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Evolution of Soils on Quaternary Reef Terraces of Barbados, West Indies

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Soils on uplifted Quaternary reef terraces of Barbados, ∼125,000 to ∼700,000 yr old, form a climo-chronosequence and show changes in physical, chemical, and mineralogical properties with terrace age. Parent materials are dust derived from the Sahara, volcanic ash from the Lesser Antilles island arc, and detrital carbonate from the underlying reef limestone. Although some terrace soils are probably eroded, soils or their remnants are redder and more clay-rich with increasing terrace age. Profile-average Al_2O_3 and Fe_2O_3 content increases with terrace age, which partially reflects the increasing clay content, but dithionite-extractable Fe also increases with terrace age. Profile-average K_2O/TiO_2, Na_2O/TiO_2, and P_2O_5/TiO_2 values decrease with terrace age, reflecting the depletion of primary minerals. Average SiO_2/Al_2O_3 values also decrease with terrace age and reflect not only loss of primary minerals but also evolution of secondary clay minerals. Although they are not present in any of the parent materials, the youngest terrace soils are dominated by smectite and interstratified kaolinite-smectite, which gradually alter to relatively pure kaolinite over ∼700,000 yr. Comparisons with other tropical islands, where precipitation is higher and rates of dust fall may be lower, show that Barbados soils are less weathered than soils of comparable age. It is concluded that many soil properties in tropical regions can be potentially useful relative-age indicators in Quaternary stratigraphic studies, even when soils are eroded or changes in soil morphology are not dramatic.

INTRODUCTION

In the past two decades, there has been a significant increase in the number of soil chronosequence studies and this work has added greatly to our understanding of how soils evolve over time. Such studies also provide a basis for the use of soils in establishing relative-age relations in geomorphology as well as for mapping and correlating Quaternary deposits. Birkeland (1999) and Schaetzl *et al.* (1994) review many of these and their summaries show that few soil chronosequence studies have been undertaken in tropical regions. Past soil chronsequence studies conducted in the tropics (Carroll and Hathaway, 1963; Lepsch *et al.*, 1977; Gieger and Nettleton, 1979; Alexander and Holowaychuk, 1983) often lack numerical age control. However, both these and more recent, better-dated soil chronosequence studies in tropical climates (Nieuwenhuyse and van Breeman, 1997; Vitousek *et al.*, 1997; Birkeland, 1999) show that certain key soil properties change over time. Solum thickness, solum redness, clay content, dithionite-extractable Fe (hereafter referred to as Fe_d), and concentrations of Fe_2O_3 and Al_2O_3 increase while SiO_2 shows decreases. In addition, important changes in clay mineralogy occur, with kaolinite content generally increasing over time and sometimes altering to gibbsite or boehmite. These results suggest that pedogenic processes in humid tropical climates mainly reflect the importance of chemical weathering, and include progressive alteration of primary minerals, loss of soluble elements, buildup of SiO_2-poor secondary clay minerals, and an overall enrichment of clay and sesquioxides over time. Changes in these properties may be useful relative-age indicators in Quaternary stratigraphic and geomorphic studies. In the present study, soils were examined on emergent reef terraces on the island of Barbados and the Florida Keys (Fig. 1).

STUDY AREAS AND FACTORS OF SOIL FORMATION

Most of the surficial rocks of Barbados are Quaternary limestones of tectonically uplifted coral reef terraces (Fig. 2). Reefs in the Holetown–Clermont Nose area of Barbados were mapped by Mesolella *et al.* (1969) and Bender *et al.* (1979) and are named, in order of increasing elevation, the Worthing (20 m), Ventnor (30 m), Rendezvous Hill (also called First High Cliff; 61 m), Durants (67 m), Cave Hill (85 m), Thorpe (94 m), Husbands (107 m), unnamed (122 m), and Second High Cliff (189 m) terraces. The Worthing, Ventnor, and Rendezvous Hill terraces have concordant $^{230}Th/^{234}U$ and $^{231}Pa/^{235}U$ ages on coral of ∼83,000, ∼104,000, and ∼117,000–129,000 yr B.P., respectively (Mesolella *et al.*, 1969; Edwards *et al.*, 1997; Gallup *et al.*, 1994). Ages of higher terraces are much less certain. The Durants–Cave Hill terrace complex has $^{230}Th/^{234}U$ age estimates of ∼190,000–215,000 yr B.P. (Mesolella *et al.*, 1969; Gallup *et al.*, 1994) that are broadly concordant with electron spin resonance (ESR) age estimates of 219,000–242,000 yr B.P. (Radtke *et al.*, 1988). The Thorpe terrace has a $^{230}Th/^{234}U$ age of ∼220,000 yr B.P. (Mesolella *et al.*, 1969) that agrees with $^{4}He/U$ age estimates of ∼210,000–220,000 yr B.P. (Bender *et al.*, 1979). The Husbands terrace, and its correlative Dayrells terrace found farther to the southeast, have concordant ESR ages of ∼344,000 yr B.P. and $^{4}He/U$ ages of 320,000–344,000 yr B.P. (Radtke *et al.*, 1988; Bender *et al.*, 1979). Second High

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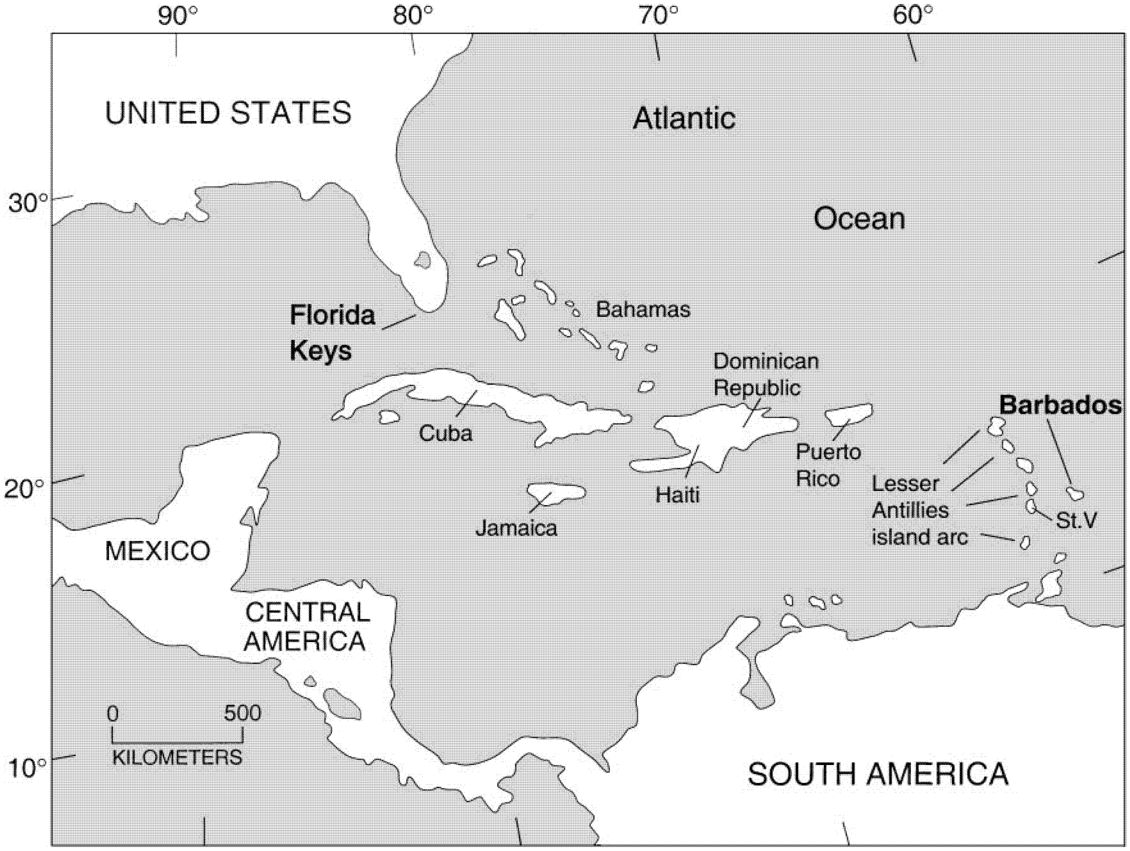

FIG. 1. Map of the Caribbean region and location of the Barbados and Florida Keys study areas. St. V, St. Vincent.

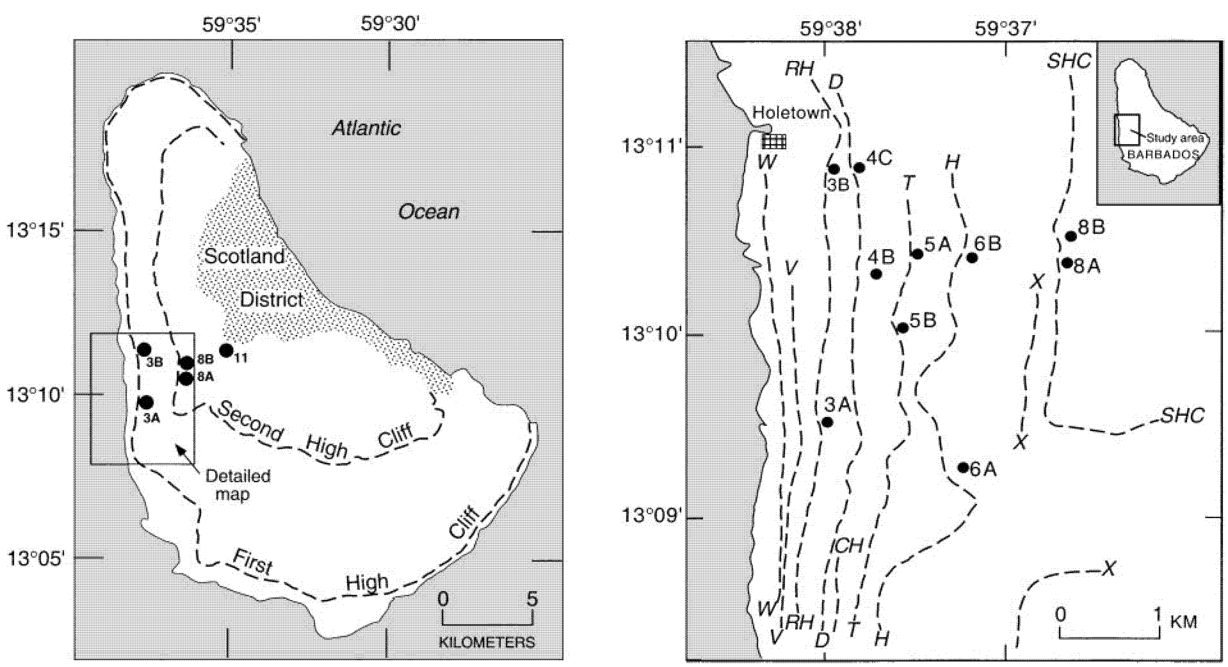

FIG. 2. (Left) Map of Barbados showing the crests of First High Cliff (also called the Rendezvous Hill terrace) and Second High Cliff, the two most prominent uplifted reef terraces, and selected pedon localities. Stippled area is the Scotland District, where Tertiary sedimentary rocks crop out. (Right) Map of reef crests in the Clermont Nose–Holetown area and pedon localities. W, Worthing; V, Venthor; RH, Rendezvous Hill; D, Durants; CH, Cave Hill; T, Thorpe; H, Husbands; X, Unnamed; SHC, Second High Cliff. Terrace data from Mesolella *et al.* (1969) and Bender *et al.* (1979).

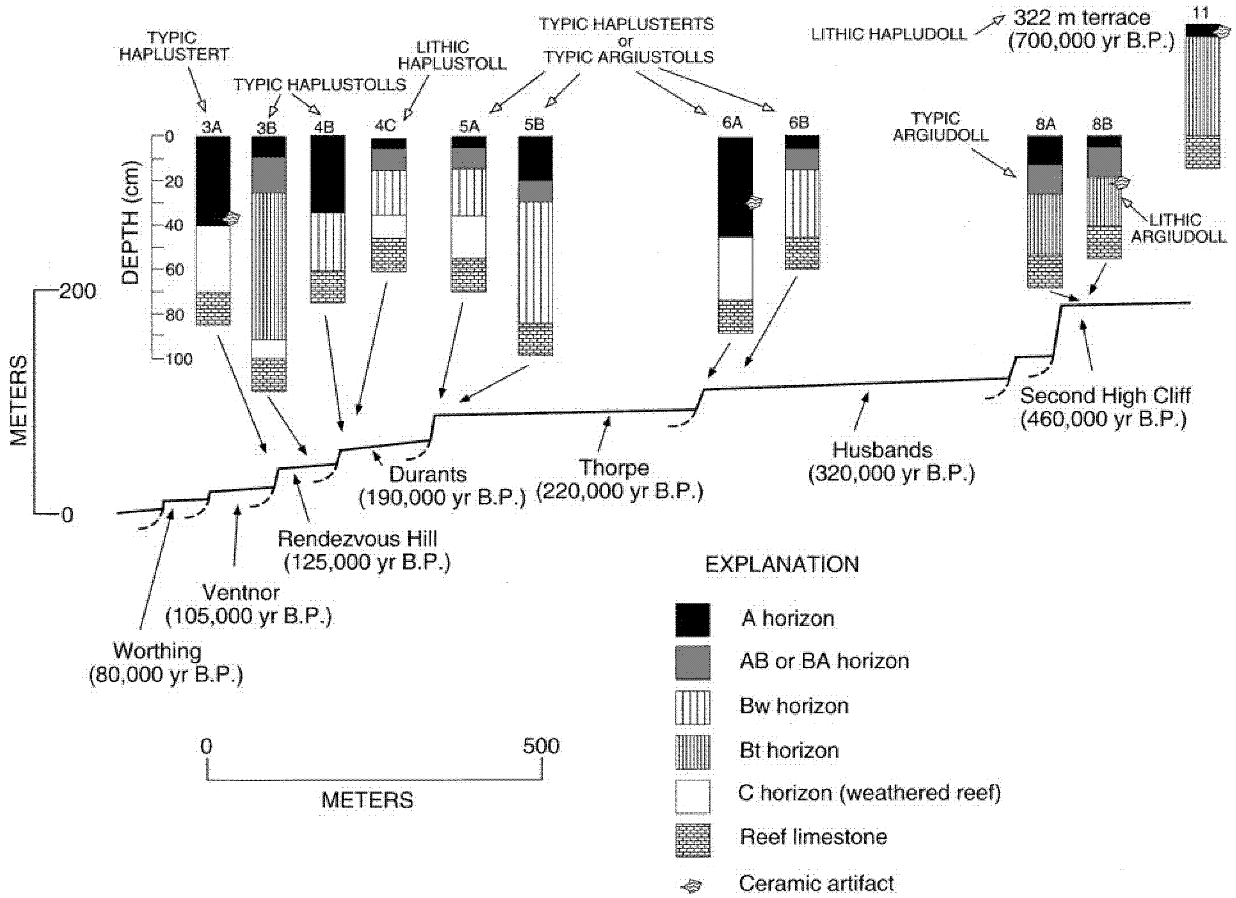

FIG. 3. Topographic profile of terrace surfaces and soil profiles in the study area.

Cliff has concordant ESR, $^{4}He/U$, and $^{230}Th/^{234}U$ age estimates of ~425,000, 440,000–460,000, and >250,000 yr B.P., respectively (Radtke *et al.*, 1988; Bender *et al.*, 1979; Mesolella *et al.*, 1969). Soils were sampled on the Rendezvous Hill, Durants, Thorpe, Husbands, and Second High Cliff terraces (Fig. 3). In addition, a pedon was sampled on one of the highest terraces (~322 m) on the island, as mapped by Mesolella *et al.* (1969). Using an assumed constant uplift rate derived from the age and elevation of the 125,000-yr-old Rendezvous Hill terrace, I date this older terrace to about 700,000 yr.

The upper Florida Keys are composed of the Key Largo Limestone, which is a reef facies limestone similar to those of Barbados. Recent U-series ages indicate that on some keys, the Key Largo Limestone dates to the last interglacial period, ~125,000 yr B.P. (Fruijtier *et al.*, 2000). However, a coral from Long Key dates to ~200,000 yr B.P. (Muhs and Simmons, unpublished U-series data) and records the penultimate interglacial high sea stand. Soils are thin or absent on most of the Florida Keys, possibly the result of relatively rapid erosion from storms due to the low (<10 m) elevations of these islands; coastal areas of southern Florida can be severely affected by hurricanes (Davis, 1995). However, thin, patchy occurrences of reddish-brown, clay-rich soils on reef limestone were observed on several keys and sampled on Windley Key, Grassy Key, and No Name Key (~125,000 yr), as well as Long Key (~200,000 yr). It is important to note that on both Barbados and the Florida Keys, the U-series and ESR ages of reef corals are *maximum-limiting* ages for the overlying soils; pedogenesis could have begun much later than the time of terrace emergence.

Highly divergent views on the parent materials for Barbados soils have been presented. Vernon and Carroll (1965) and Ahmad and Jones (1969) thought that Barbados soils were derived primarily from insoluble residues in the coral reef limestone. Based on considerations of the amount of reef dissolution required and data from immobile element geochemistry, Muhs *et al.* (1987, 1990) suggested that soils on Barbados, Jamaica, the Florida Keys, and the Bahamas are derived dominantly from Saharan dust blown across the Atlantic on the northeast trade winds. Volcanic ash from eruptions on the nearby islands of St. Vincent and Dominica probably also contributed some amount of parent material to the soils of Barbados (Borg and Banner, 1996). In a portion of the present study area on Barbados, Vernon and Carroll (1965) defined a mapping unit called the “Red Sand Association,” which includes soils with a high (as much as 63%) quartz sand content. Vernon and Carroll (1965) thought that soils of the Red Sand Association were derived from

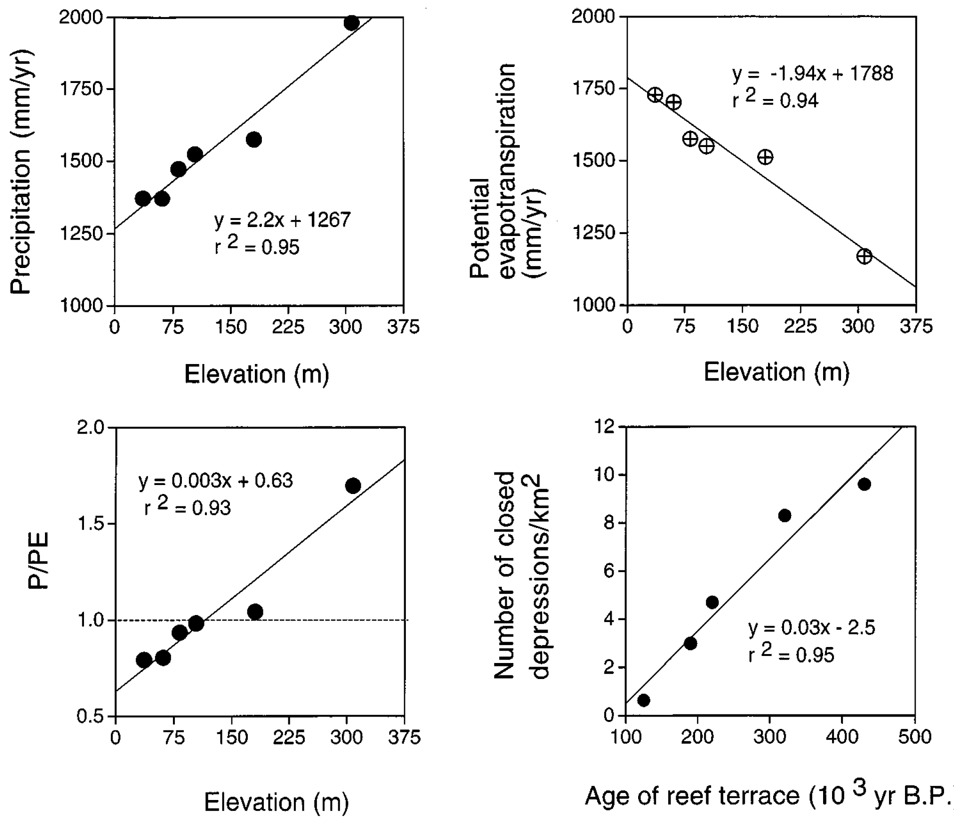

FIG. 4. Precipitation (P), potential evapotranspiration (PE), and P/PE on Barbados as a function of elevation and plot of number of closed depressions per unit area in the study area. Climate data points interpolated from maps in Rouse and Watts (1966); closed depressions were measured in the present study from 1:10,000 scale topographic maps.

beach sands deposited over reef limestone. The sources of the quartz sand are probably Tertiary rocks of the Scotland District (Acker and Stearn, 1990). Profiles 4B and 4C on the Durants terrace and 3B on the Rendezvous Hill terrace in the present study are from this soil association.

The present climate of Barbados is of the trade-wind littoral type, characterized by modest changes in temperature through the year. Mean annual temperature ranges from 24° to 28°C. Precipitation occurs in all months, but there is a distinctive dry season lasting from about December to May (Rouse and Watts, 1966). High-elevation terraces have more rainfall, lower temperatures, and lower potential evapotranspiration than low-elevation terraces (Fig. 4). Precipitation on the low-elevation terraces is as low as 1100 mm/yr, compared to 2120 mm/yr in the Scotland District, where the highest elevations on the island are found. These relations make the present array of soils on terraces a climo-chronosequence rather than a pure chronosequence. Older soils have passed through progressively wetter and cooler environments over time than have younger soils. The Florida Keys have a climatic regime similar to that of Barbados. Mean annual temperature at Marathon, Florida is ~25°C and mean annual precipitation is ~1100 mm. As on Barbados, precipitation occurs during all months but is lowest in winter.

Little of the native vegetation survives on Barbados today except in isolated pockets, as ~80% of the landscape is in cultivation, mainly for sugar cane. However, reef crests are still largely uncultivated and support sour grass (*Andropogon intermedius* var. *acidulus*), sage (*Lantana camara*), wild tamarinds (*Cassia glandulosa* var. *swartzii*), maypole (*Agave barbadensis*), columnar cactus (*Cephalocereus barbadensis*), whitewood (*Tabebuia pallida*), and *Paspalum* spp. (Watts, 1970). Based on accounts by early English explorers, forest may have been present prior to European settlement (Watts, 1970).

There are few long-term records of Quatenary paleoclimate and vegetation from Caribbean islands. The longest and most complete records are from Jamaica, and although this island is well to the west of Barbados (Fig. 1), it has a similar trade-wind littoral climate, and paleoclimatic history for the two islands may be comparable. Studies of lacustrine ostracods and land snails from cave sediments indicate that interglacial periods, such as the Holocene and the last interglacial age, were relatively warm and moist, whereas glacial periods were probably cool (4°–5°C cooler than present) and relatively dry (Goodfriend and Mitterer, 1993; Holmes *et al.*, 1995). Analysis of corals offshore Barbados also indicates last-glacial cooling of ~5°C (Guilderson *et al.*, 1994). Thus, soil development may have occurred under alternating cool, dry glacial climates and warm, wet interglacial

climates. It is likely that superimposed on glacial–interglacial cycles there were periods of greater and lesser aridity during interstadial events, such as those documented for southern Florida by Watts and Hansen (1994).

METHODS

Soils were described from hand-dug pits on reef crests following U.S. Natural Resources Conservation Service soil nomenclature. Samples were taken by horizon; where horizons were particularly thick, horizons were subdivided by equal depth increments for sampling. Particle size distribution was measured by wet sieve and pipette after removal of carbonates with HCl, destruction of organic matter with H_2O_2, and dispersion with sodium-pyrophosphate. Bulk density was measured by the clod method. Organic matter was measured using the Walkley–Black method; pH was measured on 1 : 1 soil–water pastes using a glass electrode. Iron (Fe_d) was extracted using the citrate-bicarbonate-dithionite method and measured by atomic absorption spectrometry. Calcium carbonate content was measured by gas evolution on a Chittick apparatus following dissolution with 6N HCl. Major element concentrations were measured on bulk, powdered samples using wavelength-dispersive X-ray fluorescence. Silts were isolated by wet-sieving to remove sands and repeated sedimentation and siphoning to remove clays and then X-rayed as random mounts. Clays were isolated by sedimentation after the same pretreatments as for particle size analysis, saturated with Mg, and X-rayed three times: air-dried, glycolated, and heat-treated (550°C for two hours).

SOIL MORPHOLOGY AND PHYSICAL PROPERTIES

Despite the precaution of sampling soils only on uncultivated, flat reef crests, an unexpected trend is that soils on higher terraces of Barbados are not always thicker than soils on lower terraces (Fig. 3). However, older terraces on Barbados also have more evidence of karst development. Sinkholes and solution pits, for example, are more common on higher terraces (Fig. 4); sinkholes filled with soil material eroded from adjacent parts of terrace surfaces were sometimes observed on higher, older reefs. The lower parts of most soils on Barbados are dominated by the presence of abundant detrial carbonate, derived from the underlying reef limestone. Some C horizons of lower terrace soils consist of weathered limestone fragments mixed with clay; other soils have thin (~2 mm) calcretes (cf Harrison, 1977). Soils on higher terraces do not show transitional horizonation and have clay-rich B horizons with abrupt boundaries to the underlying reef. Such abrupt boundaries may indicate that parts of older terraces may have been truncated to form erosion surfaces and then received soil materials from at least a short distance upslope. A measureable amount of carbonate is present in almost all horizons of all soils, and this probably explains the neutral to slightly alkaline pH values in all soils, including those on higher terraces.

Soil morphological properties show only a few trends with age on Barbados (Fig. 3). Overall, soil textures are clayey on all terraces except for profiles of the Red Sand Association (see Table 1 of the Appendix). For the other soils, clay content is never less than 60%, and it is >90% in all or most horizons of soils on the 460,000- and 700,000-yr-old terraces. Subangular blocky structure is more common in lower terrace soils and angular blocky structure is more common in higher terrace soils, which may be a function of the generally higher clay content of higher terrace soils. However, pressure faces and slickensides are common in the lower terrace soils, which may qualify as Vertisols. In contrast, clay films occur in argillic horizons of soils on the highest two terraces. With the exception of the Red Sand Association profiles, soil colors show gradual changes with terrace age. Soils on the lower Rendezvous Hill, Durants, and Thorpe terraces have only 10YR hues. In contrast, soils on the Husbands and Second High Cliff terraces have 10YR and 7.5YR hues, and the very highest terrace soil has 7.5YR and 5YR hues.

There are various methods used to derive overall summations of properties for an entire soil profile (see Birkeland, 1999, p. 14). Because higher terrace soils on Barbados are likely eroded, the most appropriate method is to compute a profile average. Profile averages for soil properties were calculated using horizon thicknesses and bulk densities as weights in the averaging process. The result is an overall measure of a soil property for the whole pedon that is not dependent on profile thickness. Using this approach, I find that maximum and profile-average clay contents show increases with terrace age, assuming that the average clay content of Saharan dust is a good indicator of initial clay content (Fig. 5).

CHEMICAL AND MINERALOGICAL PROPERTIES

Certain chemical properties of Barbados soils are a function of the progressive buildup of clay over time. Profile-average Al_2O_3 contents are highly and positively correlated with terrace age (Fig. 6). It is likely that much of this trend is explained by the increase in clay content with terrace age, as Al contents are high in phyllosilicate clay minerals, compared to primary aluminosilicates such as feldspars. Profile-average values for total Fe (expressed as Fe_2O_3) show a trend similar to Al_2O_3 and may also be related in part to clay buildup (Fig. 6). Fe is commonly found in certain clay minerals such as smectites. Fe_d shows high, positive correlations with terrace age on Barbados (Fig. 7).

Despite the presence of carbonate detritus and mostly neutral pH values, there is abundant evidence of chemical weathering in Barbados soils, both of primary minerals and clay minerals. X-ray diffraction analysis of the silt (2–53 μm) fractions of Barbados soils shows that the main minerals are quartz, plagioclase, K-feldspar, opal, and possibly cristobalite. In the silt fractions, ratios of weatherable plagioclase to resistant quartz show two trends. A weak trend is that most younger soils show higher plagioclase-to-quartz values than do older soils, but there

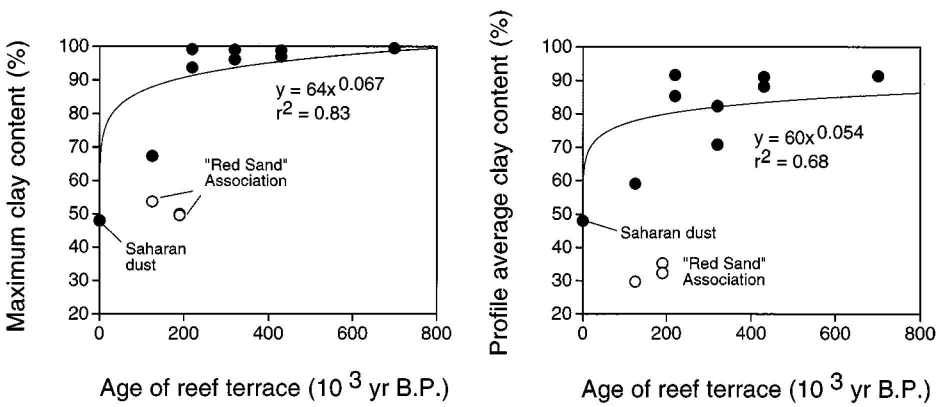

FIG. 5. Plots of maximum and profile-average clay contents in Barbados soils as a function of estimated terrace age. Estimate of clay content in Saharan dust taken from data in Prospero *et al.* (1970). Note that values for beach-sand-derived "Red Sand Association" soils were not used in calculation of regression equations.

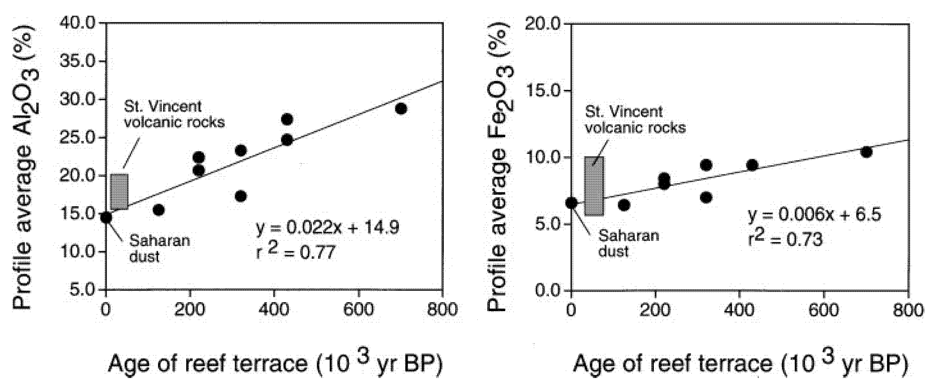

FIG. 6. Profile-average Al_2O_3 and Fe_2O_3 contents shown as a function of estimated terrace age on Barbados. Value given for Saharan dust collected on Barbados is mean of 12 values given in Glaccum (1978); shaded area shows range of concentrations for Quaternary volcanic rocks on St. Vincent given in Heath *et al.* (1998).

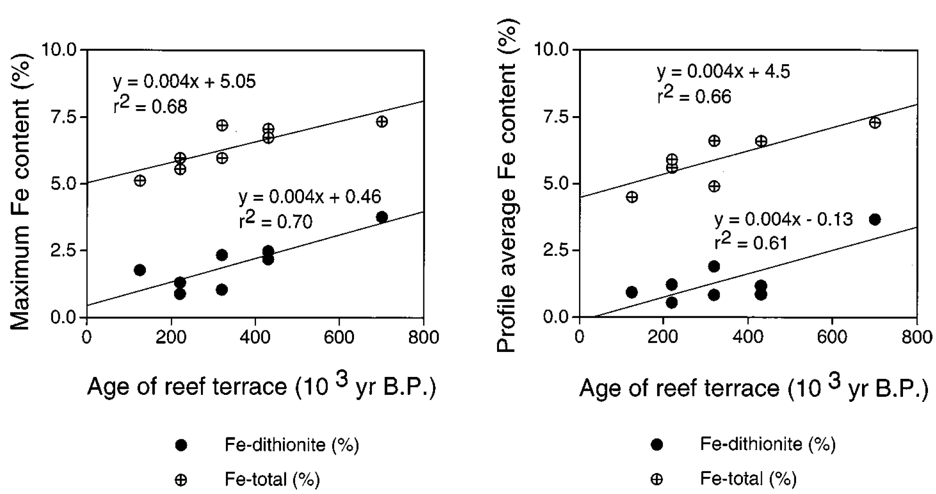

FIG. 7. Profile-maximum and profile-average values of total Fe and dithionite-extractable Fe in Barbados soils shown as a function of estimated terrace age.

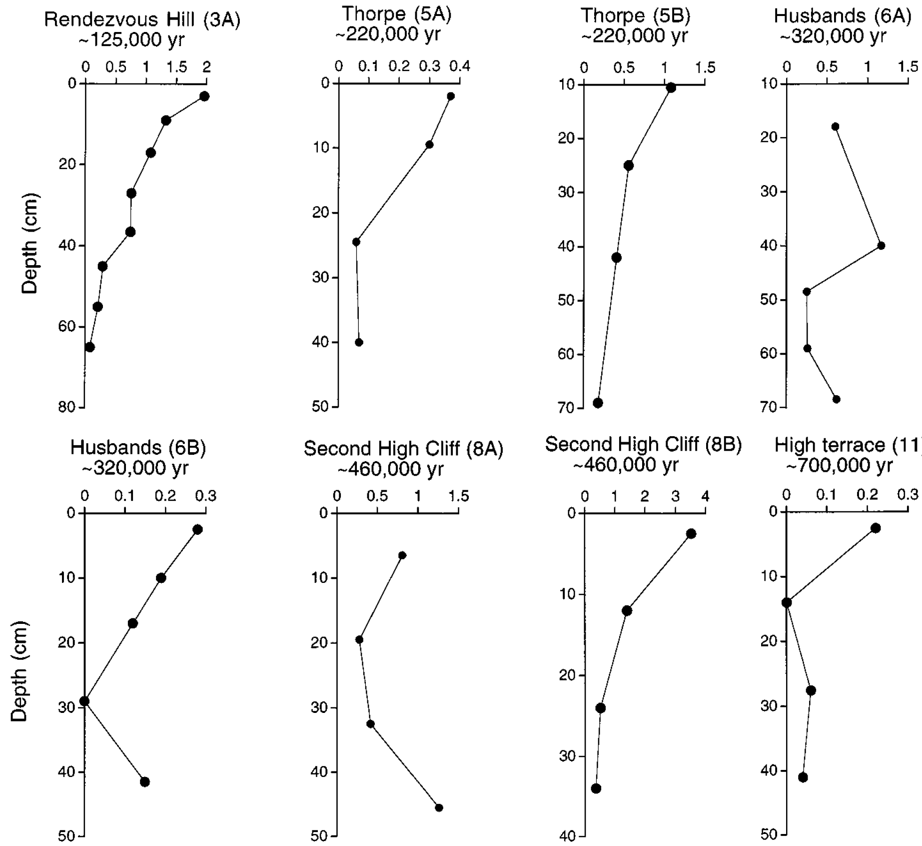

FIG. 8. Depth functions showing ratios (semiquantitative) of plagioclase (27.8° X-ray peak) to quartz (20.8° peak) in the silt (2–53 μm) fractions of selected Barbados soils.

are important exceptions, such as the soils on Second High Cliff (Fig. 8). A more consistent trend is that, in most soils, plagioclase-to-quartz values are highest in surface horizons and decrease with depth.

The degree of plagioclase depletion can also be measured by examination of the concentrations of Na_2O, a major constituent in this mineral, to those of a relatively immobile element such as TiO_2. Profile-average values of Na_2O/TiO_2 in Barbados soils are all much lower than those in either Saharan dust or St. Vincent volcanic rocks, suggesting significant plagioclase depletion (Fig. 9). One of the most common minerals reported in Saharan dust which reaches Barbados is mica (Delany *et al.*, 1967; Glaccum and Prospero, 1980), although volcanic rocks on St. Vincent are basaltic, and therefore ash falls contain little or no mica. No mica was detected in either the silt or the clay fractions of Barbados soils. However, micas are quite susceptible to chemical weathering and if Saharan dust is an important soil parent material, mica alteration should be reflected in the soil chemistry. Profile-average K_2O/TiO_2 values are quite low and show a good correlation with terrace age, which supports this hypothesis (Fig. 9).

In soil chronosequences of New Zealand, phosphorus abundances have been shown to change significantly over time (Walker and Syers, 1976). Although soil P fractionates into different forms and some of these initially increase over time, in New Zealand total P decreases over time. If Barbados soils are derived primarily from Saharan dust, then all soils show a significant depletion of total P (shown as P_2O_5/TiO_2), although the relation to age is not as strong as for other elements (Fig. 9). However, if volcanic ash from St. Vincent is the more important soil parent material, then there has been little total P loss, and some soils could actually have been enriched in this element.

One of the most commonly used indices of chemical weathering is the ratio of SiO_2 content to Al_2O_3 content, usually expressed as a molar ratio (Birkeland, 1999). Progressive depletion of SiO_2-rich minerals and enrichment in Al_2O_3-rich clays is evident from a plot of profile-average values of SiO_2/Al_2O_3 shown as a function of terrace age on both Barbados and the Florida Keys (Fig. 10). Barbados soils show SiO_2 depletion compared to either a Saharan dust or St. Vincent ash parent material. Soils on both Barbados and the Florida Keys have SiO_2/Al_2O_3 values that are much lower than average upper crust rock values, as represented by North American midcontinent loess, but are not as low as the highly weathered bauxites of Haiti (Fig. 10).

Profile-average values of SiO_2/Al_2O_3 can be compared with clay minerals that are found in Barbados soils. Low terrace soils have SiO_2/Al_2O_3 values that suggest some possible mix of smectite and kaolinite whereas higher terrace soils could have a

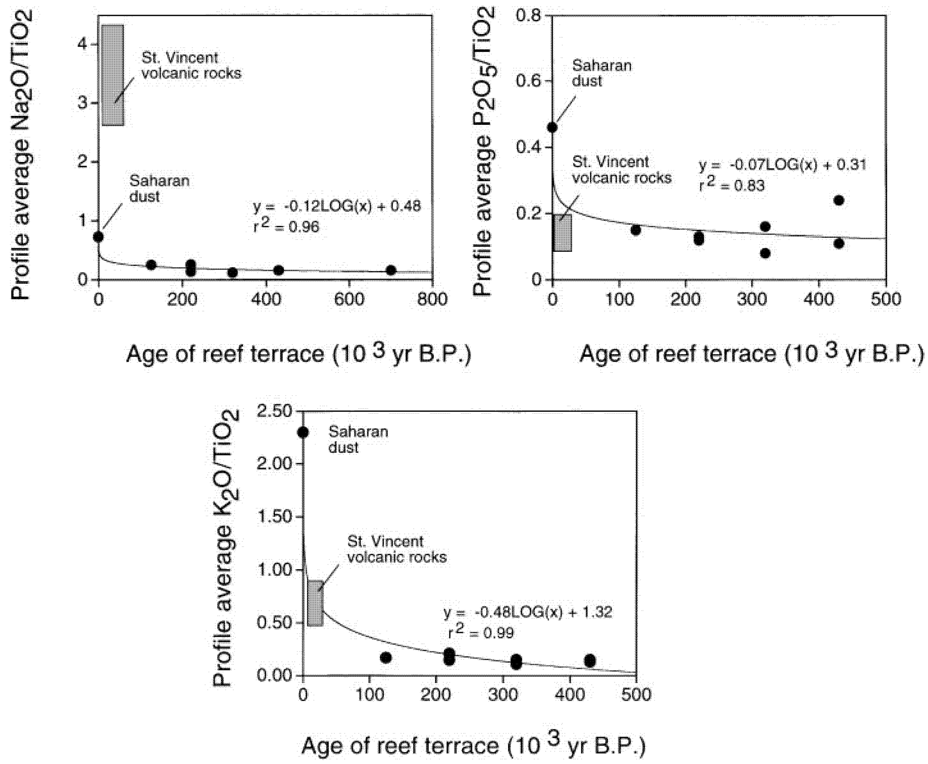

FIG. 9. Profile-average values of Na_2O/TiO_2, P_2O_5/TiO_2, and K_2O/TiO_2 shown as a function of terrace age; regression equations include Saharan dust values. Shown for comparison are approximate ranges of values for Quaternary volcanic rocks on the island of St. Vincent (shaded areas). Saharan dust values are from Glaccum (1978) for P_2O_5 and TiO_2; values for K_2O and Na_2O are unpublished mean values of Saharan dust samples analyzed by instrumental neutron activation analysis by J. Budahn, D. Muhs, and J. Prospero (same Saharan sample suite as that in Herwitz *et al.*, 1996, Table 3).

more kaolinite-dominated assemblage (Fig. 10). X-ray diffraction analyses support many of the interpretations made on the basis of chemical data. In all soils on the lower terraces, randomly interstratified kaolinite-smectite is the dominant clay mineral (Fig. 11). In Mg-saturated, glycolated samples, this mineral is characterized by peaks centering on 1.66–1.75 nm, ~0.74 nm (but ranging from 0.71 to 0.79 nm), and 0.356 nm. According to Brindley and Brown (1980), these three peaks, and the absence of a peak at ~0.56 nm, indicate mixed-layer kaolinite-smectite characterized by ~80–90% kaolinite. Particularly diagnostic of kaolinite-smectite is the form of the ~0.74 nm peak, which has a sharp dropoff on the high-angle side and a gradual tail on the low-angle side (Cradwick and Wilson, 1972). After heating to 550°C for two hours, only a peak around 1.0 nm is visible.

Higher terrace soils on Barbados show a clay mineralogy that reflects the lower SiO_2/Al_2O_3 values found in these pedons (Fig. 11). In profiles 8A and 8B on Second High Cliff, the 1.66–1.76 nm smectite peak that is observed in lower terrace soils is absent or greatly diminished, indicating a greater predominance of kaolinite layers. In profile 11, found on the highest terrace, the 1.66–1.76 nm peak is completely absent in all horizons and the highest peak centers on 0.71 nm, indicating relatively pure kaolinite. Thus, on Barbados, both the chemical data and the clay mineralogy show a trend of increasing desilication with terrace age: low terrace soils have interstratified kaolinite-smectite and relatively high SiO_2/Al_2O_3 values, intermediate terrace soils have a more kaolinite-dominated (but still interstratified) clay mineralogy with intermediate SiO_2/Al_2O_3 values, and the highest terraces have kaolinite only, with the lowest SiO_2/Al_2O_3 values.

On Barbados, few, if any, primary minerals are apparent in the clay fraction. Mica and plagioclase were not detected at any depth in any soil, which is consistent with the very low K_2O/TiO_2 and Na_2O/TiO_2 values discussed earlier. Minor amounts of clay-sized quartz were found at all or most depths in profiles 3A and 3B, at or near the surface only in profiles 4B and 4C, and in some, but not all, horizons of profiles 5A, 5B, 6B, and 8A.

DISCUSSION

Barbados soils show continued evolution over ~700,000 yr in a tropical climate. Although higher terrace soils are probably eroded, soil redness and clay content increase with terrace age. Profile-average Al_2O_3 and Fe_2O_3 (total) and dithionite-extractable Fe contents also increase with terrace age. The linear increase in Fe_d is probably due to steady buildup of secondary Fe-oxides, such as hematite, and may explain the weak but discernible trend of increasing soil redness with terrace age on Barbados. It is interesting to note, however, that the slope of the regression equation for the Fe_d trend is identical to that for

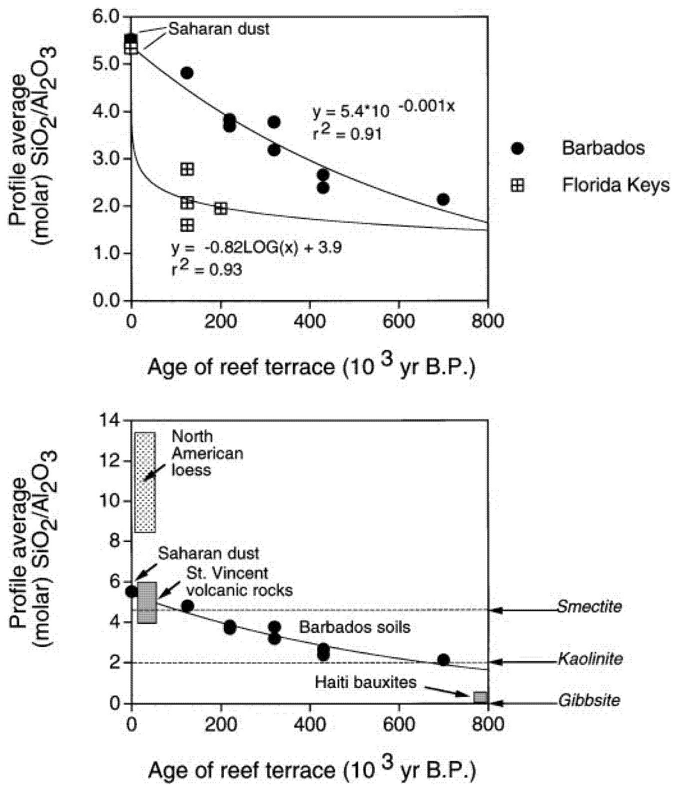

FIG. 10. Top; Profile-average SiO_2/Al_2O_3 (molar) values for Barbados and Florida Keys soils shown as a function of estimated terrace age; values for Saharan dust collected on Barbados and at Miami, Florida are included in calculation of regression equations. Saharan dust values are from Glaccum (1978). Lower: profile-average SiO_2/Al_2O_3 (molar) values for Barbados soils shown as a function of estimated terrace age and ranges for North American loess, Quaternary volcanic rocks from St. Vincent, Haiti bauxites, and clay minerals. Loess data are new analyses from localities in Nebraska, Iowa, and Illinois given in Muhs and Bettis (2000), St. Vincent data are from Heath *et al.* (1998), Haiti data are from the present study, using samples 1 and 5 of Goldich and Bergquist (1948), and clay mineral values are from Weaver and Pollard (1973).

the total Fe trend, indicating that Fe_d is building up in Barbados soils at the same rate as total Fe. Delany *et al.* (1967) reported that Saharan dust on Barbados often has a reddish-brown color, and X-ray diffraction studies of the silt fraction by those workers showed that hematite and goethite (both dithionite-extractable) are present. The trends in the soils reported here suggest that these dithionite-extractable, Fe-bearing minerals may build up in Barbados soils over time, but perhaps mostly by inheritance from Saharan dust, rather than by in situ alteration of primary, Fe-bearing minerals.

In contrast to Al_2O_3 and Fe_2O_3, profile-average K_2O/TiO_2, Na_2O/TiO_2, and P_2O_5/TiO_2 values decrease with terrace age, reflecting the depletion of primary minerals. The observation of plagioclase-to-quartz values being highest in surface horizons and decreasing with depth is contrary to the usual pattern of shallow horizons being more weathered than deep horizons in soils. Periodic additions of Saharan dust and volcanic ash to the surface of Barbados soils may serve to “freshen” the uppermost horizons and explain the observed depth functions, however. Decreasing SiO_2/Al_2O_3 values with terrace age reflect not only depletion of primary minerals but alteration of smectite and interstratified kaolinite-smectite to relatively pure kaolinite.

Despite the decrease in SiO_2/Al_2O_3 with terrace age, profile-average values for all Barbados soils are higher than soils on carbonates of comparable ages found on the Florida Keys (Fig. 10), the Bahamas (Foos, 1991), and Bermuda (Herwitz and Muhs, 1995). Higher SiO_2/Al_2O_3 values on Barbados could be a function of a higher rate of Saharan dust fall, such that weathering cannot keep as far ahead of eolian sedimentation as on the other islands. Measurements of modern Saharan dust fall are significantly greater on Barbados than in the Miami, Florida area (Prospero, 1981) and the latter rate of dust fall is probably representative of dust fall rates on the Florida Keys and Bahamas. In addition, ash falls from the Lesser Antilles are unlikely to reach Florida and the Bahamas in great amounts.

The evolution of soils over the past ~700, 000 yr on Barbados can be compared with other soil chronosequences that cover long time spans in tropical climates. Vitousek *et al.* (1997) studied soils derived from basaltic lavas (ages range from about 300 yr to over 4 Myr) and Asian dust on the Hawaiian Islands. Precipitation in this area is about 2500 mm/yr. Concentrations of Si, P, and K all show declines with age of the underlying surface. Primary minerals are mostly depleted after ~20,000 yr, but secondary kaolinite and sesquioxides show progessively higher values with soil age. Birkeland (1999, pp. 198–199) studied soils developed on reef limestones of Rota Island (in the Marianas Island chain in the western Pacific) and Maré Island (in the South Pacific).

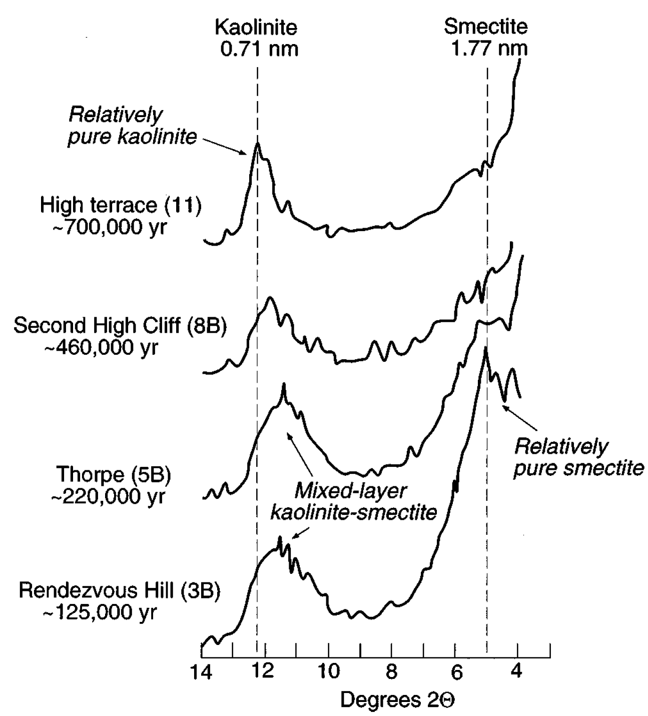

FIG. 11. Representative X-ray diffractograms (Mg-saturated, glycolated) from horizons of four Barbados soils.

These islands, like Barbados, have a reef limestone substrate, and reef terraces likely formed during the same high stands of sea as those on Barbados. Furthermore, parent materials are probably some combination of airborne dust and volcanic ash. Precipitation on Rota Island is about 2500 mm/yr, whereas Maré Island has about 1500 mm/yr. Soils on both islands are similar to Barbados in that they show few morphological changes with terrace age. However, mineralogical and chemical changes from the eolian dust and volcanic ash parent materials are dramatic. Soils of all ages on both islands have molar SiO_2/Al_2O_3 values less than 2.0, and most are less than 1.0. Clay minerals are dominated by boehmite and gibbsite, which reflect these low SiO_2/Al_2O_3 values. Dithionite-extractable Fe reaches higher levels faster (and in a cumulative sense) than on Barbados. The higher degree of weathering on Rota and Maré Islands compared to that on Barbados may be a function of higher precipitation, but it could also reflect lower rates of dust fall and volcanic ash deposition.

CONCLUSIONS

Studies from Barbados and Pacific islands show that soils in tropical climates evolve over Quaternary time. Even the youngest soils in all areas show significant depletions of primary minerals from the parent materials, losses of soluble bases and SiO_2, increases in sesquioxides, and evolution of clay minerals to simpler forms. On all these islands, the greatest rates of change occur in the first ~100,000 yr of pedogenesis. Greater precipitation and lower rates of airborne dust fall accelerate rates of chemical weathering and show how two soil-forming factors, climate and parent material, can be interchangeable. Despite this complication, the results from Barbados and other islands show that soil properties are potentially useful relative-age indicators for Quaternary stratigraphic and geomorphic studies in the tropics, even when changes in soil morphology are not dramatic.

APPENDIX

TABLE 1
Morphology and Physical and Chemical Properties of Barbados Terrace Soils

No.	Age (10^3 yr B.P.)	Horizon	Depth (cm)	Color (dry)	Structure[a]	Bound[a]	Other[a]	Sand[b] (%)	Silt[b] (%)	Clay[b] (%)	B.D. (g/cm^3)	O.M. (%)	pH (1:1)	Fe_d (%)	$CaCO_3$ (%)
3A	125	A1	0–6	10YR 3/2	2,fm,sbk	gs	o,pf	22	14	64	1.55	5.3	7.3	0.91	4.6
		A1	6–12					22	12	66	1.55	4.0	7.8	1.78	6.2
		A2	12–22	10YR 3/2	2,c,sbk	gs	c,pf	22	11	67	1.51	2.4	7.4	1.61	5.1
		A2	22–33					21	12	67	1.47	2.4	7.6	1.24	4.4
		A3	33–40	10YR 3/2	3,c,sbk	cw	c,s	21	13	66	1.65	2.0	7.8	1.23	5.2
		C	40–50	2.5YR 5/2	3,c,sbk	ai	c,s	13	6	81	1.59	1.6	8.0	0.67	22.0
		C	50–60					11	<1	88	1.77	1.3	8.0	0.39	36.0
		C	60–70					4	2	94	1.71	1.3	8.0	0.25	41.8
3B	125	A	0–7	10YR 3/1	2,fm,sbk	gs		39	7	54	1.56	5.3	6.9	0.15	41.8
		BA	7–24	10YR 3/2	2,fm,sbk	gs		44	7	49	1.47	3.0	7.3	0.33	44.3
		Bt1	24–66	10YR 4/2	2,mc,sbk	gs	o,cf	52	2	46	1.58	1.7	7.6	0.39	42.8
		Bt2	66–93	10YR 4/2	2,mc,sbk	gs	o,cf	45	6	49	1.56	1.4	7.7	0.61	30.6
		C	93–99	10YR 5/3	1,mc,sbk	aw		38	<1	61	1.49	1.2	7.8	0.43	45.0
4B	190	A	0–8	10YR 3/2	2,mc,abk	cs	o,pf	52	5	43	1.58	2.7	7.2	1.55	4.6
		A	8–17					52	5	43	1.64	2.0	7.8	1.19	5.0
		A	17–26					52	5	43	1.69	1.1	7.8	1.18	5.6
		A	26–35					53	4	43	1.44	1.3	7.8	1.24	3.3
		Bw1	35–41	5YR 4/6	2,mc,abk	gs	c,pf	50	8	42	1.63	1.0	7.8	1.09	1.5
		Bw1	41–48					54	4	42	1.59	1.1	7.8	1.83	11.3
		Bw2	48–54	7.5YR 4/6	1,mc,sbk	ai		60	<1	39	1.63	1.1	7.9	0.54	56.3
		Bw2	54–60					48	2	50	1.50	1.0	8.0	0.46	67.7
4C	190	A	0–5	10YR 3/2	2,f,sbk	cs		50	<1	49	1.44	4.6	7.7	0.09	27.4
		AB	5–14	10YR 4/2	2,fm,sbk	gs		46	5	49	1.62	2.2	7.9	0.44	26.1
		Bw	14–35	10YR 4/3	2,mc,sbk	aw		47	4	49	1.67	1.6	8.0	0.86	21.7
		C	35–45	10YR 6/6-8/1	1,m,sbk	aw		36	2	62	1.37	0.2	8.1	0.26	73.7
5A	220	A	0–4	2.5YR 2/0	3,fm,abk	cs		20	8	72	1.29	9.6	7.4	0.93	0.6
		AB	4–15	10YR 3/1	3,mc,abk	gs		19	5	76	1.57	4.0	7.8	1.26	1.9
		Bw	15–35	10YR 3/2	2,c,abk	gw	o,pf,s	13	2	85	1.53	1.5	8.3	1.31	0.9
		BC	35–55	10YR 4/3	2,m,abk	gw		<1	<1	99	1.52	1.5	8.1	1.15	4.6
5B	220	A	0–21	10YR 3/1	1,mc,sbk	gs	o,pf	19	3	78	1.48	3.8	7.8	0.43	0.3
		BA	21–29	10YR 3/1	2,fc,sbk	cs	c,pf	14	4	82	1.49	3.0	7.8	0.89	1.0
		Bw1	29–55	10YR 3/1-3/2	2,mc,abk	cw	c,s	4	4	92	1.53	1.7	8.0	0.52	4.0
		Bw2	55–83	10YR 4/2-4/3	2,c,abk		c,pf	2	4	94	1.51	1.3	8.1	0.39	9.2

Table 1—*Continued*

No.	Age (10^3 yr B.P.)	Horizon	Depth (cm)	Color (dry)	Structure[a]	Bound[a]	Other[a]	Sand[b] (%)	Silt[b] (%)	Clay[b] (%)	B.D. (g/cm^3)	O.M. (%)	pH (1:1)	Fe_d (%)	$CaCO_3$ (%)
6A	320	A1	0–18	10YR 3/2	1–2,cf,sbk	gs	c,pf	13	8	79	1.42	3.7	7.6	1.05	0.3
		A1	18–36					7	2	91	1.51	2.3	7.8	0.94	2.2
		A2	36–44	10YR 2/2	2,c,abk	cs	c,s	10	12	78	1.50	2.2	7.9	0.82	0.8
		CA	44–53	10YR 3/2, 5/6	2,fmc,sbk	gs		2	19	79	1.43	1.9	8.2	0.60	47.2
		C1	53–65	10YR 5/6	2,mc,abk	cs	c,cf	<1	<1	99	1.46	0.8	8.2	0.37	56.4
		C2	65–72	7.5YR 8/3	Massive	ai	o,cf	<1	2	97	1.19	0.5	8.2	0.28	79.6
6B	320	A	0–5	10YR 3/2	1,m, sbk	gs		16	6	78	1.35	5.5	7.1	1.26	0.2
		AB	5–15	10YR 3/2	2,mc,abk	cw		16	3	81	1.46	3.6	7.0	1.90	0.2
		Bw1	15–19	7.5YR 4/4	2,c,abk	gs	o,s, pf	12	1	87	1.46	2.2	7.5	0.91	0.2
		Bw2	19–39	7.5YR 4/4	1-2,c,abk	gw	o,s, pf	12	1	87	1.33	1.7	7.5	2.34	0.2
		Bw3	39–44	7.5YR 4/4	1,m,sbk	aw		2	2	96	1.22	2.2	7.7	1.79	9.0
8A	460	A	0–13	7.5YR 4/2	2,fm,sbk	cs		6	4	90	1.42	5.8	6.8	0.74	0.3
		BA	13–26	7.5YR 5/6	2,m,sbk	cs	c,pf	2	3	95	1.41	2.5	7.5	0.22	4.6
		Bt	26–39	7.5YR 5/6	2,mc,abk	ai	c,pf,cf	<1	<1	99	1.46	1.3	7.6	2.48	0.6
		Bt	39–52					1	<1	98	1.36	1.3	7.8	1.20	2.1
8B	460	A	0–5	10YR 3/2	2,fm,g-sbk	gs		6	6	88	1.34	5.5	7.6	2.19	3.3
		AB	5–19	10YR 3/2	2,fm,sbk	gs		6	<1	94	1.43	4.9	7.7	0.18	3.7
		Bt1	19–29	10YR 3/2	1,c,abk	gs	o,cf,pf	4	<1	95	1.41	2.8	7.8	1.47	3.4
		Bt2	29–39	7.5YR 4/6	1,c,abk	aw	o,cf,pf	2	<1	97	1.43	2.2	7.8	0.47	1.2
11	700	Ap	0–5	7.5YR 3/3	3,c,abk	cw	o,cf	3	3	94	1.46	5.4	7.7	3.77	3.5
		Bt1	5–23	5YR 4/3	3,vc,abk	gi	c,cf	2	5	93	1.39	3.0	7.8	3.52	3.3
		Bt2	23–32	7.5YR 4/4	3,fm,abk	ai	c,cf	<1	<1	99	1.30	2.5	7.8	3.77	1.0
		Bt3 (clay pocket)	32–50	7.5YR 4/4	3,c,abk	ai	c,cf	<1	2	98	1.29	2.1	7.8	3.75	0.9

[a]Abbreviations: *Texture:* c = clay; sc = sandy clay. *Structure:* 1 = weak; 2 = moderate; 3 = strong, f = fine; m = medium; c = coarse; vc = very coarse; sbk = subangular blocky; abk = angular blocky; gr = granular; mass. = massive. *Boundary:* gs = gradual smooth; gw = gradual wavy; gi = gradual irregular; cs = clear smooth; cw = clear wavy; aw = abrupt wavy; ai = abrupt irregular. *Other:* o = occasional; c = common; cf = clay films; pf = pressure faces; s = slickensides.

[b]Calculated on an organic matter and calcium carbonate-free basis.

Table 2
Major Element Concentrations and Loss-on-Ignition (LOI)

No.	Age (10^3 yr)	Horiz.	Depth (cm)	Weight percent										
				SiO_2	Al_2O_3	Fe_2O_3	MgO	CaO	Na_2O	K_2O	TiO_2	P_2O_5	MnO	LOI
3A	125	A1	0–6	49.5	15.8	6.97	0.87	4.23	0.23	0.17	0.82	0.23	0.22	21.3
		A1	6–12	50.1	16.0	6.98	0.87	5.31	0.25	0.15	0.82	0.20	0.22	19.7
		A2	12–22	52.0	16.5	7.10	0.82	4.09	0.23	0.15	0.85	0.17	0.22	17.7
		A2	22–33	51.1	16.8	7.29	0.77	4.35	0.23	0.14	0.87	0.15	0.24	17.6
		A3	33–40	52.9	16.9	7.33	0.76	3.70	0.22	0.14	0.87	0.15	0.24	16.5
		C	40–50	40.8	15.9	6.35	0.82	13.0	0.14	0.10	0.70	0.08	0.14	22.8
		C	50–60	35.1	13.8	5.34	0.75	18.3	0.12	0.09	0.59	0.06	0.07	26.1
		C	60–70	31.0	13.7	5.16	0.77	22.1	0.13	0.09	0.55	0.06	0.05	26.4
3B	125	A	0–7	36.4	7.05	3.05	0.67	23.0	0.13[a]	0.13	0.35	0.12	0.07	29.0
		BA	7–24	41.3	6.24	2.79	0.59	23.7	0.13[a]	0.09	0.36	0.1	0.08	25.1
		Bt1	24–66	39.5	6.59	2.86	0.60	25.0	0.13[a]	0.08	0.35	0.07	0.08	25.2
		Bt2	66–93	49.2	8.80	3.80	0.54	16.5	0.12[a]	0.09	0.46	0.05	0.11	20.2
		C	93–99	38.7	8.82	3.54	0.64	22.9	0.11[a]	0.1	0.39	0.06	0.07	25.1
4B	190	A	0–8	64.4	12.2	5.23	0.54	3.32	0.25	0.16	0.61	0.13	0.16	12.8
		A	8–17	67.0	11.6	4.98	0.52	3.36	0.24	0.14	0.58	0.13	0.17	11.1
		A	17–26	66.6	11.0	4.68	0.49	3.68	0.21	0.12	0.55	0.11	0.16	12.2
		A	26–35	68.1	11.4	4.83	0.43	2.56	0.22	0.13	0.58	0.10	0.14	11.1
		Bw1	35–41	66.8	13.3	5.31	0.36	1.45	0.16	0.15	0.60	0.07	0.10	11.7
		Bw1	41–48	65.0	12.4	4.88	0.37	3.93	0.15	0.15	0.53	0.07	0.11	12.3

Table 2—*Continued*

No.	Age (10^3 yr)	Horiz.	Depth (cm)	Weight percent SiO_2	Al_2O_3	Fe_2O_3	MgO	CaO	Na_2O	K_2O	TiO_2	P_2O_5	MnO	LOI
		Bw2	48–54	37.8	7.2	2.64	0.53	24.7	0.14	0.13	0.26	0.10	0.03	26.4
		Bw2	54–60	30.4	5.33	1.95	0.60	32.3	0.16	0.12	0.21	0.11	<0.03	29.6
4C	190	A	0–5	50.6	7.95	3.23	0.51	15.2	<0.15	0.14	0.37	0.10	0.05	21.8
		AB	5–14	51.8	10.0	3.92	0.54	13.7	<0.15	0.14	0.43	0.09	0.06	19.4
		Bw	14–35	52.8	10.6	4.12	0.61	12.9	0.20	0.14	0.44	0.08	0.06	17.8
		C	35–45	20.8	4.30	1.50	0.45	39.8	<0.15	0.1	0.13	<0.05	<0.02	33.7
5A	220	A	0–4	47.5	15.8	6.60	0.81	1.91	0.16	0.16	0.75	0.13	0.18	25.7
		AB	4–15	51.9	17.4	7.22	0.78	2.18	0.19	0.14	0.80	0.11	0.22	18.6
		Bw	15–35	48.9	20.7	8.09	0.77	1.85	0.20	0.16	0.86	0.09	0.21	18.1
		BC	35–55	42.0	23.5	8.55	0.91	3.04	0.25	0.20	0.79	0.09	0.08	20.5
5B	220	A	0–21	53.4	17.4	6.94	0.80	1.83	0.17[a]	0.09	0.76	0.11	0.15	18.2
		BA	21–29	50.1	19.0	7.41	0.76	2.14	0.12[a]	0.09	0.80	0.11	0.15	19.0
		Bw1	29–55	41.2	21.7	7.95	0.88	5.17	0.08[a]	0.12	0.78	0.10	0.05	22.1
		Bw2	55–83	38.7	21.4	7.83	0.88	6.85	0.07[a]	0.13	0.73	0.09	0.03	23.3
6A	320	A1	0–18	48.7	18.9	8.20	0.87	2.15	0.22	0.15	1.00	0.17	0.26	19.3
		A1	18–36	45.0	20.9	8.32	0.81	3.12	<0.15	0.13	0.91	0.12	0.16	20.4
		A2	36–44	48.1	20.1	8.55	0.79	2.07	0.17	0.14	1.02	0.15	0.25	18.7
		CA	44–53	23.7	12.9	4.63	0.65	26.5	<0.15	0.08	0.45	0.09	0.03	31.5
		C1	53–65	18.6	10.9	3.75	0.60	32.1	<0.15	0.07	0.33	0.08	<0.02	34.2
		C2	65–72	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
6B	320	A	0–5	43.1	21.2	9.06	0.63	1.37	0.17	0.11	1.04	0.13	0.23	23.1
		AB	5–15	40.7	24.0	10.3	0.62	1.21	0.19	0.11	1.21	0.11	0.28	21.5
		Bw1	15–19	44.7	24.4	9.64	0.55	0.94	0.09[a]	0.11	1.02	0.07	0.37	18.5
		Bw2	19–39	46.6	23.0	9.18	0.53	1.00	0.08[a]	0.11	0.96	0.07	0.32	17.9
		Bw3	39–44	39.8	24.2	8.43	0.63	4.60	0.09[a]	0.13	0.75	0.09	0.09	21.5
8A	460	A	0–13	38.3	25.2	10.1	0.63	1.27	0.19	0.12	1.10	0.15	0.28	22.8
		BA	13–26	38.4	27.4	9.29	0.58	2.39	0.13[a]	0.13	0.86	0.09	0.13	20.9
		Bt	26–39	39.4	28.7	9.16	0.59	1.26	0.12[a]	0.14	0.78	0.07	0.05	19.7
		Bt	39–52	38.9	28.5	9.14	0.58	2.14	0.12[a]	0.14	0.77	0.07	0.06	19.8
8B	460	A	0–5	38.5	23.1	9.34	0.78	3.91	0.27	0.14	1.00	0.33	0.19	22.5
		AB	5–19	38.1	23.6	9.30	0.73	3.92	0.24	0.13	0.99	0.30	0.18	22.9
		Bt1	19–29	38.9	24.6	9.60	0.66	3.76	0.20	0.13	1.01	0.24	0.17	21.1
		Bt2	29–39	39.9	27.0	9.64	0.54	1.73	<0.15	0.12	0.94	0.12	0.16	19.9
11	700	Ap	0–5	37.0	26.6	10.5	0.57	2.28	0.17	0.32	1.05	0.18	0.13	21.8
		Bt1	5–23	37.0	27.3	10.5	0.52	2.62	0.17	0.26	1.04	0.18	0.10	20.6
		Bt2	23–32	35.9	30.2	10.4	0.46	1.25	0.12[a]	0.21	0.84	0.13	0.05	21.1
		Bt3	32–50	35.8	30.5	10.5	0.45	1.14	0.12[a]	0.21	0.83	0.13	0.04	20.4

[a] Na_2O is below 0.15% detection level by wavelength-dispersive X-ray fluorescence; value given was determined by instrumental neutron activation analysis.

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