 6.06 Å (14.6°2θ). This peak, like the kaolinite peaks, disappears with 550 °C heat treatment. This represents boehmite, not apparent in any of the younger soils. A very small peak is present at 14 Å (6.3°2θ) in air-dry and glycolated treatments; this peak disappears after heat treatment, suggesting the presence of vermiculite or possibly low-temperature chlorite.

Overall, the soils show changes in clay mineralogy that are a function of our hypothesized ages of host deposits. All soils have kaolinite and quartz, but kaolinite peaks are sharper and more symmetrical in older soils. In the oldest soils, kaolinite is best developed of all, and in addition, boehmite is present. The sequence shows a progressively greater amount of chemical weathering with simpler clays evolving over time.

#### 4.4. Major element geochemistry

Major element geochemistry gives considerable insight into soil genesis and the nature of the carbonate substrates

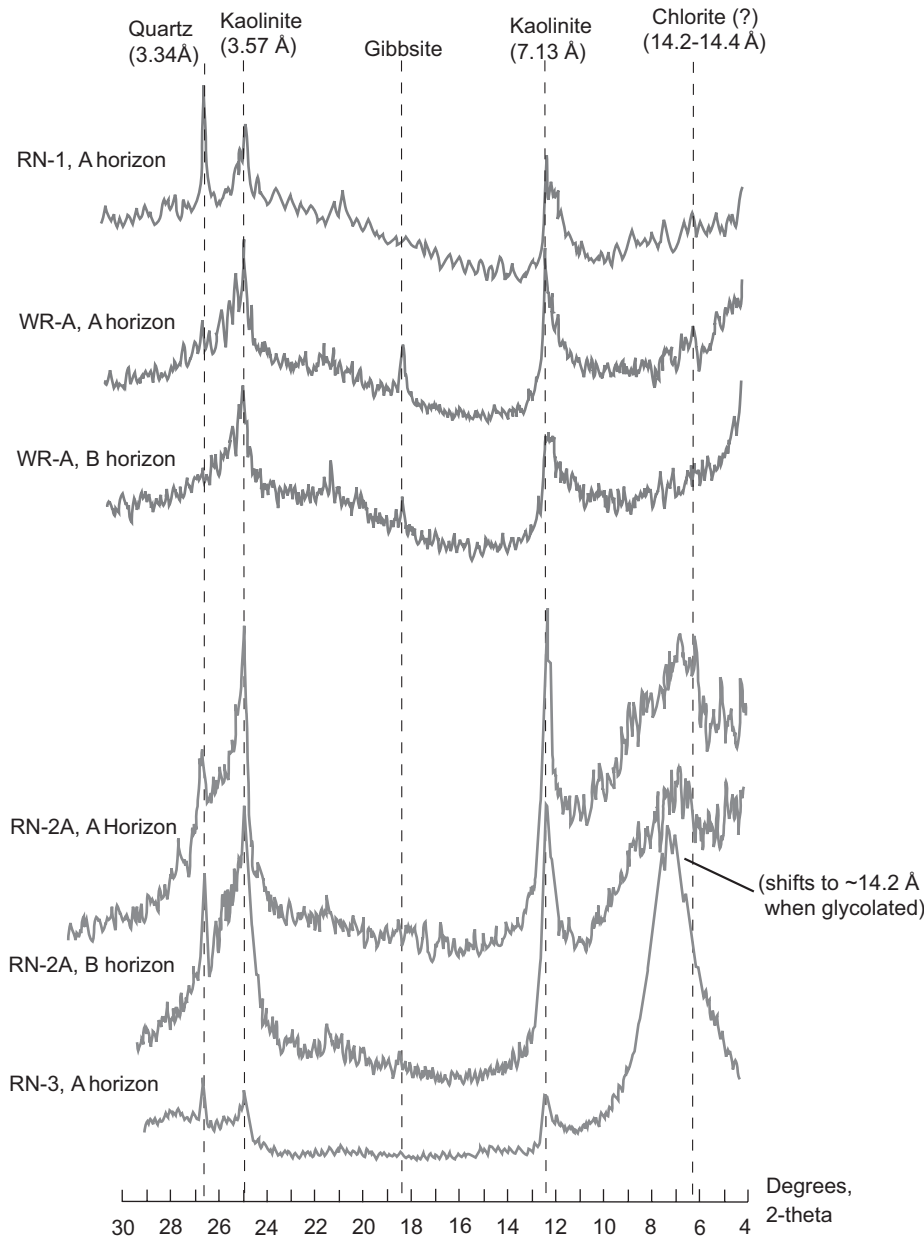


Fig. 8. Selected X-ray diffractograms (air-dry samples) of the soils studied on younger reefs.

on the north coast of Jamaica (Table 1). For the substrates under the soils, if we assume that all or most of the CaO is in carbonate and that loss on ignition (LOI) primarily represents CO<sub>2</sub> loss from carbonate, then CaO+LOI is a reasonable estimate of calcium carbonate content. Such estimates do not apply to soils such as OR-4A and OR-4B, which have high LOI and low CaO, indicating that most of the LOI is from organic matter. However, for the deepest C horizons (weathered carbonate rock) and underlying carbonate rock ("R" horizons in Table 1) in profiles WR-B, RN-2A, RN-2B, and RN-3, CaO+LOI gives approximate measures of carbonate substrate purity. Carbonate contents using this method range, for six samples, from 93% to

98%. This indicates, as reported by other workers summarized earlier, that soil formation by residual accumulation of insoluble residues, if valid, would be an extremely slow process.

Major element concentrations show that Jamaican soils are highly weathered, consistent with the clay mineralogy. Concentrations of elements that are found in primary minerals are extremely low (Table 1). For example, K<sub>2</sub>O is found mainly in K-feldspar and mica. Concentrations of K<sub>2</sub>O range from 0.2% to 0.5%, indicating very little, if any K-feldspar or mica in these soils. Concentrations of Na<sub>2</sub>O in Jamaican soils are also extremely low, below detection limits of 0.15% in many horizons. Because Na<sub>2</sub>O is found primarily in plagioclase (and to a lesser extent in



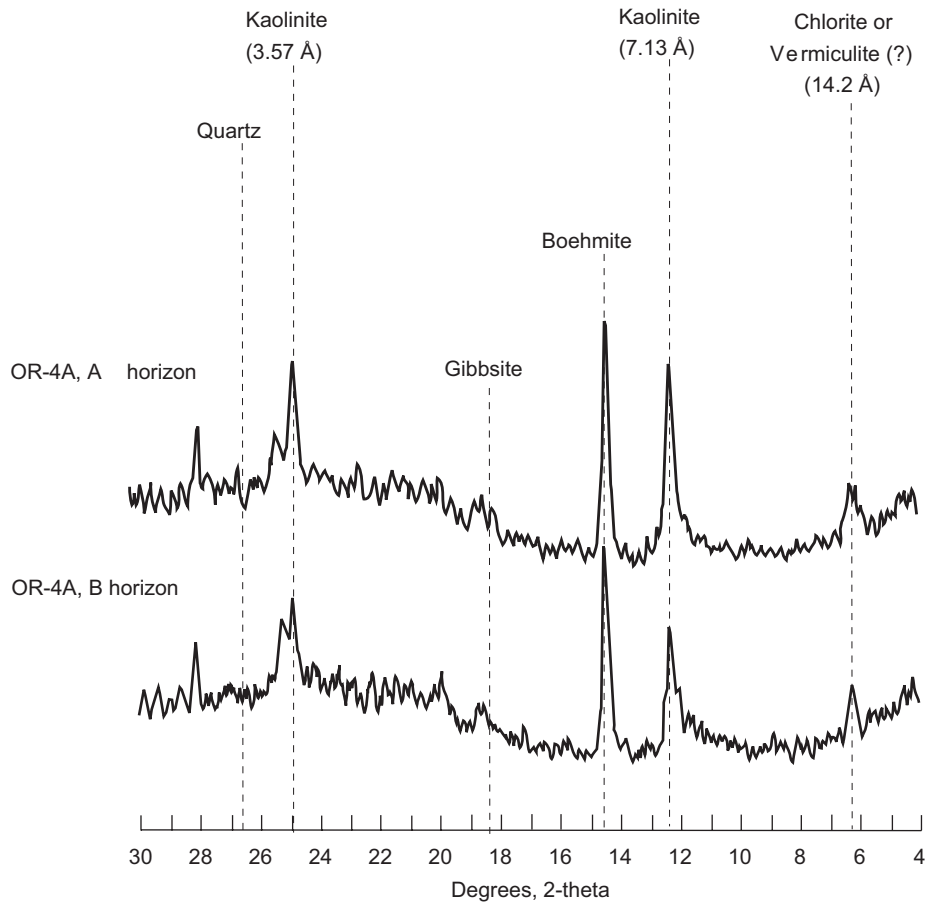


Fig. 9. Selected X-ray diffractograms (air-dry samples) of the soils studied on older reefs.

hornblende), low values of this element indicate little or no amounts of these minerals.

A commonly used measure of degree of chemical weathering in soils is the  $\text{SiO}_2/\text{Al}_2\text{O}_3$  value (Birkeland, 1999). A clay mineralogy dominated by kaolinite, or kaolinite and boehmite (OR-4A), indicates considerable depletion of  $\text{SiO}_2$  relative to mostly immobile  $\text{Al}_2\text{O}_3$ . In the Jamaican soils estimated to be of middle-to-late Quaternary age (WR-A,B, RN-1, 2A, 2B, 3),  $\text{SiO}_2/\text{Al}_2\text{O}_3$  ranges from 3.97 to 1.83 in the A and upper B horizons. In contrast, in the early Quaternary soils (OR-4A and OR-4B),  $\text{SiO}_2/\text{Al}_2\text{O}_3$  values are 0.81–0.53, reflecting the more Al-rich mineralogy. The  $\text{SiO}_2/\text{Al}_2\text{O}_3$  values for the younger soils are comparable to those for soils on middle-to-late Quaternary-age reef terraces of Barbados (Muhs, 2001). The older soils on Jamaica (OR-4A and OR-4B) have  $\text{SiO}_2/\text{Al}_2\text{O}_3$  values similar to those of soils on relatively pure Quaternary carbonate eolianites on the Bahamas (Foos, 1991) and Bermuda (Herwitz and Muhs, 1995).

In typically red or reddish-brown Jamaican terra rossa soils, dominant colors reflect the total  $\text{Fe}_2\text{O}_3$  content (Table 1). Although our data are for *total*  $\text{Fe}_2\text{O}_3$ , both that in primary minerals and that in secondary products, such as hematite and goethite, soils with redder colors also have higher total  $\text{Fe}_2\text{O}_3$  content. For example, profile RN-1 has

10YR hues and  $\text{Fe}_2\text{O}_3$  contents of ~6% in all horizons. Profile RN-2A has redder, 2.5YR hues in its B horizon and  $\text{Fe}_2\text{O}_3$  contents of ~9%. Profiles OR-4A and OR-4B have very red, 10R hues, and  $\text{Fe}_2\text{O}_3$  contents of ~16–19%. Thus, we interpret these data to mean that much of the  $\text{Fe}_2\text{O}_3$  content reflects the relative abundance of hematite, the mineral that provides a red pigment to soils. Scholten and Andriess (1986), studying soils on the Tertiary White Limestone of Jamaica, also report that a majority of total  $\text{Fe}_2\text{O}_3$  is found in secondary products.

#### 4.5. Trace element geochemistry

For provenance studies, we utilized only those elements that are considered, on the basis of high ionic potential, to be immobile in low-temperature, near-surface environments. The suite of elements chosen includes Th, Cr, Sc, Zr, and Y as well as the REE, La (the lightest REE) to Lu (the heaviest REE). The most likely host minerals for Cr and Sc are micas, amphiboles and clay minerals. Th can be hosted by micas, amphiboles, zircon, sphene and clay minerals. Zr is found almost exclusively in zircon. The REE and Y can be hosted by micas, chlorite, clay minerals, amphiboles, sphene, zircon, apatite and, to some degree, feldspars.

REE concentrations are typically normalized to chondritic meteorite compositions and we follow this protocol. In the discussions of REE patterns that follow, the terms “enriched” and “depleted” are used in descriptions and interpretations. Because all samples analyzed have higher concentrations of REE compared to chondrites, these terms refer to relative abundances of different parts of the REE suite compared to other parts, e.g., light REE compared to heavy REE. Another parameter for chondrite-normalized REE is the Eu anomaly, which is the chondrite-normalized concentration of Eu relative to Sm and Gd. The degree of Eu anomaly can be quantified by the  $\text{Eu}/\text{Eu}^*$  value, where “Eu” is the chondrite-normalized Eu concentration ( $\text{Eu}_N$ ), and “Eu\*” is  $(\text{Sm}_N \times \text{Gd}_N)^{0.5}$ . Values for  $\text{Eu}/\text{Eu}^*$  that are less than 1.0 are termed negative Eu anomalies; values greater than 1.0 are positive Eu anomalies.

There is a REE pattern that is typical for rocks from the upper continental crust (Taylor and McLennan, 1985, 1995; McLennan, 1989) or mixed sediments derived from the upper crust, such as loess (Gallet et al., 1996, 1998; Jahn et al., 2001; Muhs and Budahn, 2006). In sediments derived from the upper continental crust, light REE are enriched, there is a negative Eu anomaly, and the heavy REE are depleted. In contrast to the upper continental crust, basalt has low overall abundances of REE, relatively “flat” curves (i.e., no light REE enrichment), and no Eu anomaly (see examples from Hawaii in Budahn and Schmitt, 1985).

Garrett et al. (2004) note that many Jamaican terra rossa soils have high concentrations of certain trace elements, including Hf, Th, Ti, Sc, Cr, and the REE. As these investigators note, these relatively immobile elements tend to accumulate with the loss of more mobile constituents such as  $\text{SiO}_2$ , CaO, MgO,  $\text{Na}_2\text{O}$ , and  $\text{K}_2\text{O}$ . Our results (Table 2) agree with their observations, and fit with current theoretical understanding of trace element mobility in soil environments (Mason and Moore, 1982; Taylor and McLennan, 1985, 1995; McLennan, 1989). We report here the concentrations of Th, Cr, Sc, Zr, La, and Y as a function of estimated reef age. All of these elements show relative increases in the soils with estimated terrace age, excluding substrate-dominated horizons where concentrations are low due simply to carbonate dilution (Fig. 10). The coefficients of determination ( $r^2$  values) for trace element concentrations versus estimated substrate age range from ~40% to ~80%, and all values are significant. Muhs et al. (2007a) report similar results for many of these same elements in a chronosequence of soils on reef terraces of Barbados. The results are important, because it is these elements that are useful as provenance indicators.

Soils on limestones from the northern coast of Jamaica show many of the same REE characteristics as those on Barbados, the Bahamas, and the Florida Keys (Muhs et al., 2007a). All soils are relatively enriched in light REE, have negative Eu anomalies and relatively flat heavy REE curves (Fig. 11). As discussed above, this is a typical pattern

for loess and other sediments derived from the upper continental crust. Hence, we interpret Jamaican soils to have had upper continental crustal rocks as their ultimate source.

As is also the case on Barbados, some horizons of Jamaican soils show negative Ce anomalies. In the Rio Nuevo soil sequence, negative Ce anomalies are found mostly in the lowest, most carbonate-rich horizons of RN-2A, RN-2B, and RN-3 (Fig. 11), also the case with Barbados soils. Muhs et al. (2007a) show that unaltered fossil corals from Florida and the Bahamas do not have negative Ce anomalies inherited from sea water, but positive Ce anomalies. Thus, although we suspect that the cause of the negative Ce anomalies here (and on Barbados) may be due to the carbonate substrate, it is carbonate components other than coral that are the probable cause. Webb and Kamber (2000) show, for example, that carbonate reef microbialites have negative Ce anomalies, presumably inherited from the negative Ce anomaly found in sea water. However, Holser (1997) shows that diagenesis plays a complex, and not completely understood, role in Ce anomalies in carbonate rocks with mixtures of skeletal components.

## 5. Comparison of trace element geochemistry of Jamaican soils and possible source materials

### 5.1. *Ti–Zr–Y and Sc–Th–La–Zr–Ta as provenance indicators*

Pearce and Cann (1973) demonstrate that relative abundances of the high-field-strength (i.e., immobile in near-surface environments) elements Ti, Zr, and Y, when displayed on ternary diagrams, are powerful tools for determining the origin of volcanic rocks. The same approach can be used for soils and their candidate parent materials. The abundance of other high-field-strength elements, particularly Sc, Th, La, Cr, Ta and Hf, have been used in studies of the origin of sedimentary rocks (Bhatia and Crook, 1986; McLennan, 1989) and the sources of dust, loess, and the eolian component of deep-sea sediments (Olivarez et al., 1991; Sun, 2002; Muhs and Budahn, 2006; Muhs et al., 2007a, b; Ziegler et al., 2007). Indeed, many of these elements have been crucial in reconstructing the geologic history of the continental crust itself (Taylor and McLennan, 1985).

The specific elements we use in our comparisons of Jamaican soils and possible parent materials are a function of what limited data are available. For example, we were unable to find Sc, Th, or REE data for igneous and metamorphic rocks on Jamaica (found in the Blue Mountains and as inliers in Fig. 2). However, Jackson et al. (1989) and Jackson and Scott (2002) report Ti, Zr, and Y data for these rocks, which we compare to Jamaican soils we analyzed. Tephra from the Lesser Antilles island arc, African dust, and the fine-grained (<20  $\mu\text{m}$ ) component of lower Mississippi River valley loess have all been





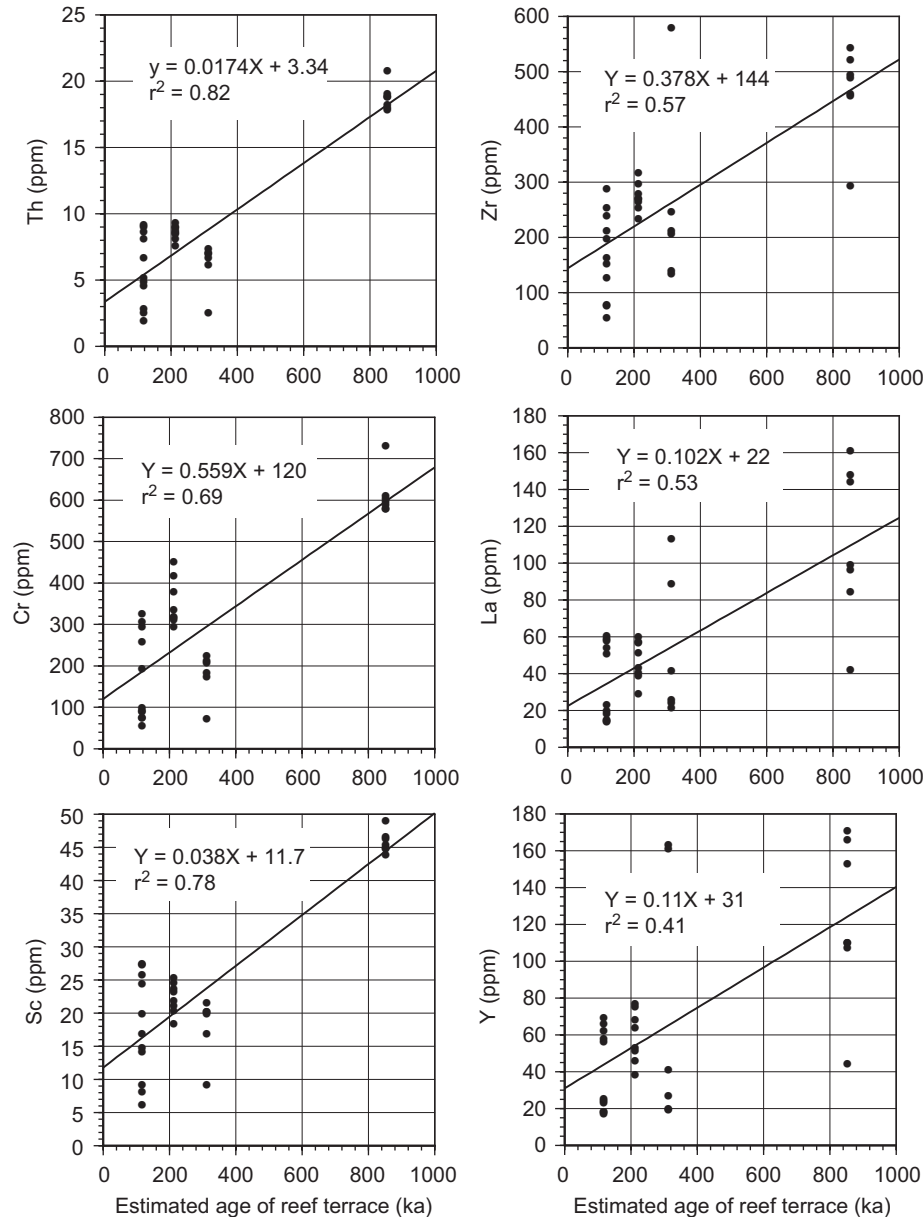


Fig. 10. Trace element concentrations of soils in the Rio Nuevo-Oracabessa chronosequence shown as a function of estimated reef-terrace age.

analyzed for Sc, Th, Zr, Ta, and the REE contents by Muhs et al. (2007a) and we use those data for comparison here. For tephra from Central American volcanoes, we use trace element data of Drexler et al. (1980) and Clift et al. (2005).

#### 5.1.1. Local non-carbonate rocks as parent materials evaluated by Ti–Zr–Y

Cretaceous igneous rocks in the Blue Mountains, in the Wagwater Belt, and in the “inliers” in the central part of Jamaica (Fig. 2) could conceivably add sediment to lower carbonate surfaces such as those in our study area. Erosion of these rocks and fluvial or colluvial transport of the eroded sediment onto an emergent reef is obviously one mechanism. Another could be fluvial transport to the insular shelf on the north coast of Jamaica during an

interglacial period. During a subsequent glacial period, with sea-level lowering, such sediments could be deflated by wind and transported back onto the emergent reef surfaces by northeasterly trade winds. Either process could produce a veneer of non-carbonate sediment on top of an emergent carbonate reef terrace and this non-carbonate sediment could serve as the soil parent material for the A and B horizons.

Using Ti, Zr, and Y data for Cretaceous rocks on Jamaica (Fig. 2) reported by Jackson et al. (1989) and Jackson and Scott (2002), we note that there is little compositional overlap with Jamaican soils (Fig. 12). Although some of these rocks have compositional similarities with one another, none has significant overlap with Jamaican soils. A few soils fall within the field occupied by the Blue Mountains plutonic rocks and the Central Inlier

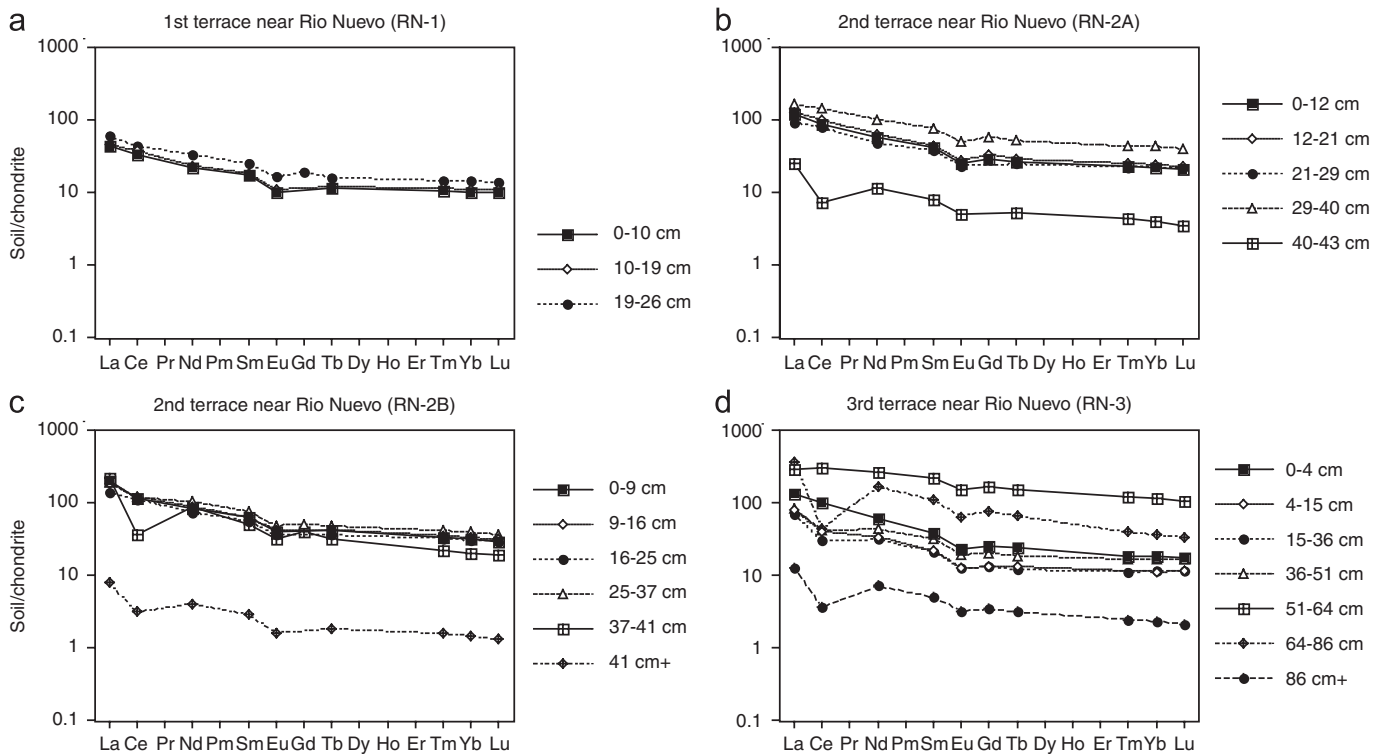


Fig. 11. Chondrite-normalized REE plots of soils in the Rio Nuevo chronosequence. (a) 1st terrace near Rio Nuevo (RN-1), (b) 2nd terrace near Rio Nuevo (RN-2A), (c) 2nd terrace near Rio Nuevo (RN-2B), (d) 3rd terrace near Rio Nuevo (RN-3).

volcanic rocks, so it is possible that some soils have had some influence from local bedrock-derived sediments. Overall, however, we interpret these data to indicate little input from local igneous rocks to the limestone-hosted soils.

### 5.1.2. African and North American dust and tephra evaluated by Sc–Th–La–Zr–Ta–Cr–Nd

The use of Sc–Th–La ternary diagrams has a long tradition in sediment provenance studies (Taylor and McLennan, 1985; Bhatia and Crook, 1986; Olivarez et al., 1991; Muhs et al., 2007a, b; Ziegler et al., 2007). To this we also add Sc–Th–Zr and Sc–Th–Ta diagrams. Bhatia and Crook (1986) point out that Sc–Th–Zr provides discriminating power for source sediments that is complementary to Sc–Th–La. We also use Sc–Th–Ta because this element suite helps discriminate between two potential source sediments, African dust and Mississippi loess, that Sc–Th–La and Sc–Th–Zr do not differentiate. Muhs et al. (2007a) report that Cr–Th–Nd also has resolving power for some of the source materials considered here.

On a Sc–Th–La diagram, African dust and Mississippi loess overlap, but Lesser Antilles tephtras and Central American tephtras are easily discriminated from one another (Fig. 13). The Sc–Th–Zr diagram shows good separation of fields for Lesser Antilles tephtras and the two eolian sources, African dust and Mississippi loess. There are too few Zr data in Drexler et al. (1980) for assessing Central American tephtras, however. African dust,

Mississippi loess and Lesser Antilles tephtras are all well differentiated on Sc–Th–Ta plots.

Based on the trace element data, Jamaican soils appear to be derived from a mix of at least two sources, most likely African dust and Lesser Antilles tephtras, and some third, as yet unidentified source (Fig. 13). Many soils plot within the Lesser Antilles field for Sc–Th–Zr, but most are closer to African dust for Sc–Th–La. The Sc–Th–La diagram indicates little input from Central American tephtras. On the Sc–Th–Ta diagram, Jamaican soils plot mostly between the African dust and Lesser Antilles tephtra fields. Finally, on the Cr–Th–Nd diagram, Jamaican soils plot well outside the fields of Lesser Antilles tephtras, Mississippi loess and African dust, but plot closest to African dust. Nevertheless, the spread of points indicates that some unidentified, high-Cr (mafic?) source must also contribute to the soils.

### 5.2. REE as provenance indicators

Certain parameters have been developed that reduce REE data and facilitate comparisons in provenance studies. A common way to do this is to compare the abundance of light (LREE), middle (MREE), and heavy (HREE) rare earths, using a representative element for each group. For example, Nakai et al. (1993) use La/Yb and Sun (2002) uses Ce/Yb to compare the abundance of LREE to HREE.

In studying possible sources for Jamaican soils, we wished to limit our consideration of tephtra sources only to

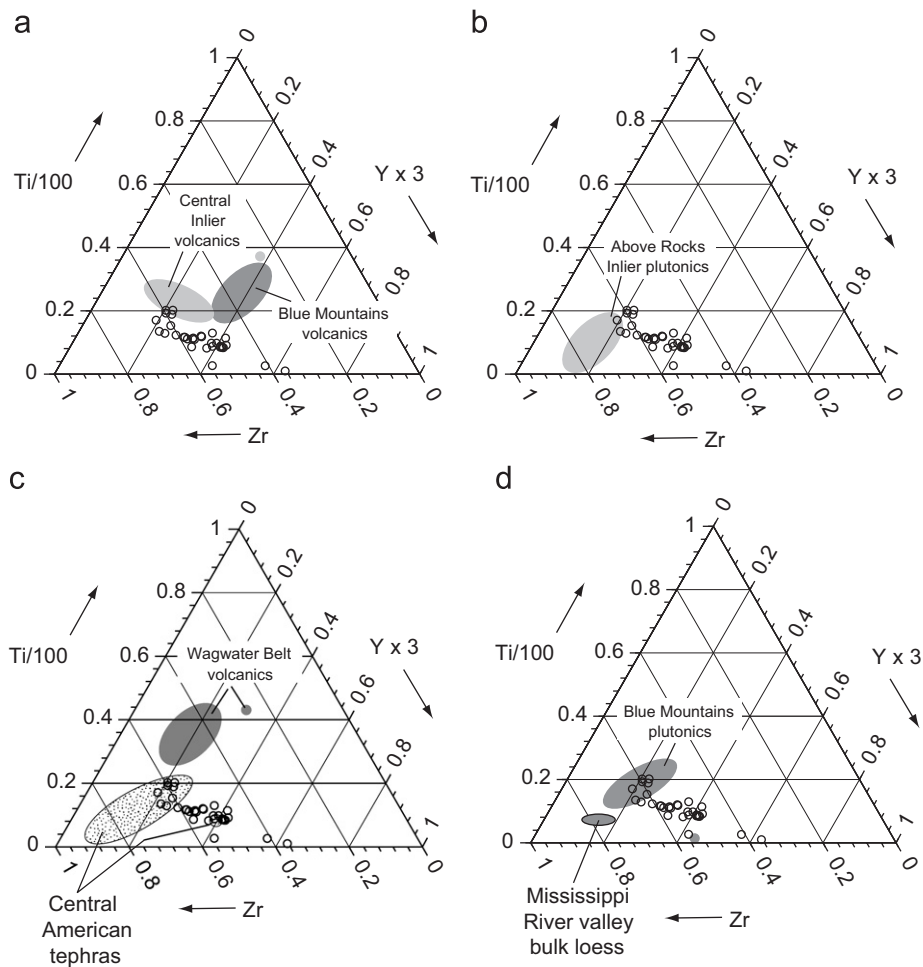


Fig. 12. Ternary diagrams of Ti-Zr-Y in Jamaican soils (shown as open circles; data from this study). Also shown for comparison are polygons showing the range of variation of these elements in local igneous bedrock (igneous rock bodies shown in Fig. 2), Central American tephras, and Mississippi River bulk loess. Geochemical data for igneous rocks are from Jackson et al. (1989) and Jackson and Scott (2002); data for Central American tephras are from Clift et al. (2005); data for bulk Mississippi River valley loess are from Muhs et al. (2001).

those that could have supplied ash to Jamaica during the time of soil formation in our study area. This requires examination only of tephras that are silicic (from explosive eruptions), glass-dominated (far-traveled), and of Quaternary age (the hypothesized ages of the soils studied). For the Lesser Antilles island arc, this includes tephras from Dominica and St. Lucia, reported by Muhs et al. (2007a). The only Central American tephra data of which we are aware that meet all these requirements are those reported in Clift et al. (2005). Their samples consist of silicic, glass-dominated tephras of Quaternary age, collected from deep-sea cores off the Pacific coast of Costa Rica. Because of the analytical method they used, Clift et al. (2005) have data only for certain REE. Thus, we use La/Yb (for LREE to HREE) and Sm/Yb (for MREE to HREE), elements common to all data sets considered here.

An earlier study by Drexler et al. (1980) shows that Central American tephras of late Quaternary age tend to be LREE-enriched. The later study by Clift et al. (2005), using tephras that span the entire Quaternary, is consistent with these results. Central American tephras have very high

Sm<sub>N</sub>/Yb<sub>N</sub> and La<sub>N</sub>/Yb<sub>N</sub> (where the subscript “N” indicates chondrite normalized) and define a compositional field that has little overlap with Jamaican soils (Fig. 14). We conclude from these data that Central American tephras, even though highly explosive and capable of being transported eastward on the upper tropospheric westerlies, apparently have played little or no role in Quaternary soil genesis on Jamaica. In contrast, Sm<sub>N</sub>/Yb<sub>N</sub> and La<sub>N</sub>/Yb<sub>N</sub> values for Lesser Antilles tephras, Mississippi loess, and African dust are all much lower (Fig. 14). Although these three source sediments have only partial overlap, Jamaican soils could conceivably have been derived from some mix of the three sources. Thus, although we can conclude from Sm<sub>N</sub>/Yb<sub>N</sub> vs. La<sub>N</sub>/Yb<sub>N</sub> that Central American tephra is not a likely source material, other REE parameters are necessary to discriminate the other three source materials.

One particularly sensitive REE parameter for provenance studies is the Eu anomaly, described earlier. Volcanic rocks or tephras without a significant continental-crustal component will have no Eu anomaly. Archean sedimentary rocks usually have positive Eu anomalies, but post-



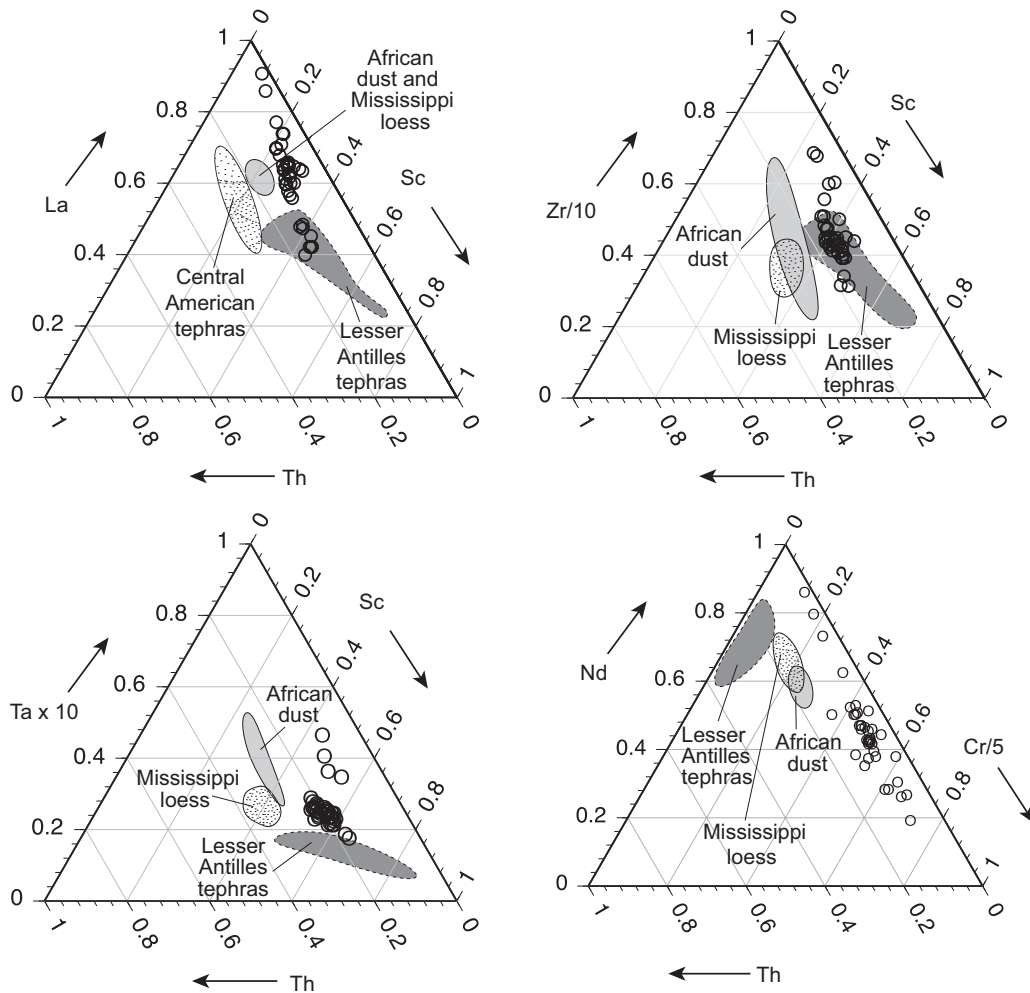


Fig. 13. Ternary diagrams for Sc–Th–La, Sc–Th–Zr, Sc–Th–Ta, and Cr–Th–Nd showing composition of Jamaican soils (shown as open circles; data from this study) and possible source sediments (data for all source sediments from Muhs et al. (2007a), except for Central American tephras, from Drexler et al., 1980).

Archean sedimentary rocks typically have negative Eu anomalies, with  $\text{Eu}/\text{Eu}^*$  values ranging from 0.6 to just under 1.0 (Taylor and McLennan, 1985, 1995; McLennan, 1989). These differences reflect the fact that Archean and post-Archean continental crusts had significant differences in composition, possibly related to different mantle sources or mechanisms of crustal differentiation. Chinese and Alaskan loesses of Quaternary age have  $\text{Eu}/\text{Eu}^*$  values that range from 0.58 to 0.68, and are very similar to post-Archean sedimentary rocks (Gallet et al., 1996; Jahn et al., 2001; Muhs and Budahn, 2006).

Two other measures of REE composition reflect the differences in abundances of light-to-heavy REE. The ratio  $\text{La}_N/\text{Yb}_N$  is a measure of the overall abundances of light REE to heavy REE, and higher  $\text{La}_N/\text{Yb}_N$  values indicate light REE enrichment. Typical post-Archean sedimentary rocks have REE compositions that yield  $\text{La}_N/\text{Yb}_N$  values less than about 15 (Taylor and McLennan, 1985, 1995; McLennan, 1989). Chinese and Alaskan loesses have, for example,  $\text{La}_N/\text{Yb}_N$  values that range from about 7 to 10 (Gallet et al., 1996; Jahn et al., 2001; Muhs and Budahn,

2006). In addition, high  $\text{Gd}_N/\text{Yb}_N$  indicate significant heavy REE depletion. Thus, plots of  $\text{Eu}/\text{Eu}^*$  vs.  $\text{La}_N/\text{Yb}_N$  and  $\text{Eu}/\text{Eu}^*$  vs.  $\text{Gd}_N/\text{Yb}_N$  help define REE compositional fields that are distinctive for sediments that have diverse origins. These REE pairs were used by Nakai et al. (1993) in studying the origin of eolian dust in deep-sea sediments of the Pacific Ocean, and by Sun (2002), in examining the sources of loess in China.

Values of  $\text{Eu}/\text{Eu}^*$ ,  $\text{La}_N/\text{Yb}_N$  and  $\text{Gd}_N/\text{Yb}_N$  are distinct for some of the soil parent materials considered here (Fig. 15). Fields defined by African dust and lower Mississippi River valley loess have considerable overlap, but African dust has generally higher  $\text{Eu}/\text{Eu}^*$ . There is some overlap between the fields defined by African dust and Lesser Antilles tephras, but it is minimal, particularly on the  $\text{Eu}/\text{Eu}^*$  vs.  $\text{La}_N/\text{Yb}_N$  plot. On both plots, the fields for Mississippi River valley loess and Lesser Antilles tephras do not overlap at all.

Soils on Jamaica have  $\text{Eu}/\text{Eu}^*$  values similar to the range found for Barbados samples (Muhs et al., 2007a), have a close overlap with African dust and a partial overlap with

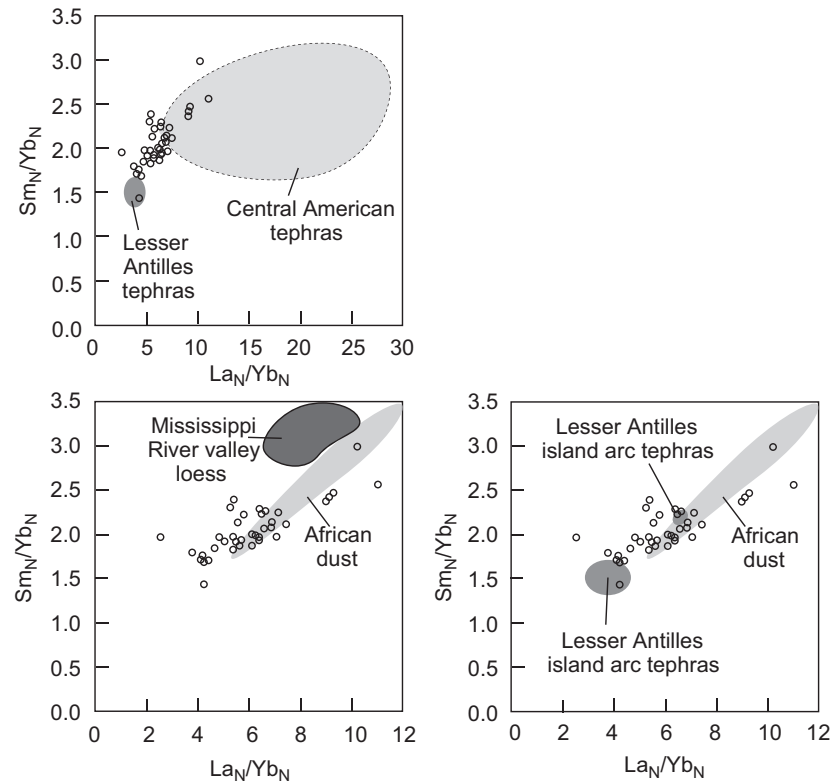


Fig. 14. Plots of  $Sm_N/Yb_N$  vs.  $La_N/Yb_N$  for Central American tephras (data from Clift et al., 2005), Lesser Antilles (Dominica and St. Lucia) tephras (data from Muhs et al., 2007a), African dust and the fine-grained ( $<20\mu m$ ) component of lower Mississippi River valley loess (localities in Muhs et al., 2001; data from Muhs et al., 2007a), and Jamaican soils, shown as circles (this study).

the field defined by Lesser Antilles tephras. Jamaican soils, as well as Barbados soils, have  $Eu/Eu^*$  values that are lower than most of the field defined by Lesser Antilles tephras and higher than those from distal loess of the Mississippi River valley. Unlike Barbados soils, Jamaican soils show generally higher values (and a much greater range) for  $La_N/Yb_N$  and  $Gd_N/Yb_N$ . Although  $La_N/Yb_N$  and  $Gd_N/Yb_N$  values for some Jamaican soils overlap the field for Lesser Antilles tephras, there is closer agreement with the range for African dust, particularly on  $Eu/Eu^*$  vs.  $Gd_N/Yb_N$ . Jamaican soils have no overlap with the field defined by Mississippi River valley loess.

## 6. Discussion

### 6.1. Soil trends with hypothesized ages

The major element abundances in soils on the northern coast of Jamaica show evidence of considerable chemical weathering over time. The abundance of primary rock-forming minerals in these soils appears to be relatively low, based on low amounts of  $K_2O$  and  $Na_2O$ , two elements that reflect the concentrations of feldspars and micas. Instead, XRD analyses of the clay fractions show that the mineral suite is dominated by secondary, phyllosilicate clay minerals. Clay minerals in soils on the younger terraces (WR-A, B and RN-1, 2A, 2B) are, with one unexplained

exception (RN-3) dominated by kaolinite. Clay minerals in soils on the higher terrace (OR-4A and OR-4B) have considerable kaolinite and in addition contain significant amounts of boehmite.

The change in clay mineralogy over time is reflected in progressive loss of Si with concomitant accumulation of Al. Soils on the younger terraces (RN-1, 2A, 2B; WR-A, B) have relatively high  $SiO_2/Al_2O_3$  values, whereas these values are low in soils on the high terrace (OR-4A, B). The  $SiO_2/Al_2O_3$  values for the younger soils are comparable to those for soils on middle-to-late Quaternary-age reef terraces of Barbados (Muhs, 2001). The older soils on Jamaica have  $SiO_2/Al_2O_3$  values similar to those of soils on relatively pure Quaternary carbonate eolianites on the Bahamas (Foos, 1991) and Bermuda (Herwitz and Muhs, 1995).

Jamaican soils show redder colors and higher  $Fe_2O_3$  contents with age. Low-terrace soils have mostly 10YR or 7.5YR hues (although WR-A has 5YR hues), intermediate-elevation terrace soils (RN-2A, B) have mostly 5YR and 2.5YR hues, and the high-terrace soils (OR-4A, B) have 10R hues. This trend in color is mirrored by increasing total  $Fe_2O_3$  contents with relative age, suggesting that much of the Fe in these soils is in the form of hematite. It is common for soils to become redder over time, a reflection of increasing hematite accumulation as a secondary product, at the expense of loss of primary minerals (Birkeland, 1999). Garrett and Lalor (2005) made

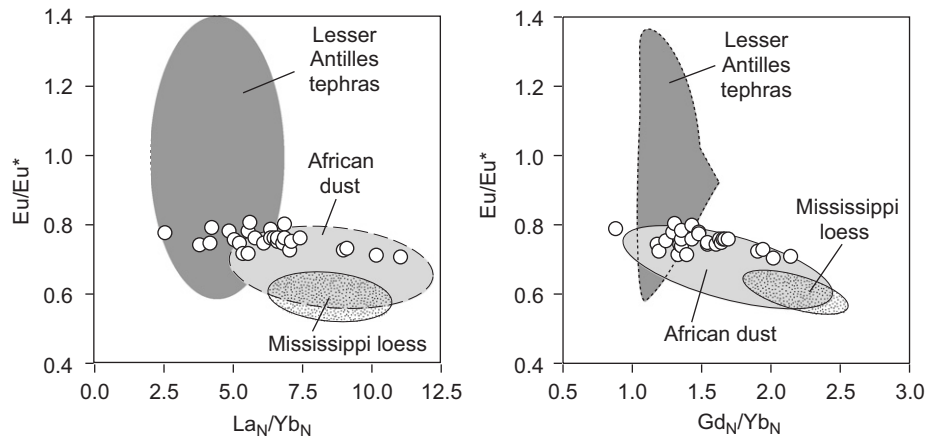


Fig. 15. (a) Plot of  $\text{Eu}/\text{Eu}^*$  vs.  $\text{La}_N/\text{Yb}_N$  for Jamaican soils (shown as circles) and ranges of these values (shown as ellipses) from Lesser Antilles (Dominica and St. Lucia) tephtras, African dust, and the fine-grained ( $<20\ \mu\text{m}$ ) component of lower Mississippi River valley loess. (b) Plots of  $\text{Eu}/\text{Eu}^*$  vs.  $\text{Gd}_N/\text{Yb}_N$  for Jamaican soils (shown as circles) and ranges of these values (shown as ellipses) from tephtras from Dominica and St. Lucia, Saharan dust, and lower Mississippi River valley loess. Data for possible soil parent materials in both plots are from Muhs et al. (2007a).

similar observations for Fe accumulation in other Jamaican soils.

Despite the high degree of chemical weathering that these soils seem to have experienced, none that we studied has a major element geochemistry that resembles high-grade Jamaican bauxite. Lyew-Ayee (1984) summarizes the mineralogy and geochemistry of Jamaican bauxite. Many of the minerals found in Jamaican bauxites—gibbsite, boehmite, kaolinite, hematite, and goethite—are identified in or inferred to be present in the soils we studied. However, with the exception of the oldest soils we studied (OR-4A and OR-4B), Jamaican bauxites have much higher  $\text{Al}_2\text{O}_3$  contents ( $\sim 44\text{--}47\%$ ), higher  $\text{Fe}_2\text{O}_3$  contents ( $\sim 17\text{--}19\%$ ), and lower  $\text{SiO}_2$  contents ( $\sim 0.3\text{--}1.5\%$ ). The high  $\text{Al}_2\text{O}_3$  contents and extremely low  $\text{SiO}_2$  contents reflect the high concentrations of gibbsite and boehmite, the major  $\text{Al}_2\text{O}_3$ -bearing minerals, and low concentrations of kaolinite, the major  $\text{SiO}_2$ -bearing mineral. Hence,  $\text{SiO}_2/\text{Al}_2\text{O}_3$  values in bauxite are very low, on the order of 0.15–0.01.

### 6.2. Sources of Jamaican soils from geochemistry

Major element geochemistry, using  $\text{CaO} + \text{LOI}$  as an indicator of carbonate content, shows that Quaternary limestones of Jamaica are very pure carbonate rocks. Thus, it is unlikely that the terra rossa soils of Jamaica formed by the accumulation of insoluble residues. If this were true, there should also be field evidence of significant carbonate dissolution on the Quaternary limestones. Although there is abundant evidence of limestone dissolution on Jamaica, in the form of spectacular karst geomorphology, these landforms are found mostly on the older, Tertiary limestones.

Immobile element suites, using Ti–Zr–Y, suggest that local igneous rocks cannot explain the origin of terra rossa soils on Jamaica. In theory, local volcanic and plutonic

rocks could be eroded from higher-elevation points on the island and transported onto lower-elevation carbonate surfaces. This material could then weather to form the terra rossa soils. However, Ti–Zr–Y plots show little overlap between local igneous rocks and terra rossa soils on Jamaica.

Immobile trace element geochemistry suggests that terra rossa soils on Jamaica have formed from more than one external parent material. Tephtras from the active Quaternary volcanoes in the Central American arc are a potential source, but a plot of  $\text{Sm}_N/\text{Yb}_N$  vs.  $\text{La}_N/\text{Yb}_N$  shows that this is not likely. However, the same plot indicates that a combination of African dust and Lesser Antilles island arc material could explain the composition of Jamaican soils. This interpretation is supported by Sc–Th–La, Sc–Th–Zr, and Sc–Th–Ta plots. Plots of  $\text{Eu}/\text{Eu}^*$  vs.  $\text{La}_N/\text{Yb}_N$  and  $\text{Eu}/\text{Eu}^*$  vs.  $\text{Gd}_N/\text{Yb}_N$  show that Jamaican soils have some overlap with the field defined by Lesser Antilles island arc tephtras and considerable overlap with African dust. However, Cr–Th–Nd indicates that some high-Cr (likely mafic) source must also contribute to the soils. Thus, on the basis of all these data, we believe that Jamaican soils could be derived from some mix of African dust, Lesser Antilles tephtra, and at least one other (mafic) source, as yet unidentified.

### 6.3. Comparison of Jamaican soils with African dust trajectory and flux modeling

Although we are not aware of any ground-based measurements of dust fall on Jamaica, back-trajectory calculations of dust that reaches the southeastern United States suggest that African dust almost certainly passes over and affects Jamaica (Perry et al., 1997). In addition, there have been at least two recent efforts to model African dust generation and transport across the Atlantic Ocean (Kallos et al., 2006; Mahowald et al., 2006). The model



presented by Kallos et al. (2006) indicates that African dust easily reaches Jamaica and points farther west at the same latitude. Mahowald et al. (2006) modeled dust generation on a global basis during both interglacial (present) and last-glacial (~21 ka) periods. Their models indicate that African dust reaches Jamaica during both glacial and interglacial climatic regimes, but North American dust does not. The dust models of Mahowald et al. (2006) further suggest possible fluxes of around  $2\text{--}5\text{ g m}^{-2}\text{ yr}^{-1}$  in the vicinity of Jamaica during the present interglacial period and fluxes of perhaps  $5\text{--}10\text{ g m}^{-2}\text{ yr}^{-1}$  during the last glacial period. The higher flux of African dust to the Atlantic Ocean during the last glacial period has been well documented from studies of deep-sea cores (see summaries by Mahowald et al., 1999; Kohfeld and Tegen, 2007). Because even the youngest soils we studied, RN-1, WR-A, and WR-B, are found on the last-interglacial Falmouth Formation, all soils in the present work would have been affected by both glacial and interglacial African dust flux rates.

#### 6.4. Implications for bauxite genesis

The results presented here may have implications for bauxite genesis on Jamaica and elsewhere. A persistent problem in bauxite genesis has been the origin of Si, Al, and Fe in these deposits whereas they are usually present only in small amounts in the host limestone. Accumulation of insoluble residues often requires unrealistic or even impossible amounts of carbonate dissolution, as discussed earlier. Fluvial additions often do not explain bauxite genesis where such deposits are found on uplands; this mechanism also begs the question of how the bauxitic deposits, later transported, formed in the first place. Thus, in the past few decades, there is an increasing recognition that external sources, such as volcanic ash (Comer, 1974, 1984; Comer et al., 1980) or airborne dust (Lyew-Ayee, 1984; Brimhall, 1988; Pye, 1988) must play a role in bauxite genesis.

The geochemical studies of Quaternary, terra rossa-type soils on Jamaica, reported here, suggest that both volcanic ash and airborne dust may play important roles in soil genesis on relatively pure Quaternary limestones. Although these soils do not have the high  $\text{Al}_2\text{O}_3$  and  $\text{Fe}_2\text{O}_3$  contents and low  $\text{SiO}_2$  contents of Jamaican bauxites, they are nevertheless far closer in composition to bauxites than are typical, mid-latitude soils of Quaternary age (see examples in Birkeland, 1999). We suggest, therefore, that the soils on Quaternary limestones on the northern coast of Jamaica may represent the early stages of bauxite formation, derived from a combination of high-Al-and-Fe airborne dust from Africa and high-Si, tephra-derived glass from the Lesser Antilles island arc.

#### 7. Conclusions

Reddish-brown or red terra rossa soils are found on emergent limestones of probable Quaternary age on the

northern coast of Jamaica. The soils show progressive changes in development that are expressed in morphology, mineralogy, and geochemistry, and indicate increasing thickness, loss of mobile constituents, accumulation of immobile constituents, and mineral alteration over time. The soils have a composition that suggests they may be precursors to the older, well-developed, aluminum-rich bauxites found elsewhere on Jamaica. Because the host limestones are relatively pure, accumulation of insoluble residues is not a likely pathway of soil formation. Trace element geochemistry also indicates that local volcanic and plutonic rocks play a minor role, if any, in soil genesis. Rare earth elements and suites of other trace elements indicate that Jamaican soils have probably formed from at least two, and possibly three extraneous parent materials. Most geochemical data indicate that the soils formed primarily by alteration of a combination of volcanic ash from the Lesser Antilles island arc and airborne dust from Africa.

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