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Bermuda solution pipe soils: A geochemical evaluation of eolian parent materials

Stanley R. Herwitz

Graduate School of Geography, Clark University, Worcester, Massachusetts 01610

Daniel R. Muhs

U.S. Geological Survey, MS 424, Box 25046, Denver Federal Center, Denver, Colorado 80225

ABSTRACT

Solution pipes found in the Quaternary eolian and marine carbonates of Bermuda are filled with reddish to reddish-brown soil material. The bulk of the soil is composed of clay and silt-sized quartz and aluminosilicate clay minerals. The carbonates are of high purity and, therefore, are not likely to have been the parent material. Previous workers have hypothesized that Saharan dust may have been the soil parent material. The fine-grained component of loess from the Mississippi River Valley of North America also could have contributed. Paleoclimate models indicate that both North Africa and North America could have been important source areas during both glacial and interglacial periods. Immobile element concentrations in Bermuda soil samples collected from the interiors of solution pipes were determined for the purpose of geochemical fingerprinting and comparisons with the hypothesized parent materials. Immobile element ratios using Al, Ti, Zr, Y, and Th suggest that neither Saharan dust nor lower Mississippi River Valley loess were the sole contributors to Bermuda soils. Eolian dust from at least one other source area such as the Great Plains may have contributed parent material to the soils of Bermuda.

INTRODUCTION

Calcareous eolianites of Quaternary age are common on many tropical and subtropical coastlines and islands where substantial supplies of carbonate sand have been mobilized by the wind. There have been many studies of the structural and diagenetic features of Quaternary eolianites (e.g., Mackenzie, 1964a; Gardner, 1983; Esteban and Klappa, 1983; McKee and Ward, 1983; Pye and Tsoar, 1990). Such features include bounding surfaces, horizontal laminar calcretes, rhizoliths, and vertically oriented solution pipes. Solution pipes are characteristically lined with secondary calcite and commonly filled with clay-rich sediments derived from overlying soil B horizons (Ruhe et al., 1961; Herwitz, 1993).

On Bermuda (Fig. 1), which consists mainly of calcareous eolianite formations and some localized marine facies (Vacher et al., 1989), soil-filled solution pipes are commonly exposed

as erosional remnants in the form of pedestals above the surrounding host eolianite or marine facies (Fig. 2A). The solution pipes also are exposed in vertical sections at road cuts and in quarries, and as cylindrical pillars in areas of active shoreline erosion (Fig. 2B). The interiors of the pipes are filled with reddish to reddish-brown (2.5YR 3/4 to 5YR 4/4) soil materials that previously supported terrestrial vegetation, as evidenced by the presence of carbonate rhizoliths (Fig. 2C). The pipes originally were referred to as "palmetto stumps" because it was thought that they were fossil casts of the trunks or taproots of the endemic palm tree species *Sabal bermudana* (Verrill, 1902). Livingston (1944) suggested that they may be fossil casts of the endemic cedar *Juniperus bermudiana*.

Solution pipes in eolianites have been reported along the east coast of the Mediterranean (Day, 1928), in southeastern Africa (Coetzee, 1975), and Western Australia (Fairbridge, 1950; Blackburn et al., 1965). We have observed them in Qua-

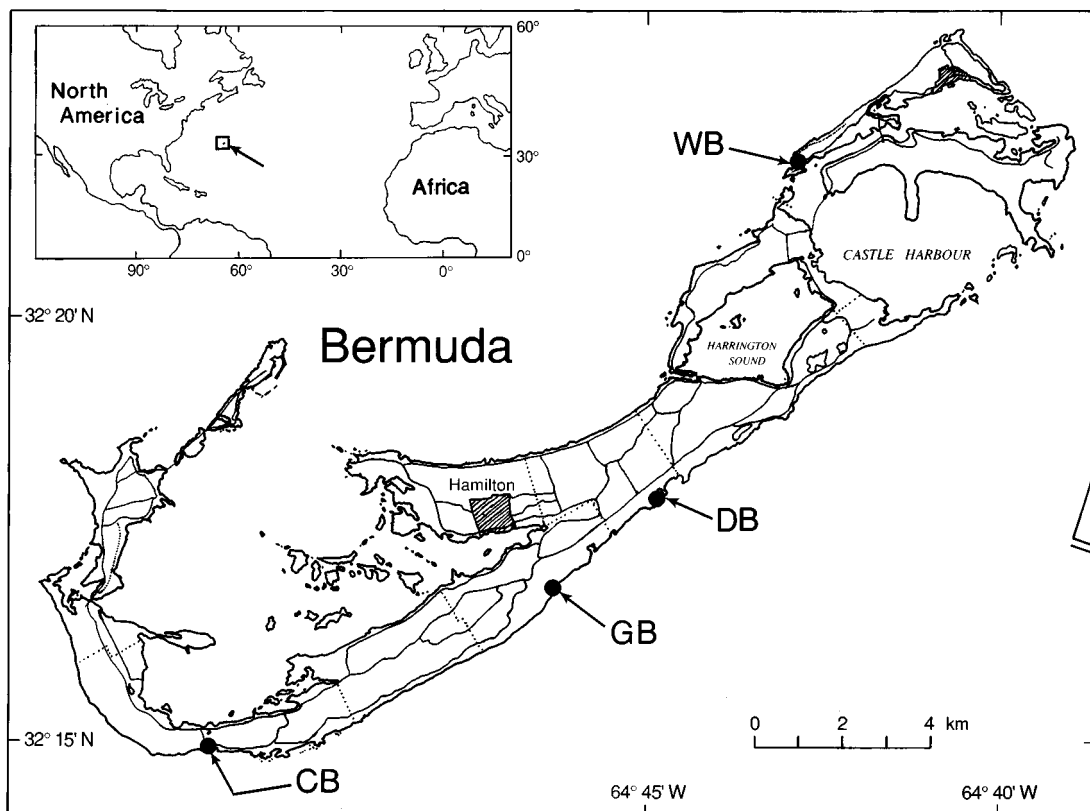


Figure 1. Location of soil-filled solution pipe sample localities on Bermuda: CB = Church Bay; DB = Devonshire Bay; GB = Grape Bay; WB = Whalebone Bay.



Figure 2. Soil-filled solution pipes (see arrows) in contrasting stages of exposure. A, Remains of lower sections of solution pipes in the form of raised soil-filled pedestals projecting above surrounding host carbonate at Whalebone Bay. B, Soil-filled solution pipes recently exposed by shoreline erosion of the surrounding host eolianite at Church Bay. C, Close-up view of the interior of one of the Church Bay solution pipes showing soil- and rhizolith-filled interior.

ternary eolianites on San Nicolas and San Miguel Islands off the coast of southern California. Some workers have assumed that the soil-filled pipes of Bermuda are simply the product of nonbiogenic solution processes (Sayles, 1931; Ruhe et al., 1961; Plummer et al., 1976). Reference to Bermudan palmetto stumps, nevertheless, has persisted (Bretz, 1960; Land et al., 1967; Land and Mackenzie, 1969; Vacher and Harmon, 1987; Rowe, 1990), perhaps because the nonbiogenic hypothesis does not explain their clustered distribution pattern, their tapering cylindrical shape, and their smooth inner calcite casing. Herwitz (1993) recently conducted a field study of stemflow drainage on Bermuda, and hypothesized that the pipes may be the product of concentrated acidic stemflow inputs from long-lived trees. The present study is aimed at understanding the origin of the soil materials that fill the interiors of these pipes.

Sayles (1931) noted "heavy red clay fillings" in the interiors of solution pipes, and reported the occurrence of typically continental minerals such as quartz (comprising as much as 43% of the insoluble fraction), orthoclase, pink garnet, hornblende, and muscovite. Sayles proposed the following possible explanations for the occurrence of these minerals: (1) ingestion and transport of these mineral grains by birds migrating between Nova Scotia and the West Indies; (2) hurricane transport of sand from the Atlantic coastal plain; and (3) attachment of the minerals to marine algae and jellyfish, and subsequent transport by sea currents.

The first detailed study of the soils of Bermuda was by Ruhe et al. (1961), who documented the presence of kaolinite and vermiculite in both the horizontal soils and the soil-filled solution pipes, but these workers did not discuss the possible parent materials. Blackburn and Taylor (1969, 1970) suggested

that Bermuda soils are residual, derived from the noncarbonate impurities in the eolianites. Bricker and Prospero (1969) and Bricker and Mackenzie (1970) argued that the soils were derived from wind-transported continental parent material based on similarities in the mineralogy of the soils and airborne dust collected on Bermuda. Bricker and Prospero (1969) suggested that the dust on Bermuda was derived from Africa. The formation of the soils on Bermuda from atmospheric dust now appears to be the generally accepted interpretation (e.g., Hearty et al., 1992), but there are no published geochemical data of which we are aware that document the source area(s) of the eolian parent materials.

Muhs et al. (1987, 1990) used immobile element ratios as geochemical "fingerprints" and concluded that red, reddish-brown, and dark brown clay-rich soils on relatively pure Quaternary carbonates on Barbados, Jamaica, the Bahamas, and the Florida Keys are probably derived from Saharan dust (Fig. 3) transported across the Atlantic Ocean by the northeast trade winds (Fig. 4). In the present study, we also adopt the geochemical fingerprinting approach to evaluate possible parent materials for the soil in the solution pipes of Bermuda. We use present-day atmospheric circulation patterns and global paleoclimate models to determine possible source regions for dust transport to Bermuda.

ATMOSPHERIC TRANSPORT OF DUST TO BERMUDA

Much research is being conducted on the transport of continental aerosols to the Atlantic Ocean. The main concern is to determine the eastward transport of pollutants from North

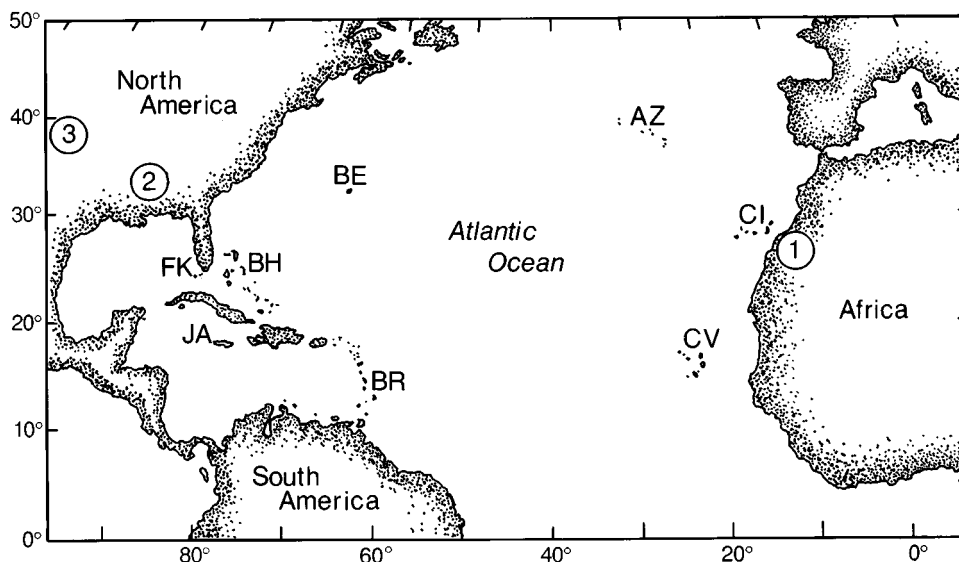


Figure 3. Location of Bermuda (BE) shown in relation to North America, the Florida Keys (FK), the Bahamas (BH), Jamaica (JA), Barbados (BR), South America, the Azores (AZ), Cape Verde Islands (CV), the Canary Islands (CI), Africa, and three continental source areas of atmospheric dust: (1) the western Sahara, (2) the lower Mississippi River Valley, and (3) the Great Plains.

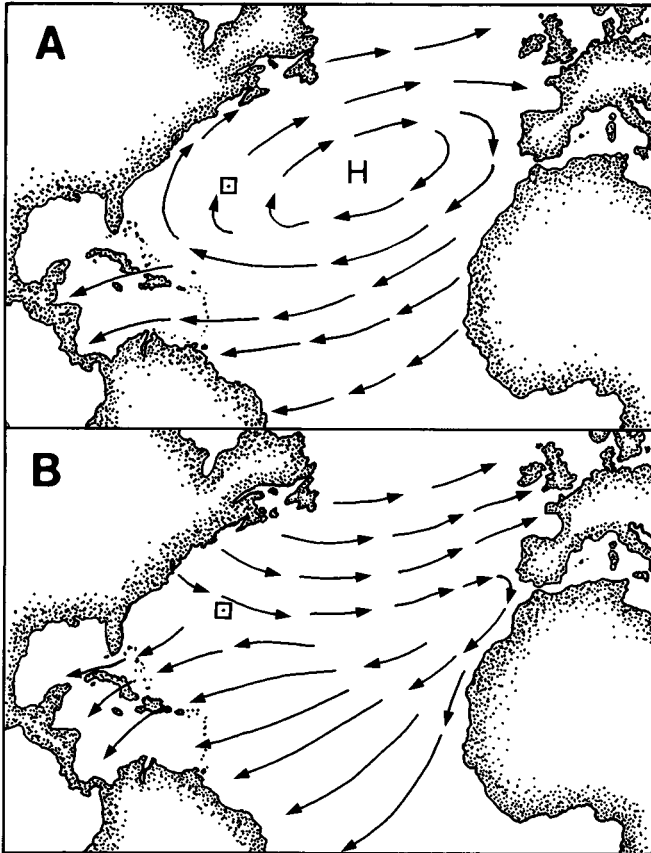


Figure 4. Circulation pattern of northeast trade winds and prevailing westerlies shown in relation to Bermuda (square/dot symbol) and Bermuda high-pressure cell (H). A, Summer season pattern; (B), winter season pattern.

America (e.g., Jickells et al., 1982; Galloway et al., 1988). Chen and Duce (1983) quantified the present-day contribution of mineral aerosols to Bermuda, and they reported that both North Africa and North America are contributing sources, with North Africa contributing more on an annual basis. Saharan dust is transported westward during the summer months by the northeast trade winds in a latitudinal belt mainly between 10°N and 25°N (Fig. 4A) at altitudes of 1.5 to 3.5 km (Rydell and Prospero, 1972; Glaccum and Prospero, 1980; Prospero, 1981; Prospero et al., 1981; Talbot et al., 1986). At 32°N, Bermuda is at the northernmost limit of the northeast trade winds. Saharan dust reaching Bermuda would most likely involve trade winds that circulate around the southern portion of the Bermuda high pressure cell (Fig. 4A). During winter, when the airflow pattern is displaced toward the equator (Prospero and Nees, 1977; Savoie and Prospero, 1977; Prospero et al., 1981), there is no apparent windflow pattern that could transport Saharan dust to Bermuda (Fig. 4B). It is during the winter months that Bermuda receives dust from North America via the prevailing westerlies.

During full-glacial times, sea-surface temperatures and atmospheric circulation patterns were not the same as they are in the present-day interglacial (Keffer et al., 1988). General circu-

lation model (GCM) experiments have shown the probable atmospheric circulation that existed during full-glacial time at ~18 Ka (Kutzbach and Guetter, 1986; Kutzbach, 1987; Webb et al., 1987). The Northern Hemisphere storm tracks were displaced considerably south of their present positions in both summer and winter. However, these GCM experiments also suggest that the northeast trade winds may have been stronger than present during full-glacial summers. GCM maps show easterly surface winds reaching the vicinity of Bermuda during full-glacial summers (Fig. 5A) (Kutzbach and Guetter, 1986; Kutzbach, 1987; Webb et al., 1987). Sediment data from several deep-sea cores from the eastern Atlantic indicate that northwest Africa generated significantly more dust during full-glacials than during interglacials (Bowles, 1975; Kolla et al., 1979; Pokras and Mix, 1985; Grousset et al., 1989). Hence, even under full-glacial conditions, North Africa may have contributed to the formation of the Bermuda soils.

Westerly winds from North America would have reached Bermuda during full-glacial winters (Fig. 5B). A likely source of dust carried to Bermuda by westerly winds at these times would be the fine-grained (<10 μ in diameter) component of

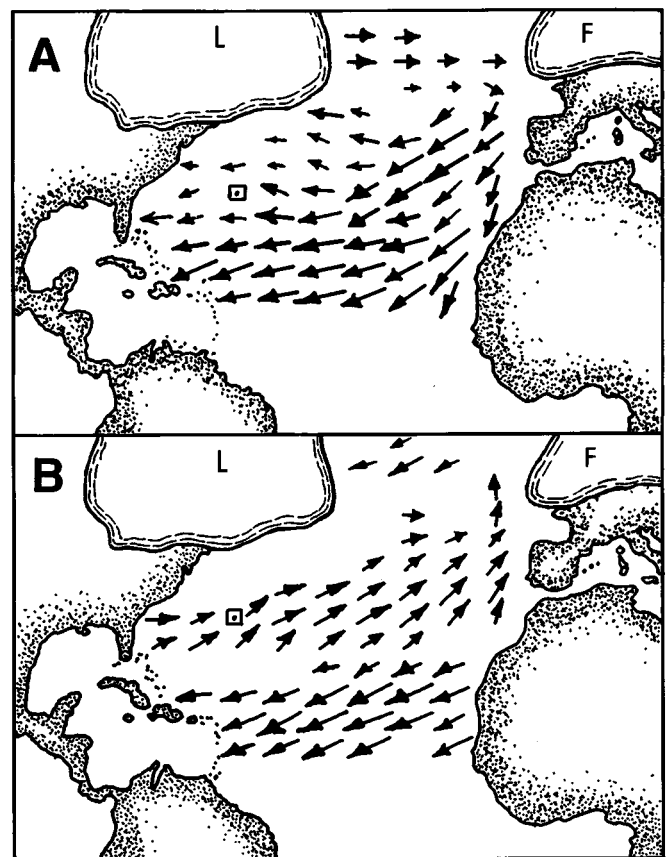


Figure 5. Surface wind circulation pattern during full glacial time at ~18 Ka based on a general circulation model (GCM). A, Summer season pattern; B, winter season pattern. Location of Bermuda shown by square/dot symbol. Also shown are the Laurentide (L), and Fennoscandian (F) ice sheets. Modified from Kutzbach and Guetter (1986).

glacial loess. Based on studies of contemporary eolian transport of silts from glacial outwash in Alaska, loess transport from continental glacial ice fronts in North America would be expected to have occurred mainly during summers, when outwash sedimentation was at a maximum (Flint, 1971). Farther south, however, along drainages distant from the North American continental ice fronts, it is possible that loess transport and deposition also took place during glacial winters. Given the latitude of Bermuda, we hypothesize that the most likely loess sources in North America would be in the lower Mississippi River Valley (Fig. 3) in the states of Arkansas, Mississippi, and Louisiana (Fig. 6).

QUATERNARY STRATIGRAPHY OF BERMUDA

Most of the surficial geology of Bermuda is dominated by Quaternary eolianites with some occurrences of marine deposits that grade into or are interstratified with the eolianites (Hearty et al., 1992; Vacher et al., 1989, this volume). The dunes, which coalesced to form irregularly defined, transverse dune ridges, were lobate-shaped sand bodies (Mackenzie, 1964a,b). Stratigraphic units on Bermuda are defined as packages of eolianite and beach/marine facies separated from older and younger sediment packages by well-developed soils (Vacher et al., 1989). These soils indicate periods of nondeposition of either eolianite or beach/marine deposits. From youngest to oldest, the major stratigraphic units (Vacher et al., this volume) are: (1) the Southampton Formation (~85 Ka); (2) the Rocky Bay Formation (~125 Ka); (3) the Belmont Formation (200 to 225 Ka); (4) the Town Hill Formation, which has both upper and lower members (upper, 325 to 350 Ka; lower, 430 to 475); and (5) the Walsingham Formation (>880 Ka). The ages of the Southampton, Rocky Bay, and Belmont Formations are derived from U-series dating of corals from the beach or marine facies of the units (Harmon et al., 1983); the age estimates of the older units are based on amino acid ratios of whole-rock eolianite samples and amino acid ratios of land snails from the eolianites, calibrated by the U-series-dated units (Hearty et al., 1992).

MATERIALS AND METHODS

Geochemical analyses were conducted on soil samples collected from the interiors of subaerially exposed solution pipes and on samples of the surrounding host eolianite or marine facies at four localities on Bermuda (Fig. 1). The stratigraphic units represented were solution pipes in the Southampton, Belmont, and upper Town Hill Formations (Figs. 7 and 8). Because soil horizons are not well defined within the solution pipes and there is no significant change in soil texture as a function of depth, the soil samples collected at different depths (>3 cm) from each solution pipe were combined to form composite samples. At least two solution pipes were sampled at each of the four localities.

The soil and host carbonate samples were passed through a

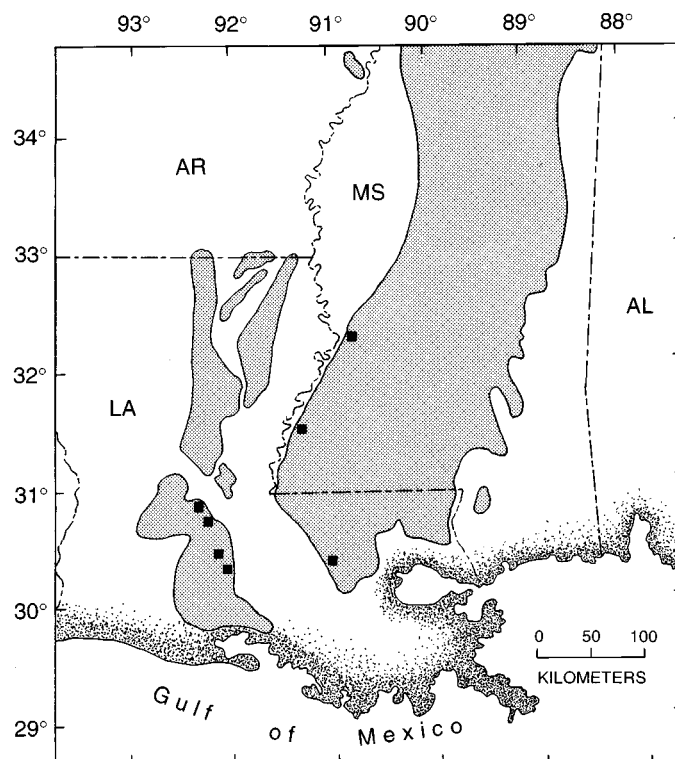


Figure 6. Distribution of loess (shown by shading) in the lower Mississippi River Valley and sample localities (solid squares) of Miller et al. (1986) and Pye and Johnson (1988) used in this study. Distribution of loess based on Thorp and Smith (1952) for Arkansas and Mississippi, and Miller et al. (1986) for Louisiana.

2-mm sieve, and then ground to <200 mesh. The concentrations of Al, Ti, Zr, Y, Nb, and Th were of particular interest because these are elements that have high (>3) ionic potentials and are not normally mobilized during chemical weathering and soil formation. Major element concentrations were determined by wavelength-dispersive x-ray fluorescence (Taggart et al., 1987), and all trace elements except Th were measured by energy-dispersive x-ray fluorescence (Johnson and King, 1987). Concentrations of Th were determined by sealed-can gamma-ray spectrometry (Bunker and Bush, 1966).

For Saharan dust, we used Al, Ti, Zr, Y, and Th data reported by Glaccum (1978) and Rydell and Prospero (1972), based on airborne dust samples collected from Sal Island (Cape Verde Islands), Barbados, and Miami, Florida. Saharan dust reaching the western Atlantic Ocean is dominated by quartz and mica, with lesser amounts of kaolinite, chlorite, calcite, and feldspars (Glaccum and Prospero, 1980). For lower Mississippi River Valley loess, we used geochemical data for the relatively unweathered portions of loess (i.e., soil C horizons) of various ages in Mississippi and Louisiana reported by Miller et al. (1986) and Pye and Johnson (1988). The loess samples (Fig. 6) were from units of several ages (Peoria loess, Crowley's Ridge loess, Sicily Island loess, and units 1 through 4 of Pye and Johnson [1988]). These loess units range in age from the late

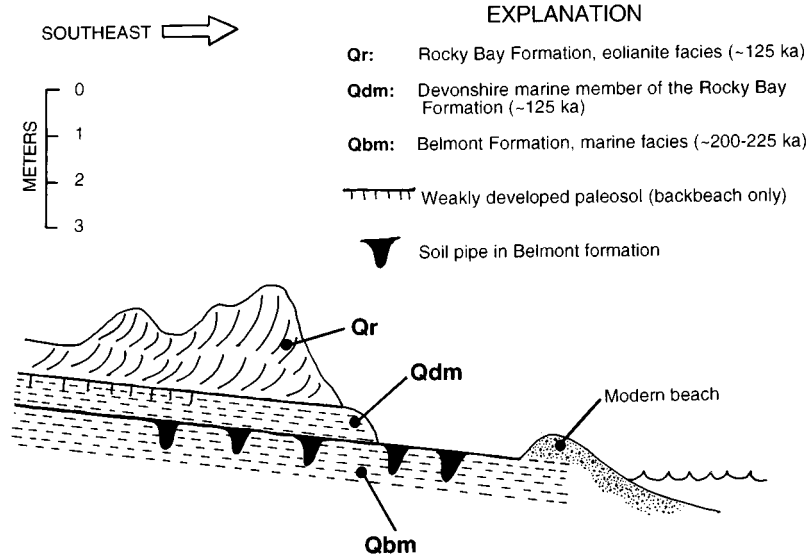


Figure 7. Coastal exposure in the vicinity of Grape Bay, Bermuda, showing relation of soil pipes to eolianite and marine units. Vertical scale is approximate.

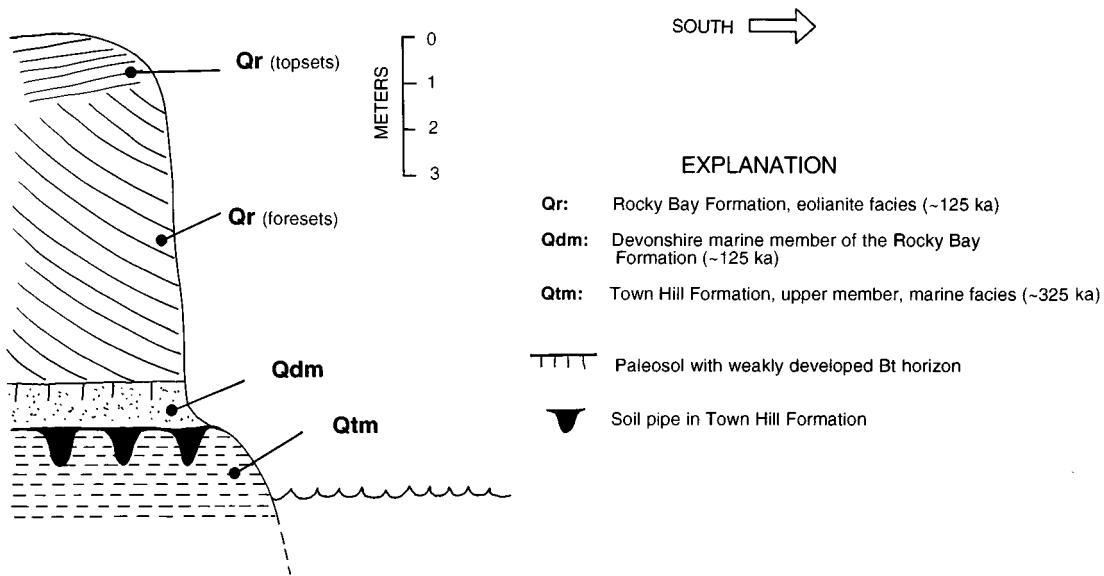


Figure 8. Exposure on the north side of Whalebone Bay, Bermuda, showing relation of soil pipes to eolianite and marine units.

Wisconsin to at least the mid-Pleistocene, based on radiocarbon dating, thermoluminescence dating, and aminostratigraphy (Miller et al., 1986; Pye and Johnson, 1988; Clark et al., 1989). Bulk lower Mississippi River Valley loess has mostly quartz, dolomite, and feldspars; clay fractions of the loess are dominated by smectite with lesser amounts of kaolinite and mica (Ruhe, 1984; Miller et al., 1986; Pye and Johnson, 1988).

It is important to note that the lower Mississippi River Valley loess data are based on analyses of bulk loess samples, which includes all particle sizes found in the deposit. Certain element ratios in the <10 μ fraction may differ from the same ratios in bulk loess; for example, Al₂O₃/TiO₃ may be higher in

the <10 μ fraction, although Ti/Y and Ti/Zr may remain relatively constant. Miller et al. (1986) reported that Ti/Zr values in the clay-rich B horizons of Mississippi River Valley loess are not significantly different from the Ti/Zr values in the clay-poor C horizons.

RESULTS AND DISCUSSION

Geochemistry of host carbonate rocks

The major element analyses indicate that the eolianites and marine facies of Bermuda are extremely pure carbonates (Table 1), which is in agreement with the observations of

Bricker and Mackenzie (1970). The concentrations of SiO₂ and Al₂O₃, the major components of clays, are <0.5% in all carbonate samples we analyzed. Many major elements are not present in detectable amounts. Assuming that all of the measured CaO was present in CaCO₃, and that the loss on ignition (LOI) is due to CO₂ loss, then CaO plus LOI is a reasonable approximation of carbonate content. These calculations show that Bermuda carbonates are 97 to 100% CaCO₃. The presence of heavy mineral grain impurities has been noted in the area of Castle Harbour (Fig. 1); it was attributed to localized subaerial exposure of the submerged volcanic platform early in Bermuda's geologic history but never again reexposed (Land et al., 1967). Volcanic detritus is most evident in the marine facies of the upper member of the Town Hill Formation at Whalebone Bay; however, Bricker and Mackenzie (1970) rejected the hypothesis that the quartz and aluminosilicate clays of Bermuda soils are derived from the basaltic platform. We observed minute amounts of black volcanic grains in hand specimens of eolianites at other localities, but these impurities constitute <1% of the samples we examined.

If Bermuda soils were derived solely from the host carbonates and their limited noncarbonate fraction, we would expect to see soil morphology dominated by secondary carbonates such as laminar, platy, or nodular calcretes (Esteban and Klappa, 1983). In the source of our field work, we saw little or no calcrete development in soils exposed in natural outcrops and in road cuts. Variable concentrations of carbonate rhizoliths were found in the soil-filled interiors of most of the solution pipes; however, there was no evidence of a carbonate-derived soil profile. The reddish, clay-rich soils, whether horizontal or in solution pipes, usually overlie or cut directly across primary sedimentary structures such as topset and foreset beds with little intervening secondary carbonate. Our findings, therefore, are in agreement with the view that the Bermuda soils originate from an external, eolian parent

material (Bricker and Mackenzie, 1970). Although dust from both North America and the Sahara reaches Bermuda today (Chen and Duce, 1983), we did not observe a modern "blanket" of dust covering the Bermudan landscape. Whatever dust has recently fallen onto Bermuda has been fully incorporated into the surface soils, similar to what Muhs et al. (1990) reported for dust-derived soils on Caribbean islands.

Immobile element ratios: Bermuda soils and hypothesized parent materials

Employing the geochemical fingerprinting approach, Al₂O₃/TiO₂, Ti/Y, Ti/Th, and Ti/Zr values were determined for the soils in Bermuda solution pipes and the two hypothesized parent materials. Not all of these immobile element ratios can be used to discriminate between the two parent materials. For example, the mean Al₂O₃/TiO₂ value for Saharan dust collected from Sal Island, Barbados, and Miami, Florida is 16 ± 2 (mean ± 1 standard deviation; n = 30), which is not significantly different from Louisiana and Mississippi loess, which is 13 ± 2 (n = 18). Similarly, the mean Ti/Y value for Saharan dust is 159 ± 12, which is not significantly different from the loess value of 137 ± 28. Thorium data are not yet available for loess, so it is not possible to use Ti/Th values for comparisons with Saharan dust and the Bermuda soils. However, Ti/Zr for Saharan dust is 37 ± 6, whereas loess is 9 ± 2. Despite the fact that only one immobile element ratio clearly distinguishes the two hypothesized parent materials, useful comparisons with the Bermuda soils can be made using the other ratios.

Two soil samples (W3 and W4) have anomalously high Ti, Zr, and Nb concentrations (Tables 2 and 3). Repeat analyses were performed using a different x-ray fluorescence spectrometer, and the same values were obtained within analytical uncertainty. Because these two samples are from the Whalebone Bay

TABLE 1. MAJOR ELEMENT CONCENTRATIONS (WT. %) IN BERMUDA CARBONATE ROCKS

Strat. Unit*	Age† (Ka)	Locality‡	Sample No.	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	MgO	CaO	Na ₂ O	TiO ₂	P ₂ O ₅	LOI**	CaCO ₃ ‡
Qs	85	CB	C14	0.12	.....	.....	2.33	53.0	.....	.....	0.07	44.9	97.9
Qs	85	CB	C15	.....	.....	.....	2.69	52.1	.....	.....	0.06	44.9	97.0
Qs	85	CB	C16	0.12	0.11	.....	2.84	52.3	.....	.....	0.06	44.8	97.1
Qb	200	DB	D7	0.18	0.20	.....	0.85	55.7	.....	.....	0.08	44.3	100.0
Qb	200	DB	D8	.....	0.12	.....	0.89	55.6	.....	.....	0.06	44.3	99.9
Qb	200	GB	G8	0.12	0.12	.....	0.73	53.8	.....	.....	0.07	45.6	99.4
Qb	200	GB	G9	0.17	0.11	.....	1.87	53.4	.....	.....	0.06	44.7	98.1
Qtu	325	WB	W7	0.20	0.21	0.08	1.03	55.5	.....	.....	0.12	44.0	99.5
Qtu	325	WB	W8	0.10	0.10	.....	2.61	52.4	0.19	0.04	0.05	44.7	97.1

K₂O and MnO not detectable in any samples.

*From Vacher et al., 1989; Qs = Southampton; Qb = Belmont; Qtu = upper Town Hill Formations.

†Estimated ages from Harmon et al., 1983; Vacher and Hearty, 1989; and Hearty et al., 1992.

‡Locality abbreviations: CB = Church Bay; DB = Devonshire Bay; GB = Grape Bay; WB = Whalebone Bay.

**LOI = Loss on ignition at 900°C.

‡CaCO₃ content estimated from sum of CaO and LOI.

area, the anomalous Ti, Zr, and Nb concentrations may be due to the volcanic heavy mineral grains present locally in the marine facies of the host upper Town Hill Formation. We collected modern Whalebone Bay beach sand that contains high concentrations of heavy mineral grains which appear to be derived from shoreline erosion of the Town Hill marine facies. These beach

sediments, even without complete carbonate removal, have Ti contents of ~29%, Zr contents of >800 ppm, and Nb contents of >4,000 ppm. It is interesting to note, however, that the concentrations of Ti, Zr, and Nb in the Whalebone Bay beach sediments and soils are all significantly higher than the concentrations of these elements reported for most basic vol-

TABLE 2. MAJOR ELEMENT CONCENTRATIONS (WT. %) IN BERMUDA SOLUTION PIPE SOILS

Host Unit*	Locality†	Sample No.	Max. Age§ (Ka)	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	MgO	CaO	Na ₂ O	K ₂ O	TiO ₂	P ₂ O ₅	MnO	LOI**
Qs	CB	C2	85	7.52	10.2	4.10	1.67	36.2	0.33	0.21	0.29	1.20	0.04	37.3
Qs	CB	C3	85	7.61	9.93	4.00	1.76	36.4	0.42	0.12	0.31	1.12	0.04	37.3
Qs	CB	C4	85	22.8	23.2	10.0	2.85	6.81	1.43	0.48	1.20	3.41	0.09	25.1
Qs	CB	C5	85	22.0	24.3	10.0	2.92	7.58	1.09	0.55	1.20	2.12	0.09	27.2
Qs	CB	C7	85	17.1	19.5	7.91	2.41	17.1	1.25	0.49	0.80	2.20	0.09	29.4
Qb	DB	D1	200	16.4	21.1	6.97	2.81	19.3	0.75	0.28	0.83	0.51	.....	29.8
Qb	DB	D2	200	16.7	22.3	7.20	2.86	18.0	0.80	0.30	0.86	0.52	.....	29.4
Qb	DB	D3	200	17.1	14.6	6.29	2.27	25.3	0.74	0.53	0.76	0.42	0.10	31.4
Qb	DB	D5	200	18.0	22.5	8.38	2.61	15.0	0.97	0.35	1.06	0.61	0.02	28.4
Qb	GB	G6	200	4.32	3.49	1.49	2.81	45.2	0.27	0.05	0.16	0.17	.....	42.2
Qb	GB	G7	200	6.30	5.27	2.26	2.25	42.3	0.33	0.06	0.24	0.23	.....	40.7
Qtu	WB	W1	325	8.39	14.3	7.21	1.81	31.9	0.27	0.32	1.34	0.66	0.04	33.4
Qtu	WB	W2	325	9.25	15.2	7.42	1.69	30.6	0.36	0.37	0.86	0.56	.....	33.3
Qtu	WB	W3	325	5.41	11.0	7.28	1.44	33.8	0.39	0.11	7.97	0.64	0.05	30.7
Qtu	WB	W4	325	8.30	13.0	9.22	3.03	26.2	1.07	0.09	7.34	0.37	0.14	29.2

*From Vacher et al., 1989; Qs = Southampton; Qb = Belmont; Qtu = upper Town Hill Formations.

†Locality abbreviations: CB = Church Bay; DB = Devonshire Bay; GB = Grape Bay; WB = Whalebone Bay.

§Maximum age estimates based on Harmon et al., 1983; Vacher and Hearty, 1989; and Hearty et al., 1992.

**LOI = Loss on ignition at 900°C.

TABLE 3. TRACE ELEMENT CONCENTRATIONS (PPM) IN BERMUDA SOLUTION PIPE SOILS

Host Unit*	Locality†	Sample No.	Max. Age§ (Ka)	Rb	Sr	Y	Zr	Nb	Th
Qs	CB	C2	85	94	5160	478	64	94	10
Qs	CB	C3	85	69	4940	468	44	...	7
Qs	CB	C4	85	51	6720	476	140	...	20
Qs	CB	C5	85	10	4410	515	122	...	24
Qs	CB	C7	85	51	5200	691	89	...	20
Qb	DB	D1	200	7	1000	336	147	...	19
Qb	DB	D2	200	4	919	368	145	...	19
Qb	DB	D3	200	19	881	428	131	...	13
Qb	DB	D5	200	4	1180	594	163	...	...
Qb	GB	G6	200	8	1160	104	28	...	4
Qb	GB	G7	200	9	1060	231	34	...	6
Qtu	WB	W1	325	19	1160	226	135	59	20
Qtu	WB	W2	325	29	877	322	111	22	16
Qtu	WB	W3	325	4	787	669	269	591	74
Qtu	WB	W4	325	2	855	108	349	509	...

*From Vacher et al., 1989; Qs = Southampton; Qb = Belmont; Qtu = upper Town Hill Formations.

†Locality abbreviations: CB = Church Bay; DB = Devonshire Bay; GB = Grape Bay; WB = Whalebone Bay.

§Maximum age estimates based on Harmon et al., 1983; Vacher and Hearty, 1989; and Hearty et al., 1992.

canic rocks (Pearce and Cann, 1973). Because of the anomalously high concentrations of Ti, Zr, and Nb in soil samples W3 and W4 due to local contamination by heavy mineral grains, we have not included them in our overall calculations of immobile element ratios.

Comparison of immobile element ratios in the Bermuda soils with the hypothesized parent materials indicates that the soils probably have been influenced by more than one parent material, and probably include source areas not yet identified. The Ti/Zr value, which distinguishes Saharan dust from Mississippi River Valley loess, shows considerable scatter for the Bermuda soils (Fig. 9), far greater than that observed by Muhs et al. (1990) for soils on Caribbean islands and other western Atlantic islands at lower latitudes. The Ti/Zr values for the soils in solution pipes in the Belmont Formation (~200 Ka) plot closely within range of Ti/Zr values for Saharan dust. Most of the Ti/Zr values for soils from solution pipes in the Southampton (~80 Ka) and upper Town Hill (~325 Ka) Formations plot above the Saharan range (Fig. 9). Because of these relatively high Ti/Zr values and because Mississippi River Valley loess has lower Ti/Zr values than Saharan dust, it does not appear that Bermuda soils are a simple mix of Saharan dust and Mississippi River Valley loess.

A complex parent material assemblage for Bermuda soils is also indicated by the Al_2O_3/TiO_2 values. The Al_2O_3/TiO_2 values of soils from solution pipes in the Southampton and Belmont Formations plot above the ranges for both Mississippi River Valley loess and Saharan dust, strongly suggesting a different parent material (Fig. 10). In the case of the Ti/Y values, soils from all three formations plot well below the range of values for loess and Saharan dust, again implying at least a third parent material

having a distinct composition (Fig. 11). A few soils, one from each formation, have Ti/Th values that plot within the range of Saharan dust, but most plot below this range (Fig. 12).

Collectively, the four immobile element ratios suggest the following interpretations: (1) the soils of Bermuda are not derived exclusively from either lower Mississippi River Valley loess or Saharan dust; (2) the soils are not derived from simple mixing of the two hypothesized parent materials; and (3) at

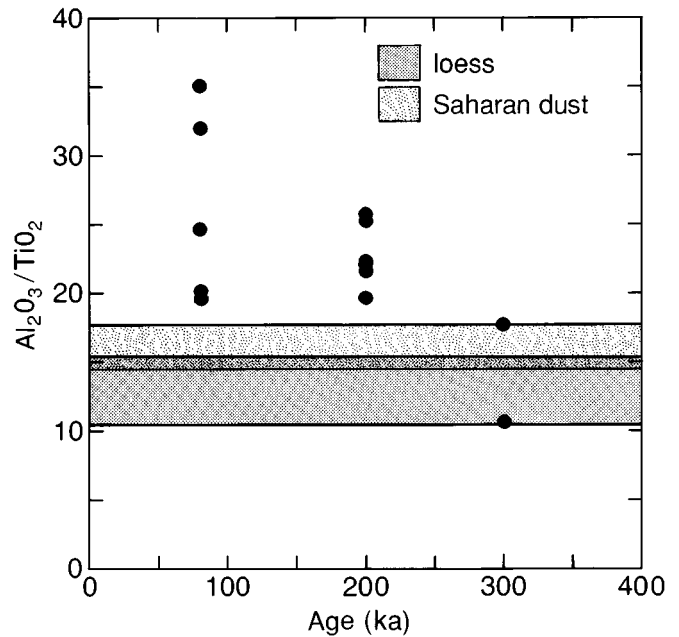


Figure 10. Al_2O_3/TiO_2 values of Bermuda soils from solution pipes formed in carbonates of different ages compared to the range (mean \pm 1 standard deviation) of Al_2O_3/TiO_2 values characterizing Saharan dust and Mississippi River Valley loess.

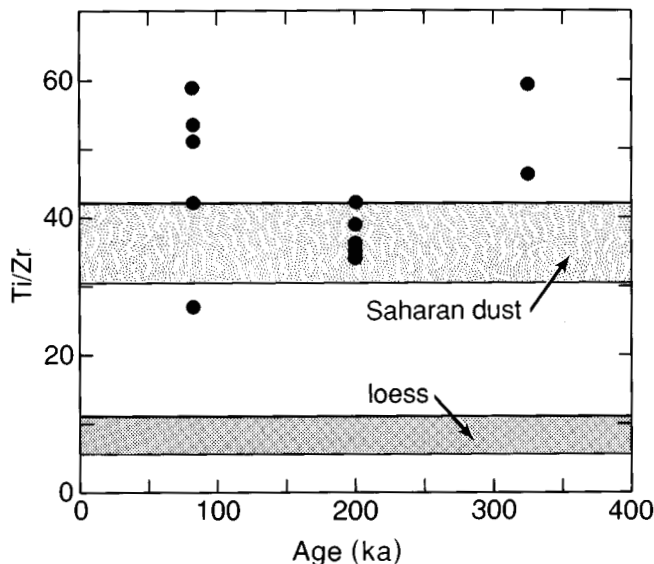


Figure 9. Ti/Zr values of Bermuda soils from solution pipes formed in carbonates of different ages compared to the range (mean \pm 1 standard deviation) of Ti/Zr values characterizing Saharan dust and Mississippi River Valley loess.

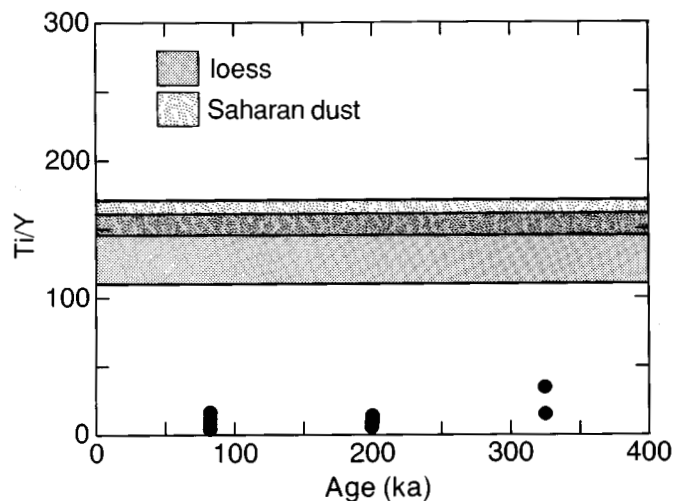


Figure 11. Ti/Y values of Bermuda soils from solution pipes formed in carbonates of different ages compared to the range (mean \pm 1 standard deviation) of Ti/Y values characterizing Saharan dust and Mississippi River Valley loess.

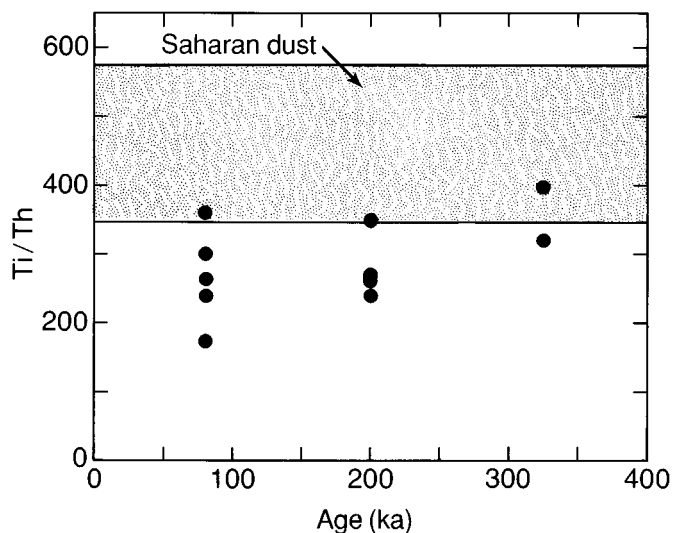


Figure 12. Ti/Th values of Bermuda soils from solution pipes formed in carbonates of different ages compared to the range (mean \pm 1 standard deviation) of Ti/Th values characterizing Saharan dust.

least one other source area must be contributing to the soils and may in fact be the most important contributor.

Degree of chemical weathering of soils in Bermuda solution pipes

A comparison of the degree of weathering of the Bermuda solution pipe soils with soils on Barbados reef terraces reinforces the interpretation that Saharan dust is not the only parent material of Bermuda soils. A useful measure of chemical weathering in soils is the $\text{SiO}_2/\text{Al}_2\text{O}_3$ value. Because Si is lost through mineral alteration by hydrolysis, while Al generally is retained, the $\text{SiO}_2/\text{Al}_2\text{O}_3$ value usually decreases as weathering proceeds. Muhs et al. (1990) found that soils (using weighted profile averages of all horizons) derived primarily from Saharan dust on uplifted reef terraces of Barbados showed a systematic decrease in their $\text{SiO}_2/\text{Al}_2\text{O}_3$ values as a function of terrace age (Fig. 13). This trend is explained by the fact that the clay mineralogy of the younger Barbados soils is dominated by mixed-layer kaolinite-smectite, whereas soils on the oldest terraces have decreasing amounts of smectite and the oldest soil has only kaolinite. On Eleuthera Island in the Bahamas, Foos (1991) reported $\text{SiO}_2/\text{Al}_2\text{O}_3$ values of 0.8 for soils developed from Saharan dust on carbonate eolianites. She interpreted these relatively low values to mean that soils on Eleuthera Island have experienced considerable chemical weathering. This interpretation is supported by the soil mineral assemblage, which consists of boehmite, hydroxy-interlayered clay, hematite, and goethite.

The $\text{SiO}_2/\text{Al}_2\text{O}_3$ values in the Bermuda pipe soils range from 0.59 to 1.24, with a mean value of 0.88 (Fig. 13). All of these values, when plotted as a function of carbonate age, fall below the Barbados time-trend line and are much closer to the

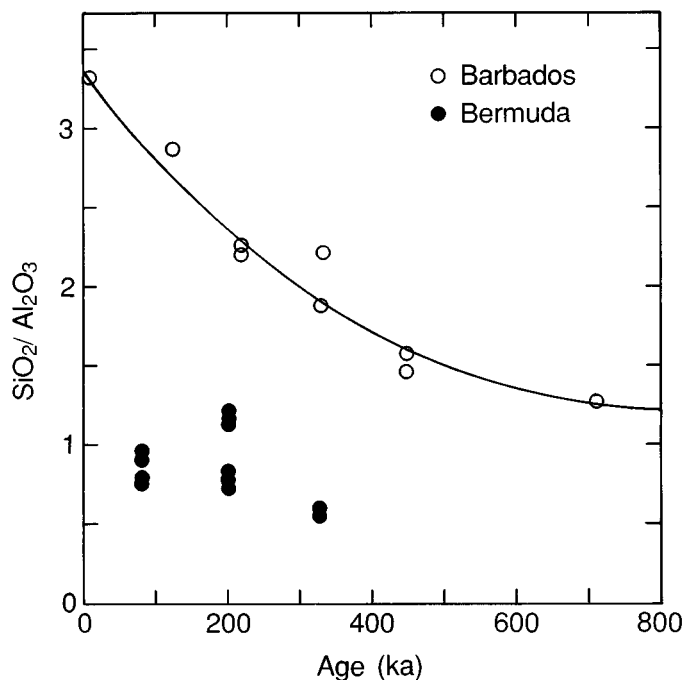


Figure 13. $\text{SiO}_2/\text{Al}_2\text{O}_3$ values of dust-derived soils in Barbados plotted as a function of terrace age (Muhs et al., 1990) compared to $\text{SiO}_2/\text{Al}_2\text{O}_3$ values of Bermuda soils from solution pipes formed in carbonates of different ages.

values reported for Eleuthera soils by Foos (1991) (Fig. 13). In their study of samples of horizontal soils and soils from the interiors of solution pipes, Ruhe et al. (1961) reported that the soils of Bermuda are characterized by amorphous material, kaolinite, vermiculite, and gibbsite (in some cases), but no mica or smectite. This mineralogy explains the low $\text{SiO}_2/\text{Al}_2\text{O}_3$ values, suggesting either that Bermuda soils have experienced a significantly greater degree of chemical weathering than Barbados soils of comparable age or that the parent material arrived in a "preweathered" condition (i.e., arrived on Bermuda with an initially low $\text{SiO}_2/\text{Al}_2\text{O}_3$ value). If Bermuda soils have experienced a greater degree of chemical weathering than Barbados soils of comparable age and the two islands had the same soil parent material, a difference in climate is a possible explanation for the different $\text{SiO}_2/\text{Al}_2\text{O}_3$ values. Localities with higher temperatures and a higher ratio of precipitation (P) to potential evaporation (PE) should experience more chemical weathering (Birkeland, 1984).

On Barbados, both P and PE vary as a function of elevation; soils on the higher terraces receive greater mean annual P totals and the rates of PE are lower than on the lower terraces (Rouse, 1966). For example, on the lower 125- and 190-Ka terraces of Barbados, P is 1,295 to 1,448 mm yr^{-1} and PE is 1,676 to 1,763 mm yr^{-1} ; whereas on the highest terrace (estimated to be about 700 Ka by Muhs et al., 1990), P is 1,981 to 2,007 mm yr^{-1} and PE is 1,168 to 1,245 mm yr^{-1} (Rouse, 1966). The P/PE values on Barbados are 0.74 to 0.86 for the 125-Ka and 190-Ka terraces, 0.89 to 1.03 for the 220-Ka and 320-Ka

terraces, 0.95 to 1.10 for the 460-Ka terrace, and 1.59 to 1.72 for the 700-Ka terrace.

On Bermuda, P is 1,463 mm yr⁻¹ and PE is about 1,366 mm yr⁻¹ (Macky, 1957). The P/PE value of 1.07 for Bermuda is significantly higher than the P/PE values for the 125-Ka and 190-Ka terraces on Barbados, but not significantly different from the P/PE values for the older (>220 Ka) terraces. Thus, the amount of moisture available for chemical weathering might explain some of the differences in SiO₂/Al₂O₃ values for the lower terrace soils on Barbados and Bermuda soils of comparable age. The amount of available moisture, however, cannot explain the differences in SiO₂/Al₂O₃ values for the older soils. Assuming that the present climatic differences between Barbados and Bermuda are representative of past climatic gradients, mean annual temperature differences as well as the P/PE values argue against a more rapid rate of chemical weathering on Bermuda compared to Barbados. Present mean annual air temperature at Bridgetown, Barbados is 26°C, while on Bermuda it is 21°C. Due to the higher temperatures, slightly higher (not lower) chemical weathering rates would be expected on Barbados.

One could argue that on Bermuda, the rate of dust influx might be lower than on Barbados, and therefore the rate of chemical weathering exceeds the rate of parent material accumulation. However, Bricker and Prospero (1969) reported that during a comparable time period of measurement, dust flux on Bermuda was a factor of six greater than that on Barbados. We conclude that neither differences in rates of chemical weathering nor rates of dust fall can explain the differences between the SiO₂/Al₂O₃ values of Bermuda and Barbados soils. The differences in the SiO₂/Al₂O₃ values, therefore, appear to be related to differences in the initial composition of the parent materials.

A Great Plains dust source for Bermuda soils?

Examination of satellite imagery suggests a third possible source area for an eolian soil parent material on Bermuda. During February 1977, a major dust storm originating in eastern Colorado and the Texas–New Mexico border area of the Texas panhandle passed over the southern United States over a 4-day period (McCauley et al., 1981). Satellite imagery from this period shows that dust reached Georgia, South Carolina, North Carolina, and much of the western Atlantic Ocean, possibly including Bermuda. On a coastal pier near Savannah, Georgia, Windom and Chamberlain (1978) collected dust-fall from this storm and found that the material was about 90% clay-sized particles, with a mineralogy dominated by mica, but also included quartz, feldspars, chlorite, and kaolinite. These observations suggest that sources in the central Great Plains and southern High Plains of the United States (Holliday, 1991) could provide dust to Bermuda. The next step in our ongoing study of soil genesis on Bermuda will involve geochemical analyses of possible dust source areas in the Great Plains.

CONCLUSIONS

Based on our initial studies of soil materials in the carbonate solution pipes of Bermuda, we conclude the following:

1. Bermuda eolianites and their associated marine facies are extremely pure carbonates based on major element analyses and, therefore, are not the parent material of the soils. We agree with Bricker and Mackenzie (1970) that eolian dust derived from outside the island is the soil parent material.

2. Compared to soils on carbonates of comparable age in lower latitudes in the Caribbean and western Atlantic, the immobile element composition of soils in Bermuda solution pipes is more variable. The results of these analyses suggest that more than one parent material may have contributed to Bermuda soils.

3. Most values of Al₂O₃/TiO₂, Ti/Zr, Ti/Y, and Ti/Th in Bermuda soils are significantly different from the values that characterize Saharan dust and lower Mississippi River Valley loess. An important finding is that the values for the Bermuda soils are not intermediate between the range of values for the two hypothesized parent materials. We conclude, therefore, that Bermuda soils are not a simple mixture of the two possible sources, and that at least one additional source must be contributing eolian dust to Bermuda.

4. SiO₂/Al₂O₃ values in Bermuda soils are significantly lower than SiO₂/Al₂O₃ values in Barbados soils that are of comparable age and are thought to be derived from Saharan dust. Climate differences cannot explain the differences in SiO₂/Al₂O₃ values between the two islands. This interpretation reinforces the conclusion, based on the immobile element ratios, that Saharan dust is not the only parent material of the soils in Bermuda solution pipes. Other possible North American source areas outside of the lower Mississippi River Valley, such as the central and southern Great Plains, must be examined in more detail.

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