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Most previous workers have regarded the insoluble residues of high-purity Quaternary limestones (coral reefs and oolites) as the most important parent material for well-developed, clay-rich soils on Caribbean and western Atlantic islands, but this genetic mechanism requires unreasonable amounts of limestone solution in Quaternary time. Other possible parent materials from external sources are volcanic ash from the Lesser Antilles island arc and Saharan dust carried across the Atlantic Ocean on the northeast trade winds. Soils on Quaternary coral terraces and carbonate eolianites on Barbados, Jamaica, the Florida Keys (United States), and New Providence Island (Bahamas) were studied to determine which, if either, external source was important. Caribbean volcanic ashes and Saharan dust can be clearly distinguished using ratios of relatively immobile elements (Al_2O_3/TiO_2, Ti/Y, Ti/Zr, and Ti/Th). Comparison of these ratios in 25 soils, where estimated ages range from 125,000 to about 870,000 yr, shows that Saharan dust is the most important parent material for soils on all islands. These results indicate that the northeast trade winds have been an important component of the regional climatology for much of the Quaterary. Saharan dust may also be an important parent material for Caribbean island bauxites of much greater age.

INTRODUCTION

The Caribbean and western Atlantic islands of Barbados, Bermuda, Jamaica, Hispaniola, Puerto Rico, the Bahamas, and the U.S. Florida Keys are characterized by coastal terrains comprising Quaternary limestones, mostly in the form of emergent coral reefs and/or calcareous eolianite. Although these limestones are usually of high purity (95–100% $CaCO_3$), often developed on them are soils containing high (up to 99%) concentrations of aluminosilicate clays. Muhs *et al.* (1987b) summarized four previously proposed modes of origin for these soils: (1) accumulation of insoluble residues from the underlying carbonate rock; (2) fluvial deposition of clays onto limestone surfaces from higher slopes; (3) weathering of volcanic ash that has fallen onto the limestone surfaces; and (4) weathering of eolian silt and clay that have accumulated on these surfaces.

Ahmad *et al.* (1966), Ahmad and Jones (1969a, b), and recently Scholten and Andriesse (1986) studied soils on Quaternary and Tertiary limestones on Jamaica, Barbados, the Bahamas, and the Cayman Islands and concluded that insoluble residues in the limestones were the parent materials for the soils. The main evidence cited for a residual origin in these studies was a similar clay mineralogy in the soils and in the insoluble residues. On Barbados, Muhs *et al.* (1987b) studied clay-rich soils that had formed on limestone terraces that are about 125,000 and 190,000 yr old, and presented pedologic and geomorphic evidence to reject the re-

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sidual hypothesis and the fluvial depositional hypothesis. Muhs *et al.* (1987b) showed that geologically unreasonable amounts of limestone solution (20 to 25 m) in the late Quaternary would be necessary to generate soils on Barbados by the residual process. In contrast, these investigators used trace-element geochemistry to show that although volcanic ash from the nearby island of St. Vincent probably provided some of the parent material for the soils, the most important parent material is eolian silt and clay transported by the northeasterly trade winds from the Saharan desert. Foos (1987) also thought that soils and paleosols on San Salvador Island in the Bahamas were derived form Saharan dust.

In this article, we test the eolian hypothesis by studies of 25 soil profiles developed on Quaternary limestones on Barbados, Jamaica, New Providence Island, Bahamas, and the Florida Keys (Fig. 1). We also studied two soils developed on late Quaternary volcanic ash on St. Vincent and two bauxites (aluminum-rich soils) developed on Tertiary limestones in Haiti. We here refer to both emergent coral reef terraces and calcareous eolianites as limestones because both generally have noncarbonate impurites of less than 5%. By studying soils on widely separated islands and on surfaces of different ages we hoped (1) to determine the possible areal extent of eolian parent material derived from distant sources and (2) to determine how important eolian influences may have been throughout much of the Quaternary.

AGES OF QUATERNARY LIMESTONES

Implicit in our studies of soils on all islands is the assumption that the age of the underlying limestone is a reasonable approximation of the beginning of pedogenesis. We recognize that U-series ages of the underlying limestones are in reality maximum ages of the soils. However, it is likely that pedogenesis began shortly after emergence of the reef terraces, when the surfaces were first subaerially exposed, or soon after stabilization of the dune surfaces, in the case of eolianites.

We studied a soil chronosequence on emergent coral terraces of Barbados in the Clermont Nose area where Bender *et al.* (1979) mapped and named the terraces (Fig. 2). We described and sampled soils on terraces that have $^{230}Th/^{234}U$ ages (of coral) of 125,000, 190,000, and 220,000 yr; two older terraces have concordant $^{4}He/U$ and electron spin resonance ages of about 320,000 and 430,000 yr (Mesolella *et al.*, 1969; Bender *et al.*, 1979; Edwards *et al.*, 1987; Radtke *et al.*, 1988). We also sampled a soil on one of the highest coral terraces on the island (not shown on Fig. 2); using an assumed constant uplift rate of 0.44 m/1000 yr derived from the age and elevation of the 125,000 yr terrace, we estimate that the older coral reef is about 700,000 yr old. All soils were sampled on 0–5% slopes near uncultivated reef crests under a cover of sour grass, except for the oldest soil, which supported a field of sugar cane.

Emergent coral reefs on Jamaica have not received as much attention as those on Barbados and we are much less certain about their ages. Cant (1970, 1973) reported that the best developed terraces are in the Oracabessa area, which is between Ocho Rios and Port Maria (Fig. 3). Remnants of the lowest terrace on the north coast of Jamaica, thought by Cant (1973) to be correlative all along this coast, have concordant $^{230}Th/^{234}U$ and $^{231}Pa/^{235}U$ ages from coral that range from about 120,000 to 140,000 yr (Moore and Somayajulu, 1974; Szabo, 1979). All corals that we examined on higher terraces are largely recrystallized to calcite, and are therefore unsuitable for U-series dating. Cant (1973) reported that deposits of the highest terrace in the Oracabessa area have reversed magnetism, and thus must be older than 730,000 yr. Cant (1973) also thought that the second and all higher terraces at Oracabessa had been uplifted at a rate of 0.21 m/1000 yr, significantly higher than the rate of 0.065 m/1000

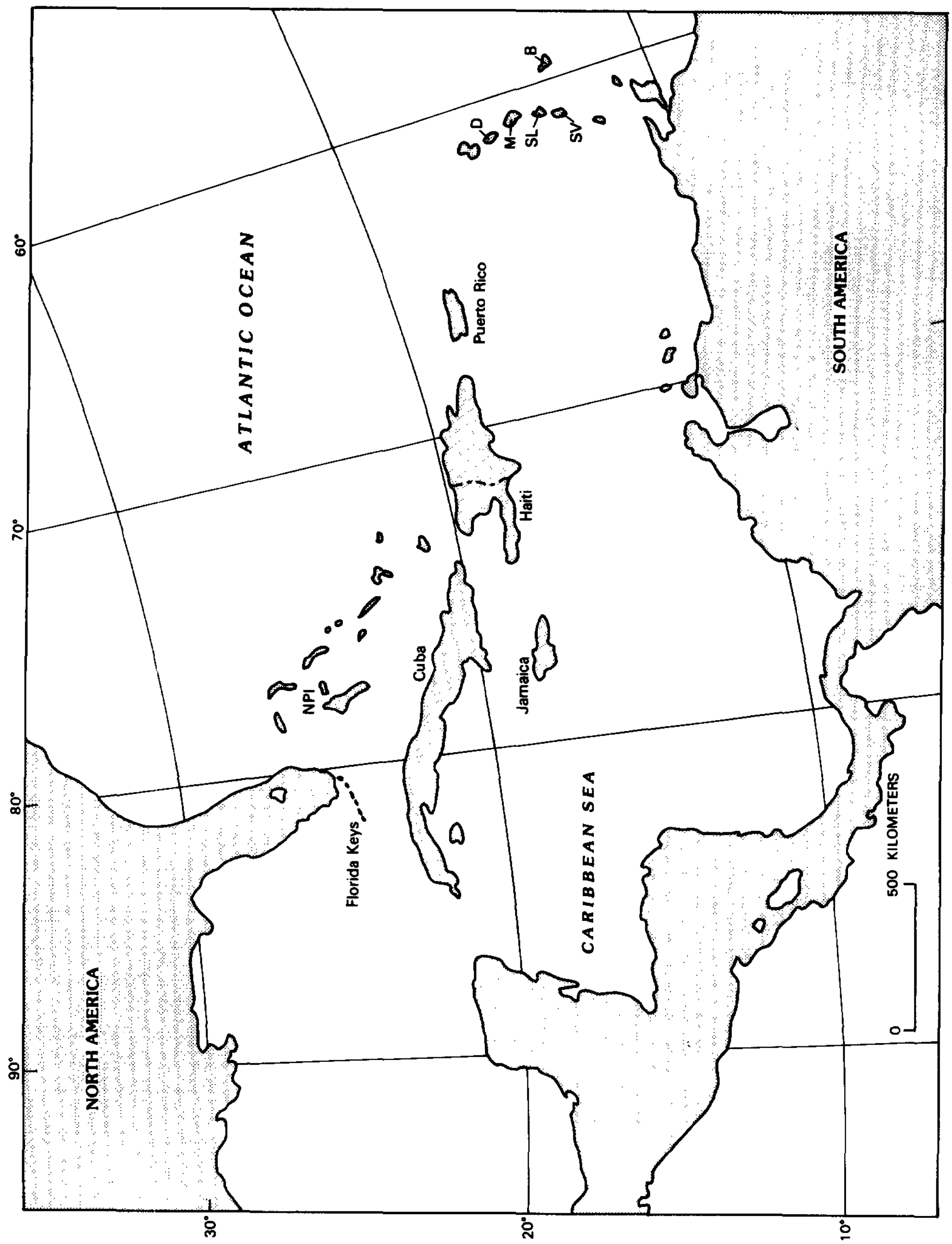

FIG. 1. Map of the Caribbean and western Atlantic showing localities studied or referred to in the text. NPI, New Providence Island; B, Barbados; D, Dominica; M, Martinique; SL, St. Lucia; SV, St. Vincent.

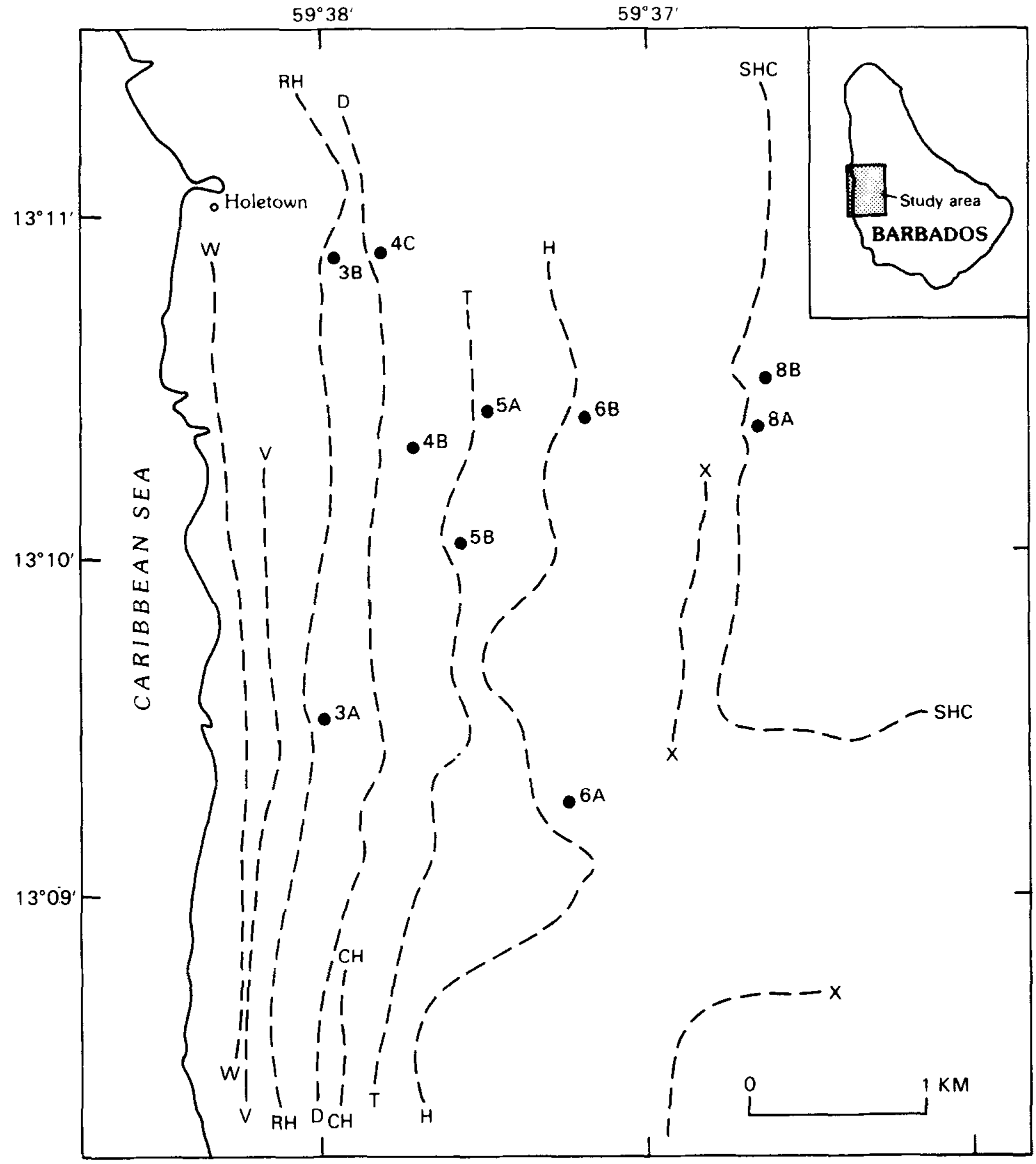

FIG. 2. Map of the Clermont Nose study area of western Barbados showing crests of reefs (dashed lines) and soil pit localities. Profile numbers are keyed to Appendix 2. Terrace abbreviations and ages are as follows (Mesolella et al., 1969; Bender et al., 1979): W = Worthing (80,000 yr); V = Ventnor (105,000 yr); RH = Rendezvous Hill (125,000 yr); D = Durants (190,000 yr); CH = Cave Hill (200,000 yr); T = Thorpe (220,000 yr); H = Husbands (320,000 yr); X = Unnamed and undated terrace; SHC = Second High Cliff (430,000 yr).

yr for the 125,000-yr terrace. Thus, he thought that the second terrace at Oracabessa was about 200,000–300,000 yr old. We were unable to find uncultivated or undisturbed soils on all terraces of any one shore-normal transect on the north coast of Jamaica. Therefore, our chronosequence comprises (1) soils (OR-A, OR-B) on a low terrace less than 15 m above sea level just east of Ocho Rios, which we assumed to be 125,000 yr old, (2) soils (RN-2A, RN-2B, RN-3) on ca 44- and ca. 63-m terraces be-

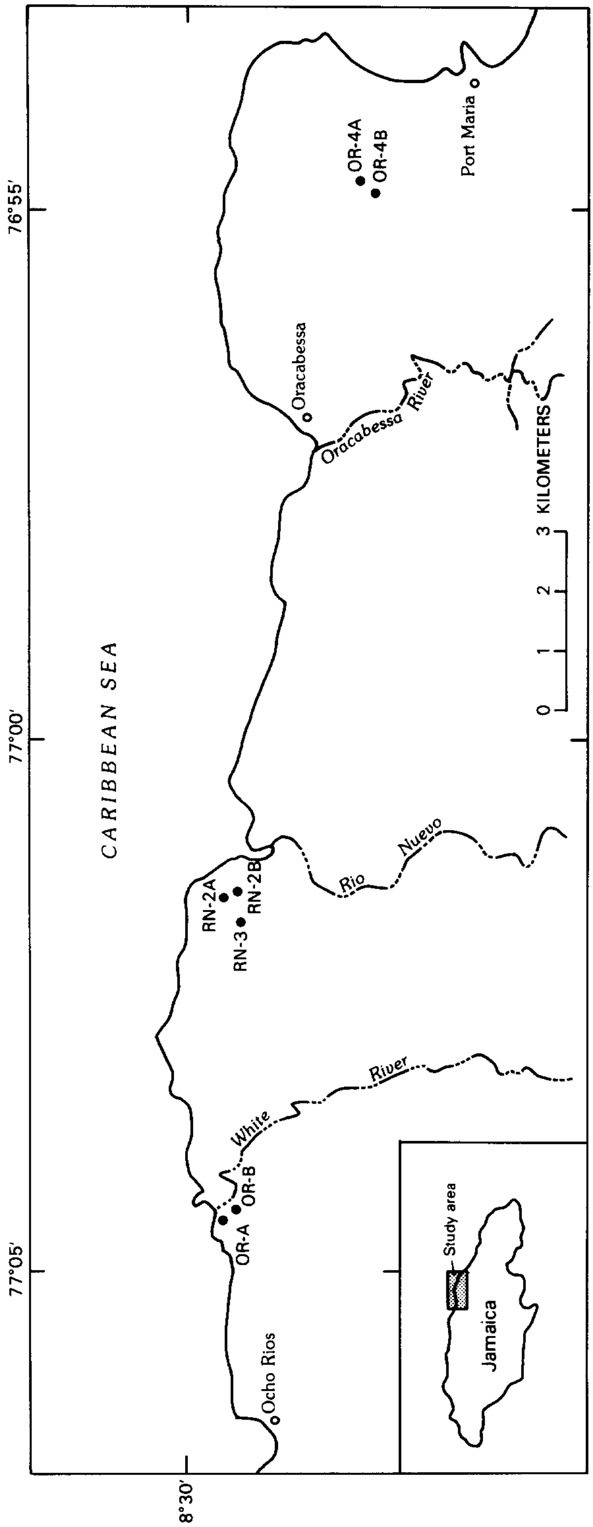

FIG. 3. Map of study area on the north coast of Jamaica between Ocho Rios and Port Maria. Soil pit localities are keyed to Appendix 2.

tween Ocho Rios and Oracabessa (near the mouth of Rio Neuvo), which we tentatively estimate to be about 200,000 and 300,000 yr old, respectively [using Cant's (1973) uplift rate of 0.21 m/1000 yr], and (3) soils (OR-4A, OR-4B) on the fourth, 183-m terrace of Cant (1970, 1973) at Oracabessa, which is >730,000 yr old by paleomagnetism and about 870,000 yr old using an uplift rate calculation (Fig. 3).

On tectonically stable New Providence Island in the Bahamas, calcareous (generally oolitic) upper and middle Pleistocene eolianites form prominent ridges over the northern and central parts of the island (Fig. 4). We sampled a soil (NPI-1) on Garrett and Gould's (1984) "unit ii" eolianite at Lyford Cay, and the paleosol (NPI-2) between their units i and ii at the same locality (Fig. 5). We also sampled a red, clay-rich paleosol (NPI-3) found between two oolitic eolianites, which were newly exposed during quarrying near Garrett and Gould's (1984) East Street locality. Uranium-series ages of aragonite separates of ooids and/or peloids from these eolianites are ca. 125,000 yr for unit ii at Lyford Cay, ca. 200,000 yr for unit i at Lyford Cay, and ca. 300,000 yr for the lower unit at the East Street locality (Muhs *et al.*, 1987a; D. R. Muhs and C. A. Bush, unpublished data).

The surficial geologic units of the Florida Keys are the Miami Oolite and the Key Largo Limestone (coral reef); the contact between these two units is found on Big Pine Key (Fig. 6). Coniglio and Harrison (1983) thought the Miami limestone was deposited during the same high sea-level stand in which the Key Largo limestone was deposited. Szabo and Halley (1988) reported an age of 145,000 ± 10,000 yr for pure aragonitic coral in the Key Largo Limestone. We found that soils on most of the upper Florida Keys (where the Key Largo Limestone is the surficial unit) are thin or absent and mangrove vegetation dominates the surfaces of many of these small islands. However, we did find patchy, reddish, clay-rich remnants of soil B horizons on Windley Key, and similar remnants of B horizons adhering to fragments of Key Largo Limestone on quarry spoil piles on Grassy Key, Long Key, and No Name Key (Fig. 6). We suspect that because the Florida Keys rise less than about 10 m above sea level, tropical storms and hurricanes may have removed soils by erosion faster than they could develop.

VOLCANIC ASH AS A POTENTIAL SOIL PARENT MATERIAL

The Lesser Antilles volcanic arc has been active during the Quaternary, and its eruptions have generated pyroclastic debris that could be deposited on distant islands. Eruptions in this arc have been mainly of two types: highly explosive silicic eruptions such as those that have been documented in Quaternary time from Dominica, Martinique, St. Lucia, and Guadeloupe, and less explosive, more basic eruptions such as those from St. Vincent (Fig. 1). Because of St. Vincent's proximity to Barbados and historical documentation of ash falls there (Flett, 1902; Harrison *et al.*, 1980), it was the only volcanic ash source that was considered by Muhs *et al.* (1987b) in their study of two Barbados soils. However, the relatively small eruptions from St. Vincent were unlikely to have generated significant amounts of ash that could have been carried as far away as Jamaica, Florida, and the Bahamas. Patterns of ash fall derived from marine cores indicate that most of the ashes from eruptions on St. Vincent were deposited to the east of the volcanic arc, due to ash transport by the antitrade winds at altitudes of 7–16 km (Carey and Sigurdsson, 1978). However, minor amounts of ash from the 1902 eruption on St. Vincent were found on Jamaica (Anderson and Flett, 1903), and this easterly direction of ash transport has been attributed to the stratospheric upper easterly winds, at altitudes above 17 km (Carey and Sigurdsson, 1978).

On the other hand, ash in highly explosive eruptions from silicic centers such as Dominica are capable of being carried to

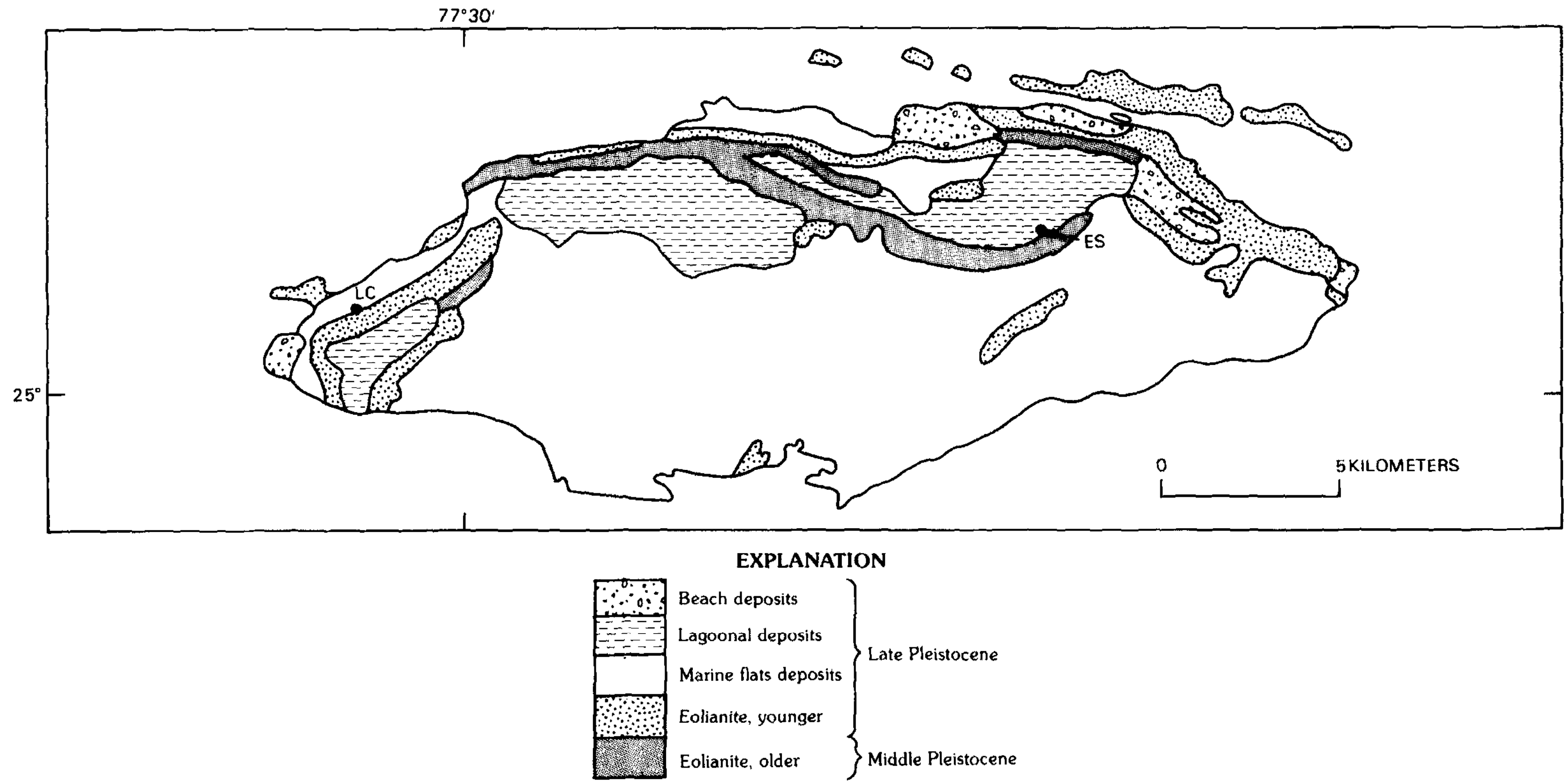

FIG. 4. Map of Quaternary deposits on New Providence Island, Bahamas, and locations of soil profiles. Profiles NPI-1 and NPI-2 (Appendix 2) are from the Lyford Cay (LC) locality; profile NPI-3 is from the East Street (ES) locality. Quaternary geology modified from Garrett and Gould (1984).

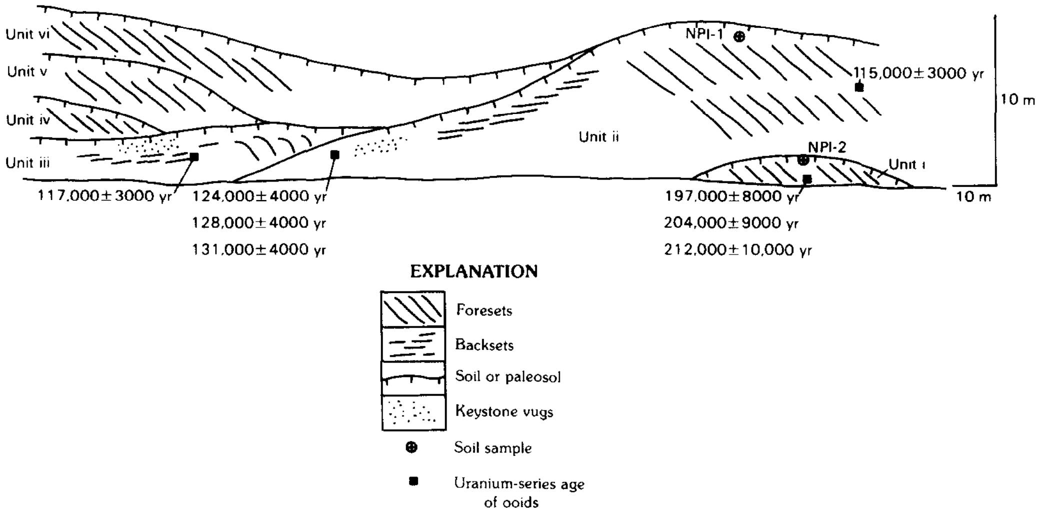

FIG. 5. Sketch of roadcut exposure of oolitic eolianites and paleosols at the Lyford Cay locality on New Providence Island, Bahamas. Uranium-series ages are from Muhs et al. (1987a) and D. R. Muhs and C. A. Bush (unpublished data). Stratigraphy is from Garrett and Gould (1984).

high altitudes and for great distances. Traces of ash from a 30,000-yr-old eruption on Dominica have been found in a marine core in the Caribbean Sea, 1200 km to the west of the arc (Carey and Sigurdsson, 1980). Analysis of a core taken 50 km east of Martinique indicates that ash from Dominica has been the most abundant pyroclastic material in the past ca. 600,000 yr; ash from St. Lucia appears to have been more important before 600,000 yr B.P. (Sigurdsson *et al.*, 1980). Sigurdsson *et al.* (1980) also showed that the ratio of crystals to glass decreases rapidly away from the source after reaching a maximum value about 100 km from the source. At distances of about 700 km from the source, little crystalline material is present in the ash. The implication of this relation is that ash falls on islands more than about 700 km from sources such as Dominica (Jamaica, Florida Keys, Bahamas) would be composed primarily of glass. Hence, we have chosen to compare the geochemistry of volcanic glass (rather than bulk ash) from Dominica to soils and to Saharan dust.

Using data from a number of cores taken around the Lesser Antilles volcanic arc, Sigurdsson *et al.* (1980) generated isopach maps showing the cumulative thickness of ash deposited in the past 100,000 yr. In the vicinity of Barbados, cumulative ash thickness for the past 100,000 yr is on the order of 30 cm, with an estimated bulk density of 1.1 g/cm^3 (Sigurdsson and Carey, 1981, Table 1). Because soils on the 125,000 yr-old-terrace on Barbados are 40–93 cm thick and have a much higher bulk density (1.47–1.65 g/cm^3) than volcanic ash, it is clear that ash cannot be the only external parent material.

SAHARAN DUST AS A POTENTIAL SOIL PARENT MATERIAL

Darwin (1846) was one of the first investigators to call attention to north African dust being deposited in the North Atlantic. Delaney *et al.* (1967) were among the earliest workers to hypothesize that dust collected on Barbados was derived from the Sahara via the northeasterly trade winds. This has been confirmed by studies of satellite imagery and by detailed measurements of the dust flux at Sal Island, Barbados, and Miami, Florida (Prospero *et al.*, 1970; Savoie and Prospero, 1977; Prospero, 1981; Prospero and Nees, 1986; Talbot *et al.*, 1986). Additional confirmation has

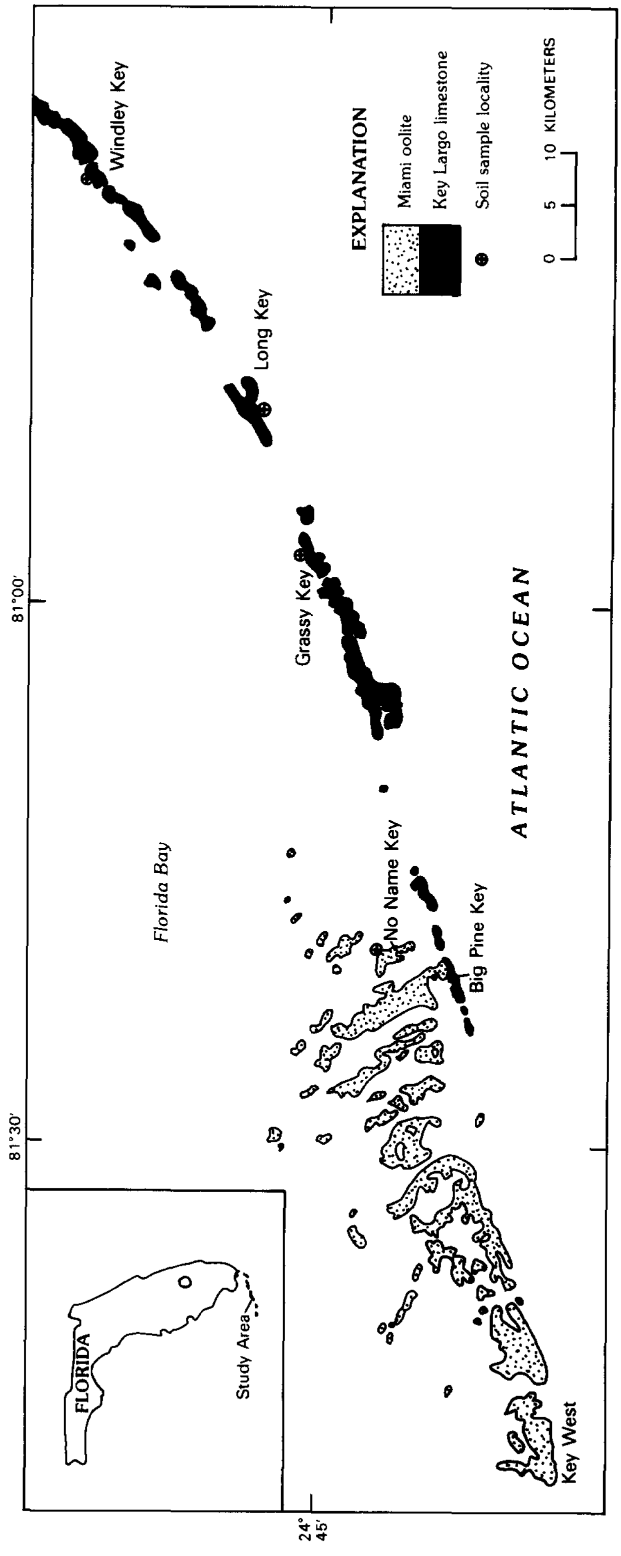

FIG. 6. Map of the Florida Keys showing Quaternary deposits and soil localities. Geology from Coniglio and Harrison (1983).

come from Sr and Nd isotope studies of dust collected at Barbados and North Atlantic marine sediments (Biscaye *et al.*, 1974; Grousset *et al.*, 1988). Droughts in north Africa increase the flux of dust at Barbados (Prospero and Nees, 1977, 1986). Contemporary dust deposition rates for the tropical North Atlantic have been estimated to be 0.4–0.5 g/cm^2/1000 yr (Glacuum and Prospero, 1980); a direct 1-yr measurement at Miami gave an extrapolated rate of about 0.13 g/cm^2/1000 yr (Prospero *et al.*, 1987). These dust deposition rates are probably minima for the Quaternary, because studies of deep-sea cores from the North Atlantic indicate that dust deposition rates were probably higher during glacial ages (Bowles, 1975; Kolla *et al.*, 1979; Pokras and Mix, 1985).

The sources, destinations, and flux magnitudes of Saharan dust vary through the seasons. During the northern hemisphere summer, dust is derived largely from the western and central Sahara (Kalu, 1979) and transported west on the trades in a latitudinal belt extending from about 10° to 25°N (Prospero, 1981). On the basis of ratios of V/Al and V/Mn in aerosol particles, Chen and Duce (1983) suggested that Saharan dust may even be carried as far north as Bermuda (lat. 32°20′ N). During the northern hemisphere winter, dust is derived from the southeast edge of the Sahara, and transport occurs along a belt extending from about 5° to 15° N (Prospero, 1981). This shift is consistent with measurements of dust flux at Barbados, which are highest in summer and 10–100 times lower in winter (Prospero and Nees, 1977). In contrast, dust flux is at a maximum in winter and early spring at Cayenne, French Guiana (4°52′ N), based on Prospero *et al.'s* (1981) measurements over a 2-yr period.

Several laboratory studies of Saharan dust have shown a consistent mineralogy and particle-size distribution. Dust collected at Barbados and Miami, approximately 2400 km apart, does not differ significantly in mineralogy; the dominant minerals are mica/illite and quartz, with much smaller amounts of kaolinite, chlorite, montmorillonite, microcline, plagioclase, and calcite (Delaney *et al.*, 1967; Prospero *et al.*, 1970; Glaccum and Prospero, 1980). Almost all of the dust collected at Barbados and Miami consists of particles less than 10 μm diameter, and 40–55% of the particles are less than 2 μm (i.e., clay size) in diameter (Prospero *et al.*, 1970). Mica/illite dominates the clay fraction whereas quartz dominates the silt fraction. Soils on Barbados have a clay mineralogy dominated by interstratified kaolinite-smectite (younger soils) or relatively pure kaolinite (older soils). Younger soils on Jamaica have mostly kaolinite; older soils have kaolinite and boehmite. Barbados soils that we studied have clay contents ranging from 43 to 99% (on a $CaCO_3$-free basis), with most horizons having 70–95% clay.

METHODS

Our method of identifying soil parent materials is by geochemical "fingerprinting" following the approach of Muhs *et al.* (1987b). In order to characterize parent materials chemically and compare them to the soils, it is essential to use elements that are relatively immobile in soils and in the near-surface geologic environment. The reason for this is that many elements are lost from soils by various processes of chemical weathering, particularly in warm, humid tropical environments such as the Caribbean and western Atlantic area. Suitable elements for fingerprinting are those that have a high ionic potential, which is defined as the charge divided by the ionic radius (Mason and Moore, 1982). We chose the elements Al, Ti, Y, Zr, Th, and Nb, all of which have ionic potentials greater than 3.00.

In order to derive immobile element ratios for soils, we analyzed the <2-mm fraction of each soil horizon separately and then reduced these data by computing a ratio for the entire profile. These single values for each profile were calculated by determining the mass of each element in a 1-cm^2 column of soil using the element concentrations, horizon thicknesses, and bulk densities (using the paraffin-coated clod method), following the method used by Muhs (1982). We lack bulk density data for all soils except those on Barbados; for soils on the other islands, ratios were determined by using horizon thickness as proxy "weights" for the concentration of each element in each horizon. Analytical methods, with estimates of precision, are given in Appendix 1 and complete analytical results are given in Appendix 2. Most soils had Nb contents below detection limits (Appendix 2); therefore, we used only Al_2O_3, TiO_2, Zr, Y, and Th data.

GEOCHEMISTRY OF ASHES, SAHARAN DUST, AND SOILS

The silicic volcanic centers on Dominica appear to have been the most important source of ash in the Caribbean and western Atlantic in the past 600,000 yr (Sigurdsson *et al.*, 1980). Therefore, we calculated Al_2O_3/TiO_2 ratios for Dominica glass shards (from the Roseau ash) using data in Carey and Sigurdsson (1980). Ratios of Al_2O_3/TiO_2 for Saharan dust, collected at Barbados, were calculated from data of Glaccum (1978). The mean Al_2O_3/TiO_2 ratio in glass shards from Dominica is 67 ± 15 (1σ), much higher than the mean ratio in Saharan dust, which is 15 ± 3 (1σ) (Fig. 7). Difference-of-means tests (*t* tests) show that Al_2O_3/TiO_2 ratios in Dominica glass and Saharan dust are significantly different at the 99.9% confidence level. Thus, Al_2O_3/TiO_3 ratios are useful for discriminating between Dominica glass and Saharan dust and provide two discrete data sets for comparison with Caribbean and western Atlantic island soils. We made a single analysis of the nonglass component of the Roseau ash from Dominica and calculated an Al_2O_3/TiO_2 ratio of 32. This is a factor of two lower than the same ratio in the glass fraction, but is

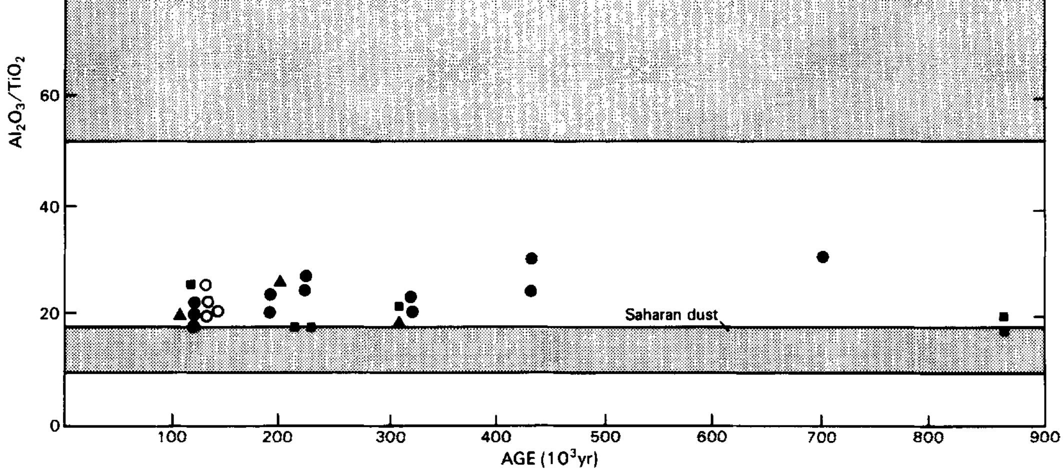

FIG. 7. Ratios of Al_2O_3/TiO_2 in soils as a function of terrace or eolianite age estimate. Also shown for comparison are Al_2O_3/TiO_2 ratios from Dominica glass and Saharan dust; shaded areas represent the mean values ± 1 standard deviation. Dominica glass data are from Carey and Sigurdsson (1980); Saharan dust data are from Glaccum (1978).

still significantly higher than the Al_2O_3/TiO_2 ratio in Saharan dust.

Although Dominica has probably been the most important source for ash falls on islands distant from the source, historical data summarized by Muhs *et al.* (1987b) indicate that the Soufriere volcano on St. Vincent may have been an important nearby source of ash for Barbados. Ratios of crystal/glass as a function of distance from St. Vincent suggest that ash falls on Barbados would have been equal amounts of crystal and glass (Carey and Sigurdsson, 1978). Therefore, we used Muhs *et al.'s* (1987b) analyses of bulk ash (also given in Appendix 2) to calculate element ratios for St. Vincent. St. Vincent ashes have a mean Al_2O_3/TiO_2 ratio of 18 ± 2, which overlaps the range of 15 ± 3 for Saharan dust (Fig. 7). Thus, we used Ti/Y, Ti/Zr, and Ti/Th ratios to distinguish St. Vincent ash from Saharan dust. St. Vincent ash has a mean Ti/Y ratio of 335 ± 35, whereas Saharan dust has a mean ratio of 150 ± 22 (Fig. 8). Similarly, the mean Ti/Zr and Ti/Th ratios in St. Vincent ash are 78 ± 12 and 5263 ± 1775 compared to Ti/Zr and Ti/Th ratios of 37 ± 3 and 487 ± 122, respectively, in Saharan dust (Figs. 9 and 10). Difference-of-means tests (*t* tests) show that Ti/Y, Ti/Zr, and Ti/Th ratios in St. Vincent ash and Saharan dust are significantly different at the 99.9% confidence level.

The Al_2O_3/TiO_2 ratios of the soils show some scatter, but in general indicate that Saharan dust is more important than Dominica glass as a parent material for soils on all islands (Fig. 7). Most soils have ratios that plot between the two parent material fields, and *t* tests show that the soils have Al_2O_3/TiO_2 ratios that are significantly different (at the 99.9% confidence level) from either Dominica glass or Saharan dust. However, when compared graphically (Fig. 7), all soils are much closer to Saharan dust than to Dominica glass. Barbados soils generally show the highest Al_2O_3/TiO_2 ratios, and suggest that there may have been some minor influence of Dominica ash in the genesis of these soils; this interpretation is rea-

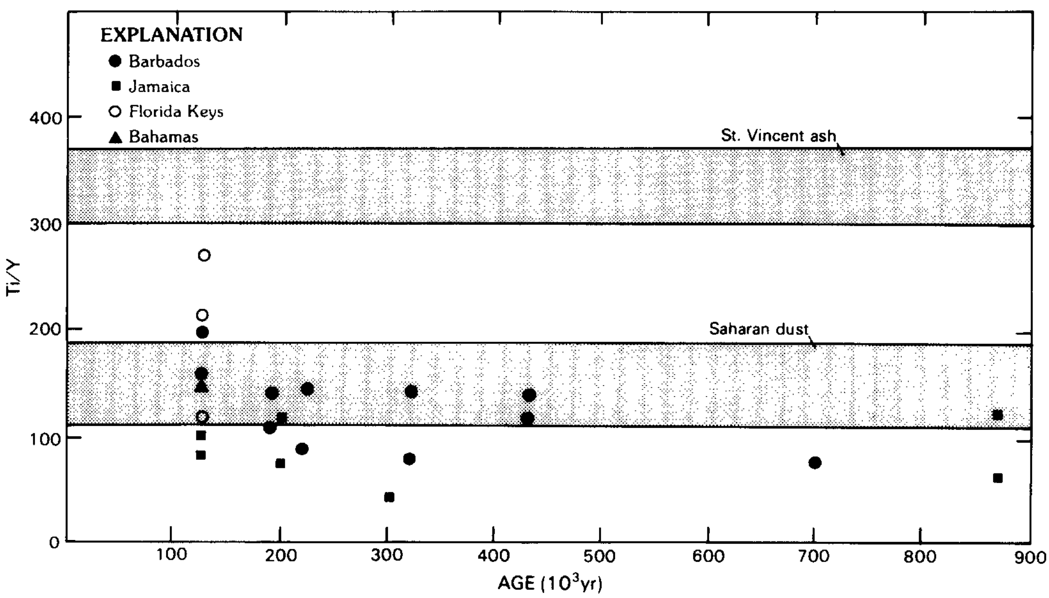

FIG. 8. Ratios of Ti/Y in soils as a function of terrace or eolianite age estimate. Also shown for comparison are Ti/Y ratios in St. Vincent bulk ash and Saharan dust; shaded areas represent the mean values ± 1 standard deviation. St. Vincent ash data are from Muhs et al. (1987b) and Appendix 2; Saharan dust data are from Glaccum (1978).

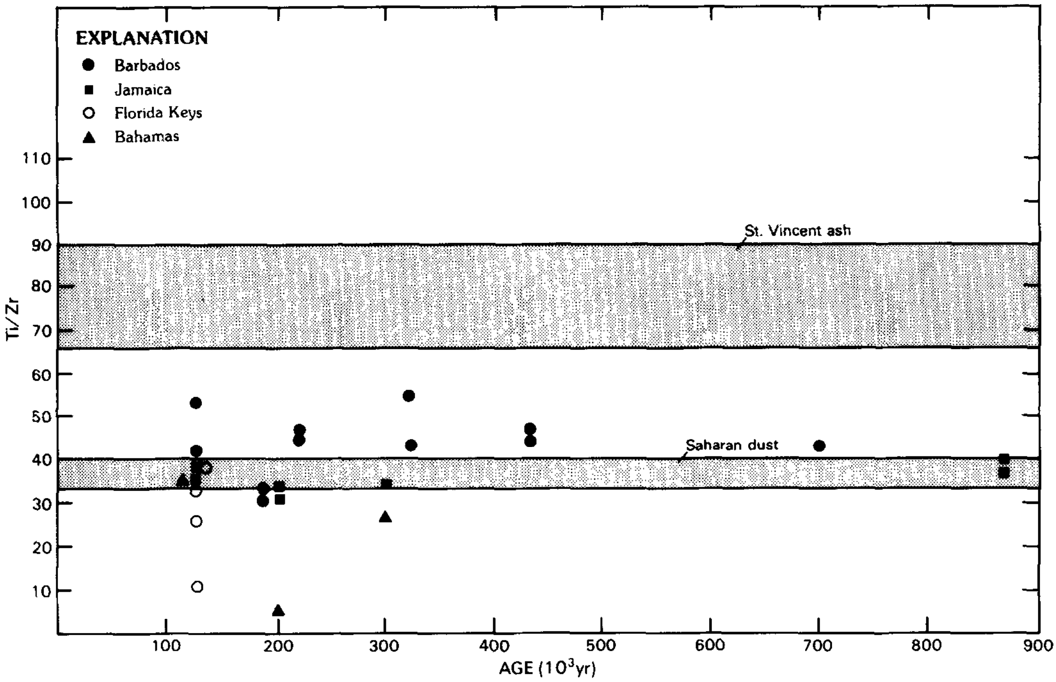

FIG. 9. Ratios of Ti/Zr in soils as a function of terrace or eolianite age estimate. Also shown for comparison are Ti/Zr ratios in St. Vincent bulk ash and Saharan dust; shaded areas represent the mean values ± 1 standard deviation. St. Vincent ash data are from Muhs et al. (1987b) and Appendix 2; Saharan dust data are from Glaccum (1978).

sonable because Barbados is closer to Dominica than any of the other islands where we studied soils (Fig. 1).

In order to assess the importance of St. Vincent ash versus Saharan dust as a parent material for the soils, particularly for soils on nearby Barbados, we used Ti/Y, Ti/Zr, and Ti/Th ratios. The t tests show that the mean Ti/Y, Ti/Zr, and Ti/Th ratios for the soils are significantly different from mean ratios for St. Vincent ash, but are not significantly different from Saharan dust, at the 99.9% confidence level. Ti/Y ratios for most soils from Barbados, Jamaica, the Florida Keys, and one soil profile on New Providence Island plot within, or close to, the range of values for Saharan dust (Fig. 8). Two of our soil profiles form New Providence island have Y concentrations below detection levels (2 ppm), so Ti/Y values cannot be calculated. For both Ti/Zr and Ti/Th, Barbados soils plot closer to the range of values for St. Vincent ash than do the other soils, although the Barbados soils are closest to the range of values for Saharan dust (Figs. 9 and 10). This suggests that although Saharan dust is the most important parent material for Barbados soils, ash falls from eruptions on St. Vincent may have influenced soil trace element composition to some degree.

In order to see the possible effects of weathering of volcanic ash on element ratios, we studied two soils developed on volcanic ashes on the island of St. Vincent (Fig. 1). One of these soils has developed on a Pleistocene ash; the other has developed on a Holocene ash. Weathering processes in both soils were previously studied by Hay (1959, 1960). If the use of our element ratios is valid, we would expect the Ti/Y, Ti/Zr, and Ti/Th ratios of the soils to reflect the chemical composition of the ashes. On the other hand, the island of St. Vincent is within the trade wind belt of the Caribbean where Saharan dust is delivered

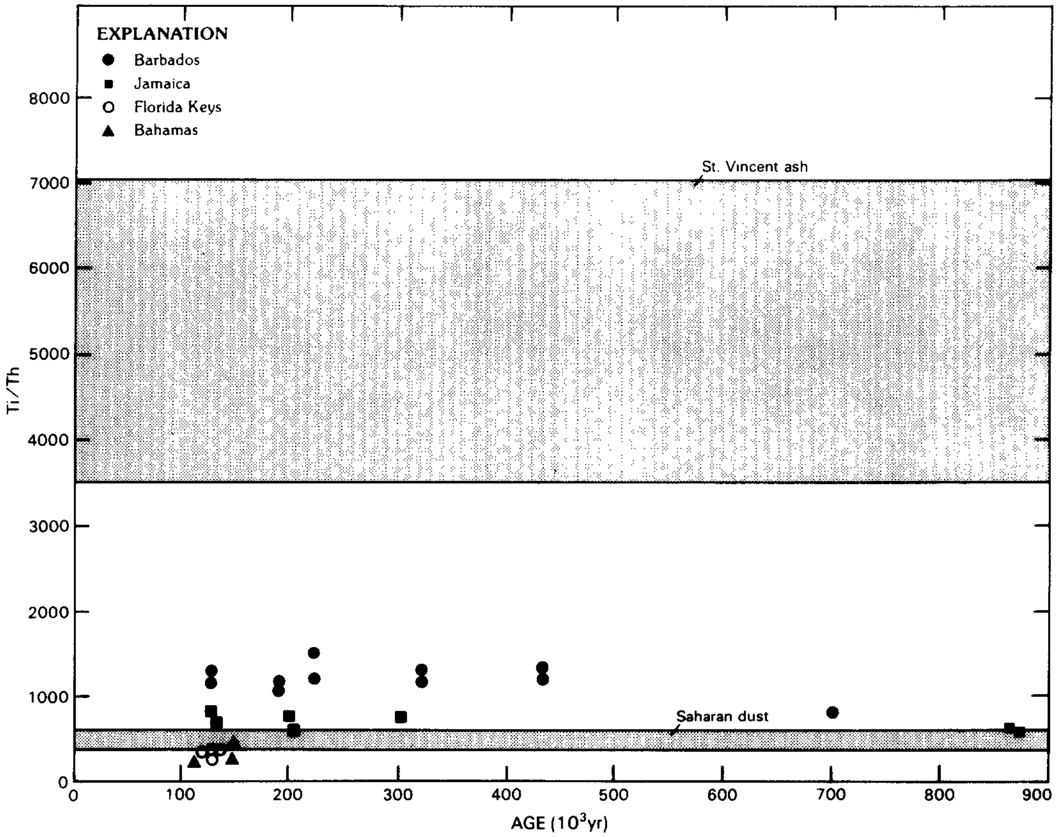

FIG. 10. Ratios of Ti/Th in soils as a function of terrace or eolianite age estimate. Also shown for comparison are Ti/Th ratios in St. Vincent bulk ash and Saharan dust; shaded areas represent the mean values ± 1 standard deviation. St. Vincent ash data are from Muhs et al. (1987b) and Appendix 2; Saharan dust data are from Rydell and Prospero (1972) and Glaccum (1978).

(Fig. 1) and therefore the soils might reflect the chemical composition of the dust to some degree as well. However, our results (Appendix 2), yield Ti/Y ratios of 294 and 271, Ti/Zr ratios of 78 and 80, and Ti/Th ratios of 5360 and 4707 for the Holocene and Pleistocene ash-derived soils, respectively. These values are in the range of, or close to the range of, values for St. Vincent ash (Figs. 8, 9, and 10). Thus, it appears that rates of ash weathering exceed rates of Saharan dust accumulation on St. Vincent. The data also indicate that the elements Ti, Y, Zr, and Th are not lost during at least early stages of weathering and pedogenesis.

One could argue that the soils on limestone we sampled, despite the fact that they are on terraces of different ages, are all derived from a single period of dust fall in the late Quaternary. In other words, possibly a late Quaternary period of dust fall left a blanket of sediment of the same age over all surfaces, and dust from the Sahara has not been deposited on Caribbean or western Atlantic islands continuously or periodically over the past 1,000,000 yr or so. Two observations cause us to reject this hypothesis. One is that we found no field evidence of paleosols buried by a recent layer of dust. The second observation is that as one progresses to older terraces, soil morphology, mineralogy, and chemistry change systematically. On Barbados, soils on successively older terraces are redder, have a higher concentration of dithionite-extractable Fe, have higher average clay contents (when expressed as weight percentages), and show a change in clay mineralogy from mixed-layer kaolinite–smectite to pure kaolinite (Muhs *et al.*, 1986). On Jamaica, soils on successively older terraces are redder, and show a change from strictly kaolinite to kaolinite and boehmite. Soils on successively older terraces on both Barbados and Jamaica show, in general, a decrease in the concentration of relatively mobile elements such as Si and an increase in the concentration of relatively immobile elements, such as Al (Fig. 11). Thus, we believe that on older terraces, we are seeing the effect of longer periods of pedogenesis.

CONCLUSIONS

We conclude that Saharan dust has been the major parent material for soils on Quaternary limestones of Caribbean and western Atlantic islands in the last 900,000 yr. We reject the residual hypothesis for soil genesis proposed by several previous workers. Furthermore, although volcanic ash falls during the Quaternary are well documented from terrestrial and marine sediment core data, we conclude that volcanic ash has had only minor influence as a parent material for Caribbean and western Atlantic island soils on Quaternary limestones. Our results add to the growing body of literature documenting the importance of eolian additions to soils [see review in Birkeland (1984)].

Our results also have implications for the origin of Caribbean bauxites found on relatively pure Tertiary carbonate rocks. Pye (1988) suggested that Saharan dust could be the parent material for Caribbean bauxites such as those found on Jamaica and Haiti. Two bauxites from Haiti that we studied (Appendix 2) have Al_2O_3/TiO_2 ratios of 17 and 18, Ti/Y ratios of 102 and 43, Ti/Zr ratios of 38, and Ti/Th ratios of 563 and 573. These values fall into the same general range of values for the Quaternary soils and Saharan dust (Figs. 7–10). It is interesting to note that Brimhall *et al.* (1988) also

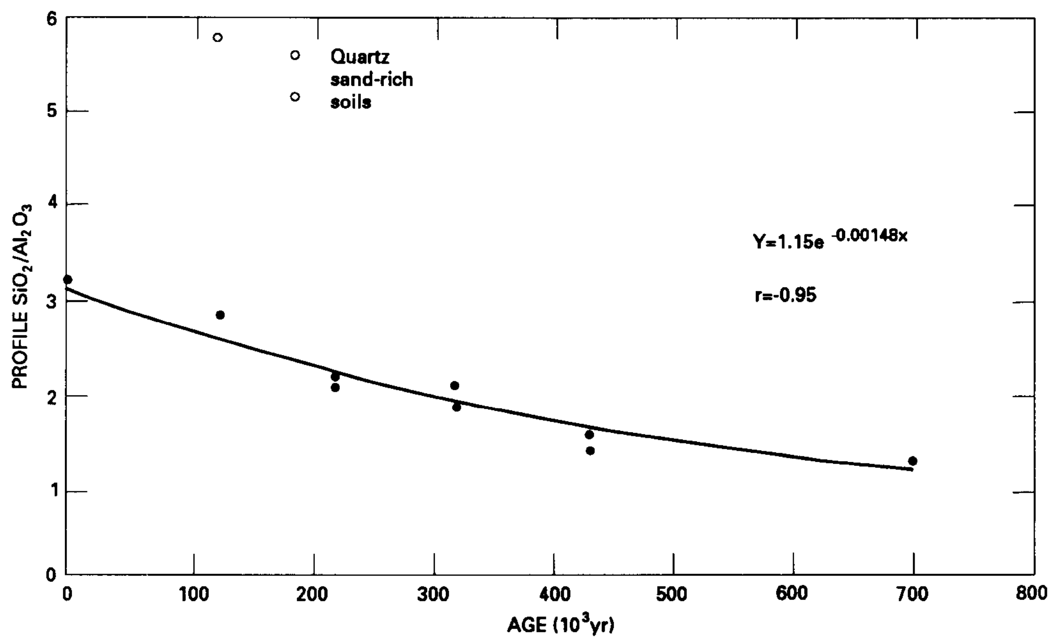

FIG. 11. Plot of SiO_2/Al_2O_3 ratios in Barbados soils (calculated as profile summations) as a function of terrace age. Three profiles (3B, 4B, and 4C) are plotted but not included in the calculation of the regression equation because most horizons of these soils have 45–55% quartz sand, derived from Tertiary sandstones on Barbados. The point plotted at an age of zero years is for Saharan dust collected at Barbados and is the mean of twelve measurements reported by Glaccum (1978).

present evidence supporting an eolian origin for bauxite parent material in Western Australia.

Our conclusions about Saharan dust as a soil parent material have paleoclimatic significance. Studies of deep-sea cores by Bowles (1975), Kolla *et al.* (1979), and Pokras and Mix (1985) all suggest that the southwestern Sahara and Sahel regions of tropical northwest Africa were drier during glacial ages than during interglacial ages. The increased aridity in northwest Africa during glaciations is thought to be due to an equatorward displacement of the westerlies and the subtropical high pressure cell due to ice sheet growth at higher latitudes (Pokras and Mix, 1985). These observations suggest that the majority of Saharan dust that was deposited on ca. 125,000-yr-old surfaces in the Caribbean and western Atlantic came during the last glaciation, rather than during the Holocene interglaciation. Because even the oldest soils in our chronosequences on Barbados and Jamaica carry a Saharan dust signature, our data imply that the Sahara has been periodically arid enough during glacial times to generate dust throughout the last ca. 900,000 yr. In addition, because dust from the Sahara is carried to the western Atlantic and the Caribbean via the northeasterly trade winds, our data indicate that these winds have been an important component in tropical latitudes throughout much of Quaternary time.

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APPENDIX 1: ANALYTICAL METHODS

Analyses of glass shards from Dominica (Al_2O_3 and TiO_2) were done by electron microprobe and were taken from Carey and Sigurdsson (1980). Analyses of Saharan dust samples collected at Barbados were done by emission spectrograph for Al_2O_3, TiO_2, Y, and Zr and are from Glaccum (1978). Th data for Saharan dust samples are from Rydell and Prospero (1972) and were done by isotope-dilution α spectrometry. Analyses of all soils were made on the entire <2-mm fraction. Al_2O_3, TiO_2, and SiO_2 were measured by wavelength-dispersive X-ray fluorescence (XRF) following the method of Taggart *et al.* (1987), and Y, Zr, and Nb were measured by energy-dispersive XRF. For most soils, Th concentrations were determined by γ-ray spectrometry using a sample treatment method similar to that of Bunker and Bush (1966); data were reduced using a linear least-squares regression program. For Barbados soils 3A and 4B, soils and ashes from St. Vincent, and the bauxites from Haiti, Th was measured by isotope-dilution α spectrometry using a ^{229}Th spike (Rosholt, 1985). For New Providence Island soil NPI-3, Th was determined by neutron activation (McKown and Millard, 1987). Precision for the various methods are based on repeated analyses and are as follows (±1 standard deviation): wave-length-dispersive XRF, 0.12–1.1%, energy-dispersive XRF, 7.4–11%; γ-ray spectrometry, 3%; isotope-dilution α spectrometry 0.5–2.0%; emission spectrography, 1–13%.

APPENDIX 2. CONCENTRATIONS OF Al_2O_3 AND TiO_2 (WEIGHT PERCENTAGES) AND TRACE ELEMENTS (ppm) IN CARIBBEAN AND WESTERN ATLANTIC ISLAND SOILS AND BAUXITES

Profile	Age (10^3 yr)	Horizon	Depth (cm)	Al_2O_3	TiO_2	Y	Zr	Th	Nb
Barbados soils									
3A	125	A1	0–6	15.8	0.82	30	122	3.6	<10
		A1	6–12	16.0	0.82	28	115	3.7	<10
		A2	12–22	16.5	0.85	29	119	3.7	<10
		A2	22–33	16.8	0.87	28	119	3.8	<10
		A3	33–40	16.9	0.87	30	125	3.9	<10
		C	40–50	15.9	0.70	28	102	3.3	<10
		C	50–60	13.8	0.59	22	85	2.8	<10
		C	60–70	13.7	0.55	27	78	2.8	<10
3B	125	A	0–7	7.0	0.35	11	62	2.1	<10
		BA	7–24	6.2	0.36	11	59	1.6	<10
		Bt1	24–66	6.6	0.35	9	62	1.9	<10
		Bt2	66–93	8.8	0.46	15	74	2.3	<10
		C	93–99	8.8	0.39	15	67	2.1	<10
4B	190	A	0–8	12.2	0.61	24	118	3.0	<10
		A	8–17	11.6	0.58	26	106	2.9	<10
		A	17–26	11.0	0.55	24	105	3.0	<10
		A	26–35	11.4	0.58	22	117	3.1	<10
		Bw1	35–41	13.3	0.60	19	117	3.4	<10
		Bw1	41–48	12.4	0.53	25	98	3.2	<10
		Bw2	48–54	7.2	0.26	12	62	2.0	<10
		Bw2	54–60	5.3	0.21	7	42	1.6	<10
4C	190	A	0–5	8.0	0.37	16	72	1.9	<10
		ABt	5–14	10.0	0.43	22	82	2.1	<10
		Bt	14–35	10.6	0.44	26	77	2.6	<10
		C	35–45	4.3	0.13	<3	24	nd[a]	<10
5A	220	A	0–4	15.8	0.75	27	109	3.3	<10
		AB	4–15	17.4	0.80	28	119	4.0	<10
		Bt1	15–35	20.7	0.86	42	112	4.4	<10
		BC	35–55	23.5	0.79	32	99	3.6	<10
5B	220	A	0–21	17.4	0.76	56	106	3.2	<10
		BA	21–29	19.0	0.80	84	105	3.7	<10
		B1	29–55	21.7	0.78	52	98	2.8	<10
		B2	55–83	21.4	0.73	34	91	2.9	<10
6A	320	A1	0–18	18.9	1.00	37	130	4.7	<10
		A1	18–36	20.9	0.91	43	116	4.3	<10
		A2	36–44	20.1	1.02	35	132	4.8	<10
		CA	44–53	12.9	0.45	24	57	2.0	<10
		C1	53–65	10.9	0.33	12	45	1.4	<10
6B	320	A	0–5	21.2	1.04	30	139	4.6	<10
		AB	5–15	24.0	1.21	35	167	4.8	<10
		Bt1	15–19	24.4	1.02	22	139	5.2	<10
		Bt2	19–39	23.0	0.96	86	137	4.8	<10
		C	39–44	24.2	0.75	173	101	nd[a]	<10
8A	460	A	0–13	25.2	1.10	62	136	5.0	<10
		BA	13–26	27.4	0.86	36	116	3.7	<10
		Bt	26–39	28.7	0.78	25	116	4.6	<10
		Bt	39–52	28.5	0.77	29	108	3.8	<10
8B	460	A	0–5	23.1	1.00	38	126	4.4	<10
		AB	5–19	23.6	0.99	43	123	4.6	<10
		Bt1	19–29	24.6	1.01	36	131	4.9	<10
		Bt2	29–39	27.0	0.94	73	123	5.0	<10

APPENDIX 2—*Continued*

Profile	Age (10^3 yr)	Horizon	Depth (cm)	Al_2O_3	TiO_2	Y	Zr	Th	Nb
11	700	A	0–5	26.6	1.05	45	151	7.3	<10
		Bt1	5–23	27.3	1.04	58	147	7.1	<10
		Bt2	23–32	30.2	0.84	116	117	6.4	<10
		Bt3	32–50	30.5	0.83	73	115	6.4	<10
Florida soils (120,000–140,000 yr B.P.)									
Windley Key		Bt	—	3.95	0.18	4	42	2.9	<10
Grassy Key		Bt	—	1.54	0.06	<2	32	1.5	<10
Long Key		Bt	—	7.41	0.36	10	58	6.7	<10
No Name Key		Bt	—	14.0	0.72	36	129	11.6	<10
Jamaican soils									
OR-A	125	A	0–13	19.3	1.21	66	192	8.3	20
		AB	13–25	21.3	1.12	62	192	9.2	21
		Bt	25–40	24.8	0.98	56	150	8.3	18
OR-B	125	A	0–10	19.6	1.01	69	167	7.4	18
		AB	10–19	16.9	0.77	58	137	6.6	16
		Bt1	19–27	7.7	0.28	24	45	2.9	10
		Bt2	27–34	7.0	0.26	23	47	nd[a]	10
		Bt3	34–41	5.4	0.21	18	38	1.7	<10
		K	41–45	0.3	<0.02	<2	2	0.2	<10
		CK	45–66	0.6	<0.02	4	9	0.2	<10
		C	66+	0.7	<0.02	2	6	0.2	<10
RN-2A	200	A	0–12	14.5	1.07	46	184	7.4	15
		AB	12–21	16.7	1.08	53	204	8.2	19
		BAt	21–29	20.0	1.04	38	178	8.5	16
		Bt	29–40	21.8	0.92	75	163	8.5	16
		C	40–43	1.8	0.03	13	18	0.5	<10
RN-2B	200	A	0–9	15.3	0.88	64	163	7.4	12
		AB	9–16	16.7	0.95	68	173	7.8	13
		BAt	16–25	18.4	0.96	51	173	8.9	17
		Bt	25–37	17.9	0.92	77	169	8.8	14
		C	37–41	6.7	0.24	72	66	nd[a]	<10
		R	41+	0.4	<0.02	3	9	0.3	<10
RN-3	300	A	0–4	14.2	0.83	41	152	6.4	15
		BAt	4–15	15.6	0.85	19	146	6.9	13
		Bt1	15–36	17.0	0.88	20	155	7.0	15
		Bt2	36–51	17.8	0.83	27	151	6.3	14
		Bt3	51–64	17.2	0.73	163	126	6.2	17
		Bt4	64–86	8.0	0.28	161	56	2.6	12
		C	86+	0.9	<0.02	10	15	nd[a]	<10
OR-4A	870	A	0–26	34.1	2.02	110	310	18.7	34
		Bt1	26–70	36.8	1.97	107	314	19.7	33
		Bt2	70–105	37.2	1.97	110	306	19.7	33
		Bt2	105–140	35.6	1.79	44	274	18.2	28
OR-4B	870	A	0–25	34.5	1.73	153	260	18.3	30
		Bt	25–33	36.7	1.81	166	272	19.8	33
		Bt	33–42	38.0	1.88	171	294	19.6	34
New Providence Island soils									
NPI-1	125	A	0–3	10.1	0.53	20	86	9.7	20
		Bt	3–13	17.9	0.93	35	158	16.4	35

APPENDIX 2—*Continued*

Profile	Age (10^3 yr)	Horizon	Depth (cm)	Al_2O_3	TiO_2	Y	Zr	Th	Nb
NFI-2	200	Bwb	0–15	0.72	<0.02	<2	86	0.72	<10
		Btb	15–60	1.56	0.06	<2	60	0.90	<10
NPI-3	300	Bwb	0–4	0.34	<0.02	<2	76	0.34	<10
		Btb	4–8	7.82	0.39	<2	85	7.07	<10
St. Vincent ashes and soils									
Ignimbrite, 1902 eruption			—	18.5	0.93	18	59	1.37[b]	<10
Ignimbrite, Holocene			—	18.7	0.95	18	85	1.44[b]	<10
Scoria, Pleistocene			—	17.1	1.09	17	89	0.84[b]	<10
Soil, Holocene			—	19.4	1.03	21	78	1.14	<10
Soil, Pleistocene			—	21.4	1.54	34	116	1.96	<10
Haiti bauxites[c]									
Composite 1	—	—	—	49.4	2.95	174	466	31.4	46
Composite 5	—	—	—	48.7	2.67	371	425	28.9	42

[a] nd, not determined.
[b] Incorrectly reported as 0.61, 0.64, and 0.44 ppm Th, respectively, by Muhs *et al.* (1987b).
[c] These composite soils correspond to composites 1 and 5 of Goldich and Bergquist (1948).

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