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# Mineralogical evidence for a local volcanic origin of the parent material of Bermuda Quaternary paleosols

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ABSTRACT

The alternation of carbonate deposits and paleosols compose the emerged part of the Bermuda archipelago. The pedological units present a complex and diversified mineralogy. Former studies demonstrated that the paleosols are not primarily a product of the unique dissolution of the surrounding carbonates, but contain a massive input of allochthonous non-carbonate detrital material. Researchers during more than the past three decades have attributed this flux of insoluble residues (IR) to Saharan dusts. We carried out systematic field and mineralogical analyses on the Quaternary paleosols from the Bermuda archipelago. Their mineralogical assemblage predominantly includes carbonates, clay minerals (kaolinite, chlorite and chlorite/vermiculite), phosphates, and aluminium and iron oxides/hydroxides. This assemblage is strikingly close to the mineralogy of the weathered volcanic substrate of Bermuda, but noticeably different from the mineralogy of Saharan dust. Moreover, we found volcanic lithoclasts in numerous paleosol profiles all over the archipelago and in all the recorded time intervals. We thus consider the volcanic seamount underlying Bermuda as the main source of non-carbonate minerals detected in the paleosols. This hypothesis further resolves the anomalous maturity of Bermudan paleosols compared to their southern counterparts in the Bahamas and Barbados.

## Introduction

In this paper, we present new mineralogical and geochemical data from Bermuda paleosols, and propose a model to explain the origin of the additional source of non-carbonate parent material of these paleosols. The fossil soils exposed on the Bermuda archipelago are clay-rich (up to 60%) and contain iron oxides, large amounts of phosphate minerals and rare gibbsite (Sayles, 1931; Ruhe et al., 1961; Blackburn and Taylor, 1969). Because this mineralogical diversity contrasts with the chemical monotony of the surrounding carbonate rocks, the origin of these paleosols remained enigmatic for a long time (Blackburn and Taylor, 1970; Herwitz and Muhs, 1995; Herwitz et al., 1996). According to Blackburn and Taylor (1969, 1970), Bermuda paleosols result from the dissolution of the underlying carbonates and the subsequent concentration of insoluble residues (IR). The latter are volcanic lithoclasts, present in the underlying carbonates and originating from the buried Bermuda volcano. Land et al. (1967) and Bricker and Mackenzie (1970) demonstrated that the high clay content of the paleosols cannot merely result from dissolution/accumulation processes because Bermudan limestones are almost pure carbonates, the IR representing less than 0.5% (Herwitz and Muhs, 1995). It would require at least 150 m of limestone dissolution to produce 1 cm of paleosol (Bricker and Mackenzie, 1970) and such amount of dissolution has never been reported locally. Therefore, other sources for non-carbonate minerals have to be considered.

Isolated in the Northwestern Atlantic Ocean, the Bermuda archipelago is sheltered from continental detritus. Therefore, it was thought airborne dust solely can secure a noticeable flux of non-carbonate minerals over the islands. Today, these lie in the trajectory of the Saharan dust plume (Prospero, 1996 and references therein). Moreover, African dust played a major role in the formation of Quaternary paleosols in the Florida Keys, the Bahamas and Barbados (Syers et al., 1969; Muhs et al., 1990, Boardman et al., 1995, Muhs et al., 2007). Consequently, atmospheric dust from the Saharan (essentially illite, quartz, kaolinite, chlorite and feldspar minerals, (Glaccum and Prospero, 1980) was suggested as the main parent material of Bermudan paleosols (Bricker and Mackenzie, 1970). This hypothesis is supported by the mineralogy of the airborne dust reaching Bermuda today (Bricker and Prospero, 1969). Recent data on trace-element ratios from the paleosols (Herwitz and Muhs, 1995; Herwitz et al., 1996), imply that Bermuda paleosols are geochemically closer to Saharan dust than to North American loess material. Nevertheless, Herwitz and Muhs (1995) further suggest that a significant amount of non-carbonate parent material was likely derived from a yet unknown source located in North America. This

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assumption was supported by the only mineralogical data obtained so far from Bermudan paleosols (Ruhe et al., 1961) which clearly differ from the composition of Saharan dust. Finally, thickness, clay content, and SiO2/Al2O3 ratio of Bermuda paleosols suggest they are equally and even more mature than their southern counterparts in the Bahamas. Despite probable different precipitation ratio, this is paradoxical considering their respective location (Herwitz and Muhs, 1995). Recent studies demonstrated that the parent material of Caribbean Quaternary paleosols is composite and more complex than previously thought (Muhs et al., 2007). Saharan dust is neither the only (Bahamas), nor the main (Barbados) parent material of the soils and paleosols.

## Geological setting

The Bermuda archipelago is located in the northwestern part of the Atlantic Ocean (Fig. 1A). It lies on the top of an extinct Meso-Cenozoic volcanic seamount truncated during a late Oligocene episode of subaerial erosion (Pirsson, 1914a; Reynolds and Aumento, 1974; Vacher and Rowe, 1997) (Fig. 1A). Little is known about this volcano because, today, it is entirely drowned or covered by a carbonate cap (Fig. 1B). However, examination of rock samples retrieved from deep drill cores through the carbonate cap indicate that the Bermuda volcano is composed of tholeiitic lava flows intruded by strongly undersaturated melilite nephelinites (Aumento and Gunn, 1974; Peckenham, 1981; Pirsson, 1914b; Reynolds and Aumento, 1974). The uppermost 300 meters of the volcano have been intensively weathered by marine, meteoric and hydrothermal alteration processes. This spilitization results in the massive replacement of the primary phyllosilicates by calcite, albite, and chlorite (Aumento and Gunn, 1974). Today, the only evidence of the Bermuda volcanic basement are modern and fossil volcanic beach sands located in Whale Bone Bay (WBB) (Blackburn and Taylor, 1969, 1970; Vacher and Rowe, 1997) (Fig. 2). The presence of coarse-grained detritus of weathered basalt has also been reported from Government's Quarry (Hearty and Olson, 2007) (Fig. 2), unfortunately, these deposits were quarried away 30 yr ago.

The Bermuda islands consists of several sets of carbonate dunes (i.e. eolianites) and paleosols that have been dated and integrated in a detailed stratigraphic framework spanning the last million years (Vacher et al., 1989, 1995; Vacher and Rowe, 1997 for synthesis) (Fig. 1B). The stratigraphic column is characterized by the regular recording of the main glacio-eustatic cycles from MIS (Marine Oxygen Isotope Stage) 11 to the present, and by a gap between these deposits and the older Walsingham formation. The high degree of cementation of this unit and aminostratigraphy suggest an early Pleistocene age (Hearty et al., 1992). The drill core observations of Aumento and Gunn (1974) and Pirsson (1914a) complement Vacher et al. (1989, 1995)) stratigraphic column (Fig. 1B). Aumento and Gunn (1974) identified at least, one main ante-Walsingham carbonate unit and correlated it to the early Pleistocene. This undated deposit must be younger because the Walsingham Formation is already attributed to the early Pleistocene (Hearty et al., 1992; Vacher et al., 1995; Vacher and Rowe, 1997). The buried paleosol, known as the “Primary Red Clay,” which directly overlies the volcanic basement, reflects a long period of surface weathering of igneous rocks (Foreman, 1951).

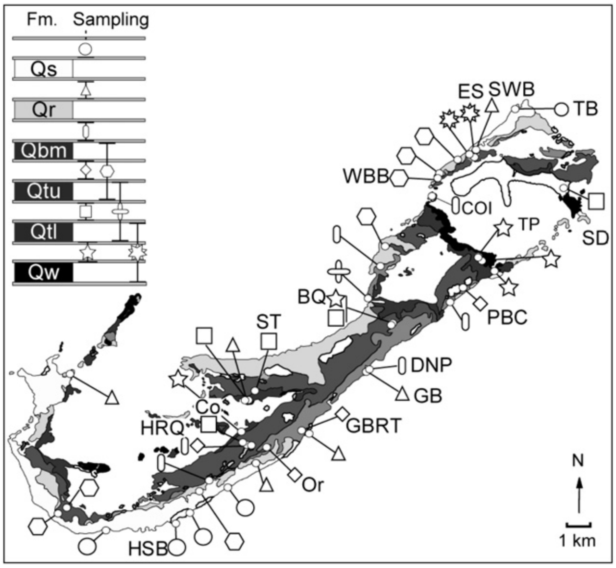


**Figure 2.** Geological map of the Bermuda islands (Vacher et al., 1989) showing the location of the studied sites and their estimated ages. BQ: Bierman's Quarry, Cà: Coob's Hill Road—CO in Figure 4, COI: Coney Island, DNP: Devonshire National Park, ES: Esso Tanks, GB: Grape Bay, GBRT: Grape Bay Railway Track, HRQ: Harvey Road Quarry, HSB: Horse Shoe Bay, Or: Ord Road, PBC: Pink Beach Club, SD: Saint David, ST: Stadium, SWB: Swing Bridge, TB: Tobacco Bay, TP: Tucker's Point, WBB: Whale Bone Bay.

According to former sedimentation models, eolianites accumulate at the onset of regressions, at the very end of interglacial periods, when newly emerged marine sediments are exposed to wind remobilization, whereas soils develop between episodes of dune progradation (Vacher and Rowe, 1997). Other models developed for the Bahamian quaternary deposits rather suggest that the most extensive and largest packages of

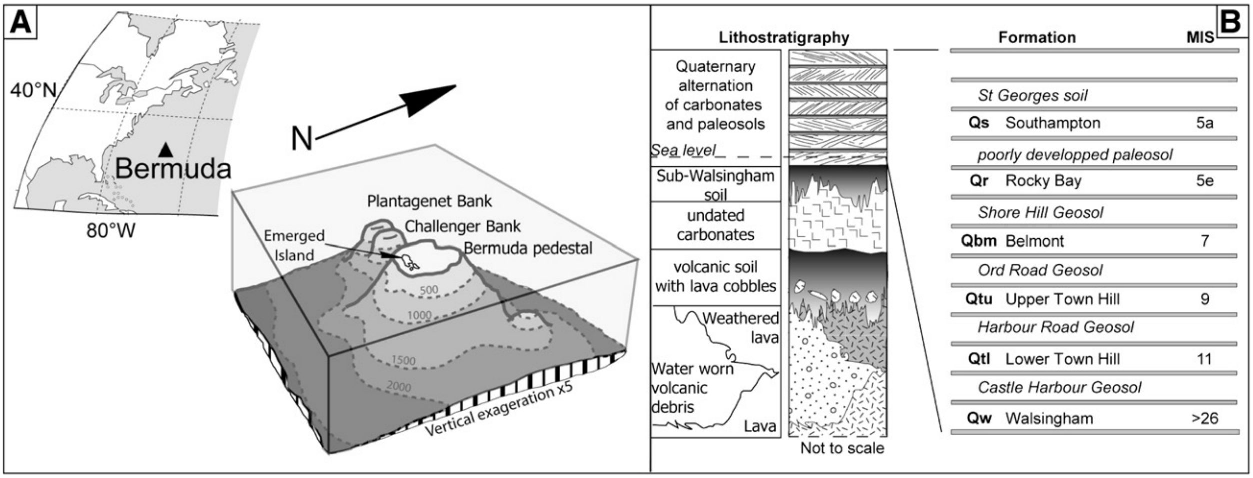


**Figure 1.** (A) location of the Bermuda archipelago. Emerged islands, composed of Quaternary deposits, lie on the summit of a truncated volcano (Dunbar, 2001). (B) Schematic lithostratigraphic column of Bermuda from the buried volcano, up to the Quaternary deposits (Pirsson, 1914a; Aumento and Gunn, 1974; Peckenham, 1981; Vacher et al., 1995). The time intervals covered by the paleosols sampled for this study, and the stratigraphic attribution of the carbonate formation use the Vacher et al.'s (1989, 1995) stratigraphic scheme. MIS: Marine Oxygen Isotope Stage.

eolianite were produced during the transgression that occurs during the platform flooding associated with sea-level rise at the start of an interglacial highstand (Carew and Mylroie, 1995, 1997).

Paleosols, solution pipes, karst fillings and colluvium deposits mainly consist of reworked soils compose the paleo-pedological formations of Bermuda. Paleosols are easily identifiable because they commonly are unconsolidated and brightly colored, subhorizontal layers, sandwiched between carbonate units. They have been long recognized as major discontinuities in the Bermuda record (Sayles, 1931). Vacher et al. (1989, 1995 and references therein) classified them as geosols, i.e. stratigraphic units. Ruhe et al. (1961) classified paleosols according to their maturity and their mineralogy, although in a now out-of-date stratigraphic framework. These authors recognized slightly weathered paleosols, or protosols *sensu* (Vacher and Hearty, 1989, Vacher et al., 1989, 1995), represented by "unconsolidated rock in which few or no clearly expressed soil characteristics have developed," terra-rossa paleosols. The latter group comprises a large spectrum of profiles with diverse maturities. The mineralogy of paleosols is function of this hierarchy: regosols being mainly composed of calcium carbonate with minor iron oxides and organic matter, and terra rossa including carbonates, clay minerals (kaolinite, vermiculite), calcium aluminium phosphate (crandallite, the origin of which is linked to guano deposits), and iron and aluminium oxides (Ruhe et al., 1961).

Colluvium deposits are present in many locations and can disturb the stratigraphic interpretation (Hearty, 2002), or accumulate in large fossil-rich cone deposits in caves (Hearty et al., 2004). Karst and solution-pipe fillings represent major zones of pedological material accumulation, but their dating is poorly constrained. Solution-pipe formation in Bermuda eolianites is commonly is the result of dissolution of the underlying carbonate substratum by acidic streaming by stem flow from palmetto trunks (Herwitz, 1993). The geochemical properties of pipe fillings have been used as evidence for the Saharan origin of the airborne dust reaching Bermuda during the Quaternary Period (Herwitz and Muhs, 1995; Herwitz et al, 1996).

## Methods

We mainly focused on the mineralogy of Bermudan paleosols. Modern soils are considered too impacted by human activities to be integrated in this study, and colluvium deposits, solution pipes and karst fillings have been avoided as much as possible because of their dubious ages. We thus studied and sampled 41 paleosol profiles, covering most of the archipelago surface, and spanning the entire Quaternary stratigraphic record (Fig. 2). We relied on Vacher et al.'s (1989, 1995) geologic map and stratigraphy. Outcrop profiles were measured and described at centimeter scale, their colors being assigned on site, according to the Munsell chart (Munsell, 1975).

The bulk mineralogical composition of 250 non-oriented samples from paleosol profiles and surrounding carbonates was obtained by X-ray diffraction (XRD) at the Mines-ParisTech laboratory. Clay mineralogy was further determined for 70 of these samples whose clay content exceeded 5%, according to a procedure described by Thiry et al. (1983). A quantitative estimate of the main minerals was made by comparing peak areas to calibration charts. The total amount was normalized to 100% to minimize sample preparation and matrix effects. Estimated error for both bulk rock and clay mineralogy is ± 5%. We applied the test of Tamura (1957) and the test of Rich (1968) to distinguish Hydroxy Interlayered Clays (HICs) from chlorite minerals on eight samples from five sites. According to this test, the XRD spectrum of HICs is modified by the collapse of the interlayer space after heating causes the 14 Å peak to shift to 10 Å.

Chemical analyses were carried out on 23 paleosols samples mainly from Bierman's Quarry (BQ), Ord Road (OR) and Whale Bone Bay (WBB) (Fig. 2) with a Perkin Elmer 5000 mass spectrometer (ICP-MS) at the CRPG Laboratory in Nancy (Table 1). Some profiles yielded dark polymineralic lithoclasts and quartz grains that were retrieved from 80- and 33-μm sieves during sample preparation for clay-mineral analyses. The chemical composition of 68 randomly selected grains from WBB beach sands and from six profiles (BQ, GBRT, SD, SWB, TP, WBB) was determined by electron microprobe analyses at the University of Paris VI (Table 2).

## Results

### Paleosol description

Fossil soils are irregular, commonly unconsolidated, more often subhorizontal layers, located at the interface between large carbonate units. In this study, we classify the paleosols according to their degree of maturity. Three types are described hereafter:

(1) Protosols commonly show a homogeneous sandy texture and a white to pale orange color (Fig. 3A), indicating a low degree of

**Table 1**

Results of ICP-MS analyses on Bermuda paleosols matrix. OR: Ord Road Geosol (terra-rossa paleosols); WB: Whale Bone Bay paleosol (site where volcanic clasts occur in modern beach sands); BQ: Bierman's Quarry (one of the most mature of the Bermuda profiles). Tabulated abundances are wt.%.

| | $SiO_2$ | $A1_2O_3$ | $Fe_2O_3$ | MnO | MgO | CaO | $Na_2O$ | $K_2O$ | $TiO_2$ | $P_2O_5$ |
|---|---|---|---|---|---|---|---|---|---|---|
| 99-OR-02 | **x** | 0.27 | **x** | **x** | 1.43 | 47 | 3.93 | **x** | **x** | **x** |
| 99-OR-03 | 0.24 | 0.46 | 0.17 | **x** | 1.03 | 50.85 | 1.14 | **x** | 0.03 | **x** |
| 99-OR-04 | **x** | **x** | **x** | **x** | 1.56 | 50.68 | 1.29 | **x** | **x** | **x** |
| 99-OR-05 | **x** | **x** | **x** | **x** | 1.69 | 51.27 | 0.75 | **x** | **x** | **x** |
| 99-OR-06 | 1.76 | 3.1 | 1.16 | **x** | 0.51 | 48.98 | 0.24 | **x** | 0.15 | 0.28 |
| 99-OR-07 | 1.55 | 2.71 | 0.95 | **x** | 0.53 | 49.38 | 0.31 | **x** | 0.14 | 0.25 |
| 99-OR-08 | 8.51 | 12.26 | 4.98 | **x** | 1.05 | 33.93 | 1.46 | 0.24 | 0.61 | 0.09 |
| 99-OR-09 | 6.24 | 9.75 | 3.75 | **x** | 0.98 | 38.92 | 0.3 | 0.13 | 0.48 | 0.07 |
| 99-WB-03 | **x** | **x** | **x** | **x** | 0.8 | 51.37 | 1.01 | **x** | **x** | **x** |
| 99-WB-04 | 5.68 | 9.84 | 6.29 | 0.11 | 3.6 | 30.14 | 2.85 | 0.24 | 5.74 | 0.23 |
| 99-BQ-01 | 1.04 | 1.91 | 0.52 | 0.03 | 0.55 | 51.27 | 0.26 | **x** | 0.08 | 0.19 |
| 99-BQ-02 | **x** | 0.22 | **x** | **x** | 1.37 | 47.71 | 2.81 | **x** | **x** | **x** |
| 99-BQ-03 | 20.19 | 31.38 | 14.14 | 1.69 | 1.54 | 4.8 | 0.15 | 1.37 | 1.65 | 2.95 |
| 99-BQ-04 | 23.1 | 27.19 | 12.28 | 0.08 | 1.56 | 7.48 | 0.16 | 1.71 | 1.45 | 4.41 |
| 99-BQ-05 | 16.22 | 20.94 | 8.56 | 0.2 | 1.28 | 20.54 | 0.15 | 1.29 | 1.04 | 3.04 |
| 99-BQ-06 | 18.86 | 22.17 | 9.77 | 0.35 | 1.23 | 17.94 | **x** | 1.44 | 1.16 | 2.61 |
| 99-BQ-07 | 14.75 | 17.7 | 6.92 | 0.4 | 1.05 | 25.57 | **x** | 1.09 | 0.84 | 2.14 |
| 99-BQ-08 | 15.19 | 18.28 | 7.46 | 0.51 | 1.05 | 24.78 | **x** | 1.08 | 0.89 | 3.87 |
| 99-BQ-09 | 11.13 | 14.82 | 5.92 | 0.31 | 0.9 | 31.23 | 0.19 | 0.85 | 0.71 | 2.44 |
| 99-BQ-10 | 21.88 | 27.11 | 12.01 | 0.41 | 1.54 | 8.26 | 0.17 | 1.67 | 1.39 | 5.13 |
| 99-BQ-11 | 16.02 | 21.06 | 8.38 | 0.24 | 1.1 | 20.71 | **x** | 1.16 | 1.06 | 4.44 |
| 99-BQ-12 | 20.01 | 27.75 | 12.19 | 0.05 | 1.19 | 6.54 | 0.17 | 1.54 | 1.37 | 9.72 |

**Table 2**
Results of microprobe analyses on the minerals found in Bermuda paleosols. TP: Tucker's Point; WBB: Whale Bone Bay, SD: Saint David. (See Fig. 2 for site location) CPX: Clinopyroxene. Tabulated abundances are wt.%.

| | TP CPX | TP chrornite | WBB leucite | TP ulvöspinel | SD perovskite | WBB-sand chlorite | WBB-sand chromite | WBB-sand perovskite | WBB-sand titanite |
|---|---|---|---|---|---|---|---|---|---|
| $SiO_2$ | 48.21 | 0.37 | 57.57 | 0.24 | 0.07 | 30.23 | 0.26 | 2.01 | 31.08 |
| $TiO_2$ | 2.41 | 2.66 | 0.00 | 38.46 | 55.33 | 0.27 | 1.69 | 54.75 | 36.77 |
| $A1_2O_3$ | 5.63 | 19.67 | 24.14 | 2.11 | 0.16 | 15.69 | 20.83 | 0.19 | 0.31 |
| $Cr_2O_3$ | 0.25 | 35.90 | 0.00 | 0.71 | 0.00 | 2.55 | 39.43 | 0.00 | 0.00 |
| FeO | 4.87 | 24.31 | 0.67 | 50.83 | 0.87 | 6.15 | 26.02 | 0.74 | 1.68 |
| MnO | 0.02 | 0.21 | 0.06 | 0.34 | 0.00 | 0.96 | 0.36 | 0.09 | 0.00 |
| MgO | 14.26 | 13.66 | 0.17 | 4.11 | 0.02 | 24.29 | 9.95 | 0.00 | 0.00 |
| CaO | 23.23 | 0.01 | 0.11 | 0.00 | 36.69 | 0.09 | 0.00 | 37.22 | 27.46 |
| $Na_2O$ | 0.42 | 0.36 | 0.63 | 0.02 | 0.33 | 0.08 | 0.04 | 0.36 | 0.18 |
| $K_2O$ | 0.00 | 0.05 | 13.84 | 0.02 | 0.01 | 0.02 | 0.00 | 0.00 | 0.02 |
| $P_2O5$ | 0.05 | 0.00 | 0.02 | 0.00 | 0.06 | 0.08 | 0.01 | 0.00 | 0.00 |
| F | 0.00 | 0.01 | 0.00 | 0.00 | 0.00 | 0.00 | 0.85 | 0.00 | 0.00 |
| $H_2O$ | | | | | | | | | |
| CI | 0.00 | 0.09 | 0.09 | 0.01 | 0.00 | 0.14 | 0.02 | 0.02 | 0.01 |
| Total | 99.35 | 97.21 | 97.31 | 96.85 | 94.37 | 80.54 | 100.04 | 97.56 | 99.30 |

maturity. Protosols are further characterized by the quasi-absence of pedological and sedimentological structures and often appear as a simple stratum of colored marine sands. Thin-section examination reveals the predominance of well-rounded bioclasts (Fig. 3B). Their formation probably reflects a short time of subaerial exposure. Their weak structural development, the absence of clay accumulations, and the abundance of primary material indicate minimal weathering. Protosols mainly characterize the youngest stratigraphic intervals in Bermuda (Qs/Qr, post Qr; Fig. 1B), but can be found also in older intradunal deposits.

(2) Terra-rossa paleosols usually show a homogeneous, sandy texture with weakly marked pedological horizons. Soil color varies from pale orange to brown (7.5 YR 3/4) (Fig. 3C). Terra-rossa paleosols can further contain numerous *Poecilozonites* land snails (GBRT, WBB), roots traces of rhizoliths and rhizomorphs (WBB), coal fragments (HRQ, Fig. 3C), and black pebbles (HRQ), the latter suggesting the existence of former forest fire or wetlands (Strasser, 1984). Micro-scale observations reveal a clayey matrix with a blocky aggregate structure, the porosity being often filled by secondary calcite (Fig. 3D). Most of the time, the absence of marine clasts attests for an effective ancient weathering (Fig. 3D). Nonetheless, primary minerals can be found intact, or with visible traces of dissolution, which indicates paleosol weathering processes. Isolated volcanic minerals present in the pedological matrix are too altered to be identified. Terra-rossa paleosols are better developed than protosols, but their morphology, described above, still suggests moderate weathering. Terra-rossa paleosols include the Shore Hills, Ord Road and Harbour Road geosols of Vacher et al. (1989, 1995) stratigraphy.

(3) The most mature of the Bermuda profiles is represented by the Castle Harbour Geosol (Fig. 1B) capping the Walsingham Formation, and corresponding to more than 0.5 Ma of subaerial exposure. At Bierman's Quarry (Fig. 3E), the paleosol texture is homogeneous, blocky, slightly columnar, and shows cohesive soil structures. This paleosol is 1.2 m thick and shows an intense reddish-brown color (5YR5/8 to 2.5YR4/4), trending towards purple. The clay content is important, especially in some pockets, and clay minerals prominently coat soil aggregates. Numerous bioturbations are filled by secondary calcite and integrated in black, rounded clayey aggregate forming oxides nodules (Fig. 3F). The oriented clay films coating the nodules and the presence of shrinkage cracks result from numerous wetting/drying cycles. Volcanic lithoclasts are also present in the matrix. On other sites, analogous formations deeply incised their substratum through deep pipes (Fig. 3G). Thus, the original thickness is difficult to appreciate.

The presence of reworked material, unrelated to the maturity of a paleosol, is responsible for segregation of a profile into pedological horizons. The reworked material often constitutes the top horizon of a fossil soil. Horizons dominated by reworked older sediment may be hard to recognize on outcrops, but it can be identified in thin sections (Fig 3H), where clay films coat unaltered rounded marine fragments or clasts. This peculiar pattern is common in many colluvial deposits.

### The dark lithoclasts and quartz grains in paleosol matrix

Dark, polymineralic lithoclasts have been found in paleosols of diverse age, scattered over the entire archipelago (Fig. 4A). Most grains are black or brown and rounded. Some are vitreous and show an octahedral shape, whereas others present distinct cleavages. Their abundance is greater in the paleosols close to site Whale Bone Bay (WBB), where volcanic clasts occur in modern beach sands (Blackburn and Taylor, 1969). Lithoclasts abundance varies from 1 to 2 grains (site DNP) up to several grams of grains (Site ES) per 100 g of paleosol sample. Clast size frequently exceeds 200 μm and can exceptionally reach 2 mm at site SWB (Fig. 4B). Half of the 68 isolated grains analyzed under the microprobe are too weathered to be identified. The other half includes perovskite with veins of titanite, Ti-rich garnet, leucite, Al-diopside, Ti-magnetite with exsolutions of ulvöspinel (Fig. 4C), Fe-Mg-spinel, chromite and phosphate mineral (Table 2).

Dark lithoclasts are often associated with quartz grains. The size, abundance and morphology of the latter grains are highly variable. They are absent from numerous profiles, but very abundant in paleosols from sites ES and TP. There, the average quartz grain size approaches 600 μm and can reach 2 mm. Most of the quartz grains show some degree of rounding but the largest ones are angular.

### Paleosol mineralogy

The mineralogy of several profiles established across diverse Bermuda paleosols is presented in Figure 5. Bermuda paleosols are rich in carbonates, but the concentration of these minerals is very variable from site to site and along a same profile. Carbonate content is linked to the presence of fossil fragments, secondary nodules and substratum debris. It is also linked to the massive presence of sparite in the paleosol porosity. Micromorphological analyses demonstrate that this precipitation occurred after the main pedogenesis processes. Clay content broadly oscillates between 10% and 30%, with concentrations reaching over 60% in some samples from Bierman's Quarry (BQ). The clay content is broadly correlated to profile age, but many exceptions occur, as at GBRT (terra-rossa paleosol) where the clay content is higher than at ES (Castle Harbour Geosol, Fig. 5H). The clay mineral assemblage consists of kaolinite (20% to 50%), chlorite (20% to 40%) and minerals with a main diffraction peak near 14 Å (30% to 50%) (Fig. 6). These clay minerals can be interpreted either as random

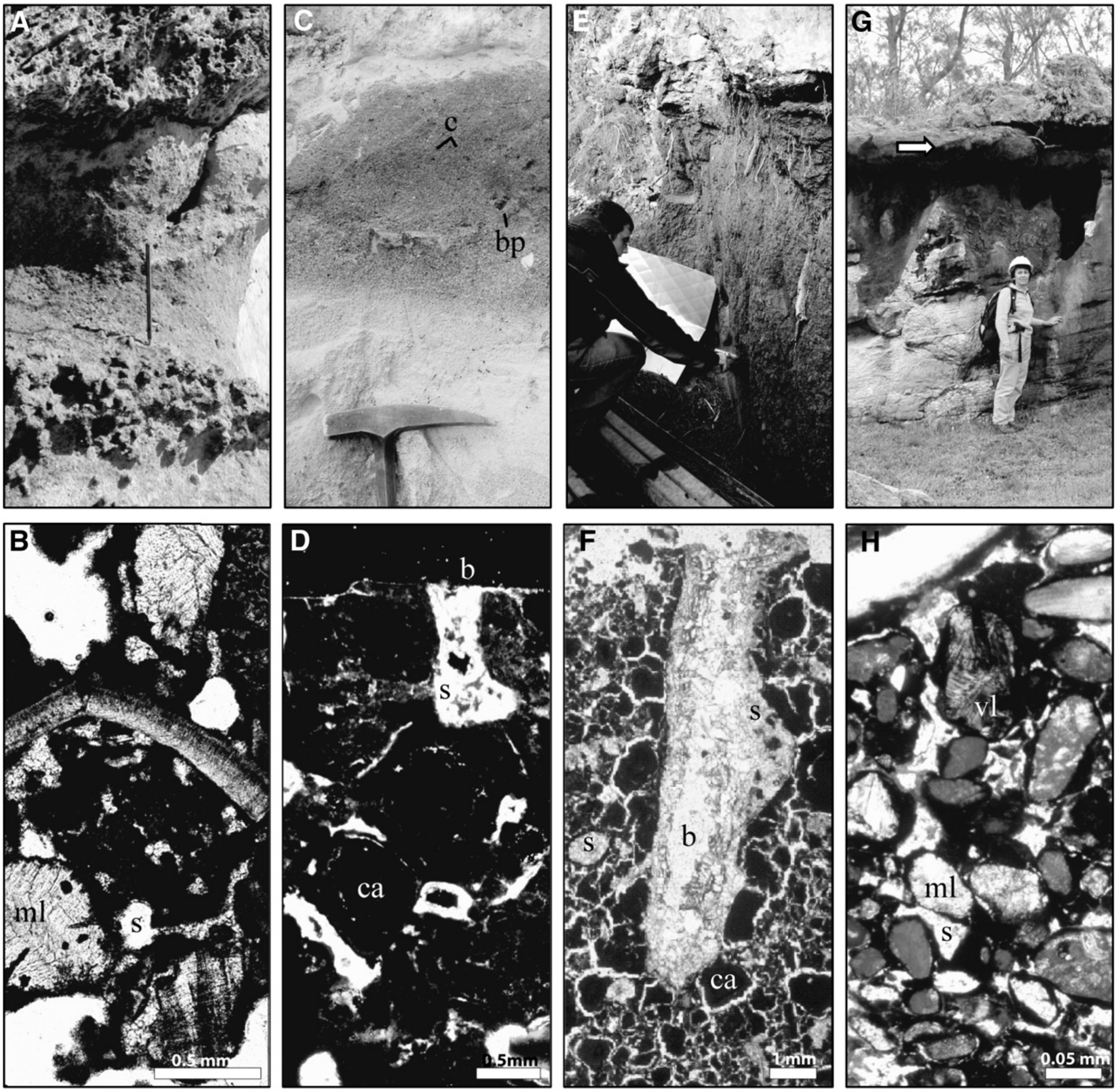


**Figure 3.** Some typical Bermuda profiles, macro and micromorphology. b: bioturbation, c: coal fragments, s: sparitic cement, bp: black pebble, ca: clayey aggregate, ml: marine clast, vl: volcanic lithoclast. (A) Weakly weathered profile interpreted as a protosol characterized by its apparent absence of sedimentary or pedological structure, GB-Grape Bay (Qs/Qr). (B) Thin section of the GB protosol, marine clasts are quasi unweathered, only early pedogenic micrite is visible, plane polarized light. (C) A "terra-rossa" paleosol, HRQ-Harvey Road Quarry (Qbm/Qtu). Pedological units contain numerous primary carbonate clasts, black pebbles and coal fragments, which suggest the reworking of the upper pedological unit subsequent to a forest fire. Lower unit is in place. (D) Thin section from the lower part of the HRQ profile, cross polarized light. There is no more primary carbonate after weathering. (E) Castle Harbour geosol, Bierman's Quarry (BQ) profile (Qw/Qtl). (F) Details on the BQ microstructure, plane polarized light. Decarbonatation is complete. Plane-polarized light. (G) ES site (Qtu/Qw). White arrow point the reworked horizon. (H) Thin section of the reworked horizon, site ES. All thin sections demonstrate the soil porosity filling by secondary sparitic calcite. Plane-polarized light.

interstratified chlorite/vermiculite or as HICs. Because diagrams remain unchanged after applying the tests proposed by Tamura (1957) and Rich (1968) for distinguishing interlayered aluminium hydroxydes from expandable clays, the 12–14 Å clay minerals found in Bermuda paleosols are inferred to be random interlayered chlorite/vermiculite and not HICs (Fig. 6). This assemblage is homogeneous from site to site, despite the age of the profile. Moreover, the clay mineral assemblage does not evolve along a same profile, which is surprising in pedological evolution.

The paleosols may also contain quartz, as at Horse Shoe Bay (HSB) where concentration of this mineral reaches 30%. However, at all other sites, quartz is present in minor proportion (5%) or even absent. Significant amounts of calcium aluminium phosphate from the crandallite group ($CaAl_3(PO_4)_2(OH)_5.H_2O$) have been found in many paleosols of diverse ages. Crandallite is particularly important in profiles overlying the oldest eolianites exposed on the islands (Walsingham Formation), where it can reach an unusually high content of up to 60%). Gibbsite ($Al(OH)_3$) and its polymorph, nordstrandite, occur in most profiles in low concentration (5%). These minerals typically represent the weathering products found in mature soils, but they are present in some of the youngest Bermuda paleosols. Goethite, FeO(OH), regularly appears in most profiles from all time intervals, its proportion ranging between 5% and 10%. The presence of halite (NaCl) at the HSB site is related to its facing-ocean situation.

Bulk mineralogy analyses broadly confirm the classification of paleosols based on morphology, but reveal many particularities that cannot be ignored. Minerals typical of intense weathering (gibbsite,

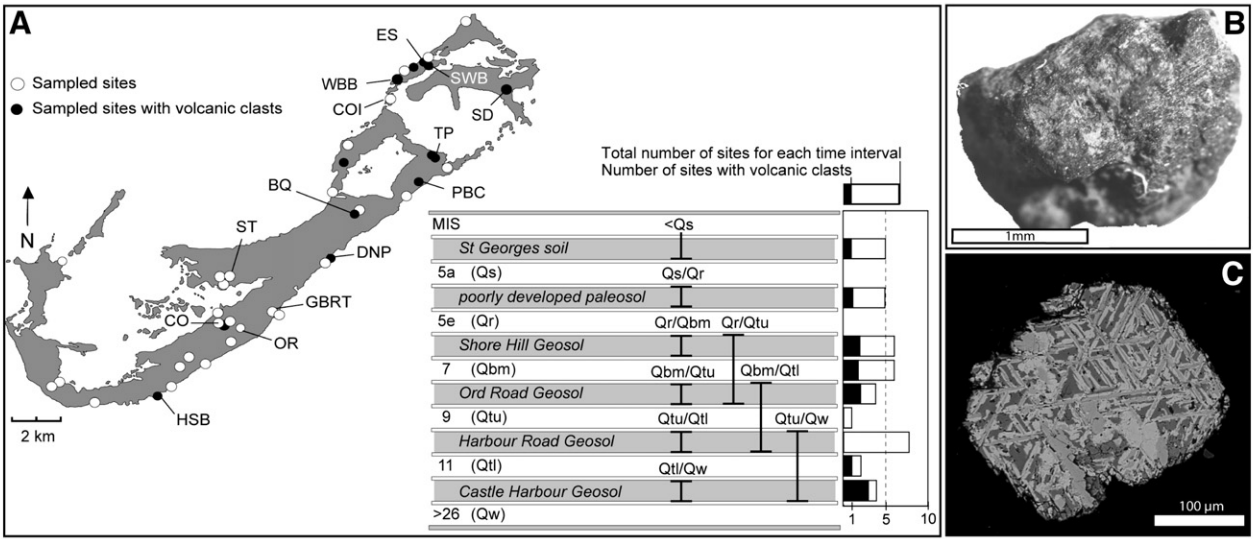


**Figure 4.** (A) Occurrence of the volcanic material in Bermuda paleosols; note this material was found all over the island and in all the preserved stratigraphic intervals. (B) largest basaltic lithoclast found in a Bermuda paleosol. Swing Bridge site (SWB). (C) exsolution lamellae of titanomagnetite in magnetite and ulvöspinel, site TP (Qtu/Qw).

nordstrandite, kaolinite) occur in most Bermudan paleosols, even in the youngest, which is paradoxical in view of the moderate degree of weathering inferred from their morphology. These minerals are distinctive of advanced laterization and bauxitisation, but coexist in Bermuda paleosols with minerals that are sensitive to hydrolysis, such as carbonates, chlorite, and chlorite/vermiculite. Thus, the mineralogy of Bermuda paleosols is not a strict function of the profile age.

## Discussion

### Origin and transport mechanism of the dark lithoclasts

Microprobe analyses indicate that the dark rock fragments found in Bermudan paleosols include minerals of volcanic origin such as perovskite, titanite, garnet or pyroxenes, that could possibly derive from the underlying volcanic seamount (Fig. 7A). The link between the lithoclasts and the Bermuda volcanics is further reinforced by: (1) the large size of the lithoclasts which imply a proximal origin; (2) the occurrence of peculiar minerals, such as perovskite, in all the assemblages (Fig. 7A); (3) the striking similarity in the chemical composition of the unusual Al-diopside identified in some of these fragments and that of phenocrysts of the same mineral analyzed by Peckenham (1981) on core samples (Fig. 7B), and (4) the presence, in the paleosols, of some grains with typical exsolution lamellae of titanomagnetite in magnetite and ulvöspinel (Fig. 4C), a pattern previously recognized in the lava from the Bermuda volcano (Aumento and Gunn, 1974). We demonstrate here the widespread occurrence of volcanic material in paleosols all over the Bermuda archipelago and throughout the stratigraphic record (Fig. 4A). This statement distinguishes our study from previous ones, which minimize the occurrence of dark grains within the paleosols (Ruhe et al., 1961), restrict it to only two profiles (Blackburn and Taylor, 1969, 1970), or limit it to the immediate vicinity of the WBB site (Herwitz and Muhs, 1995; Herwitz et al., 1996).

The transport mechanism of the volcanic material discovered in the paleosols is, however, not straightforward because the seamount is presently flooded, and partly covered by carbonate sediments. Nonetheless, this carbonate cap is locally very thin (~2 m near the ES site, W. Sterrer, personal communication, 2005). Moreover, in his description of the 1912 core, Pirsson (1914a) noted a 30 m-thick layer of water-worn, dark, igneous debris sandwiched between the basalt and the overlying carbonates, at a depth of 160 m. This layer can be related to an Eocene-Oligocene erosion phase of the volcano (Tucholke and Vogt, 1979) or to a karstic river deposit, formed near the interface of the carbonate rocks and the volcanic substratum (J. Mylroie, personal communication, 2006). The horizon of igneous debris represents a stock of previously fragmented volcanic material potentially available to be reworked. The macromorphological description of the igneous deposits is consistent with that of the WBB beach sands. Our recovery of rounded volcanic grains on the coast of Coney Island (COI) after a few days of heavy weather confirms the presence of this stock. The occurrence of such grains in COI modern beach sands demonstrates either the existence of submerged, but uncapped, volcanic outcrops subject to active marine erosion, or the incomplete burial of the anomalous deposits identified by Pirsson (1914a).

Thus, the incorporation of volcanic grains in Bermudan paleosols probably resulted from the remobilization of volcanic material of local origin by wind-driven processes at the very end of interglacials and during glacial periods. This material was subaerially exposed consecutively to sea-level falls and to the reworking of interglacial marine sediments in eolianites (Vacher and Rowe, 1997) (Fig. 8). The Bermuda platform spent most of the Quaternary period in a low sea-level configuration, which favored the local volcanic input into the whole IR flux recorded in Bermuda paleosols. The exposed volcanic material was then transported inland by traction-saltation and/or coastal wind and waves after heavy weather. The material affected by this remobilization probably came from the superficial weathered belt of the volcanic seamount, composed of albitized and chloritized basalt. The heaviest volcanic minerals were probably trapped in the proximal zone and in beach lags, as in WBB, and the lightest minerals, such as albite, quartz or chlorite, probably were preferentially blown inland.

### Impact of the volcanic material on the paleosol mineralogy and geochemistry

Two groups of minerals compose the mineralogical assemblage of Bermuda paleosols. The first group includes carbonates and some clay minerals, especially chlorite and chlorite/vermiculite, and it is characteristic of immature soils; the second group consists of much kaolinite, nordstrandite, gibbsite and crandallite, which are characteristic of more intensely weathered and more mature soils.

The massive presence of carbonates in bulk-rock analyses is linked to the occurrence of marine bioclasts in the paleosol matrix as occurs at site GBRT, and to the secondary precipitation of sparite in the

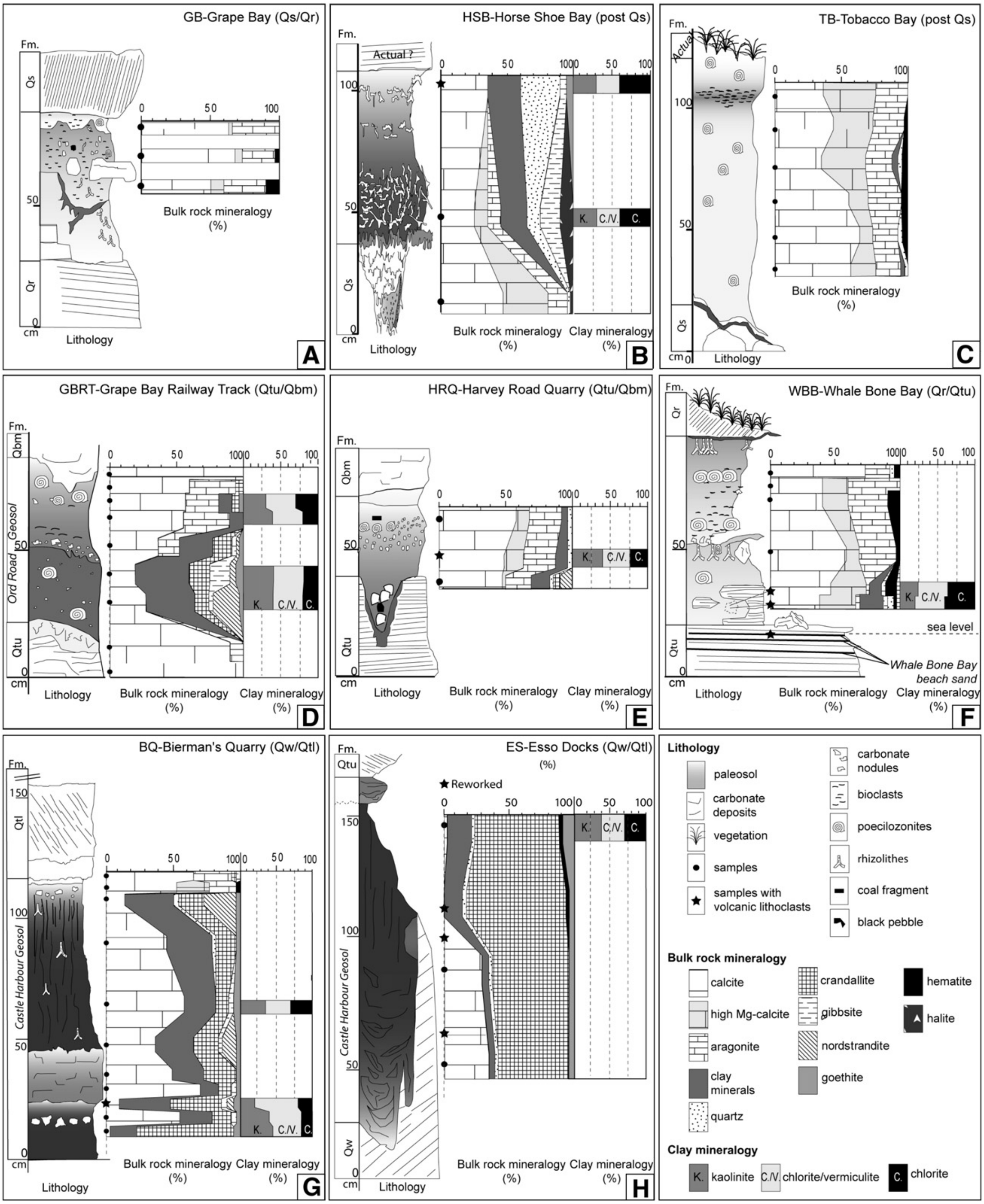


**Figure 5.** Lithology and mineralogy of typical Bermudan paleosols. (A, B and C) weakly developed paleosols or protosols. (D, E and F) common Bermuda paleosols, known as "terra rossa." (G and H) highly developed profiles from the Castle Harbour geosol.

paleosol pore opening after pedogenesis (Fig 3B, D and F). These phenomena explain the coexistence in Bermuda paleosols of a significant carbonate content and of minerals that require an important decarbonatation to be formed, such as gibbsite at site HSB or site GBRT (Fig. 5).

Chlorite and chlorite/vermiculite are classically attributed to the weathering of volcanic materials. Because Aumento and Gunn (1974) observed that the buried lavas underwent an early phase of marine alteration characterized by the albitization and the chloritization of the seamount, we consider the weathered Bermuda volcano as the source of the chlorite found in the paleosols. The widespread occurrence of the volcanic clay minerals in profiles located all over the island and spanning the entire stratigraphic record emphasizes the persistence of the input of volcanic material as indicated by

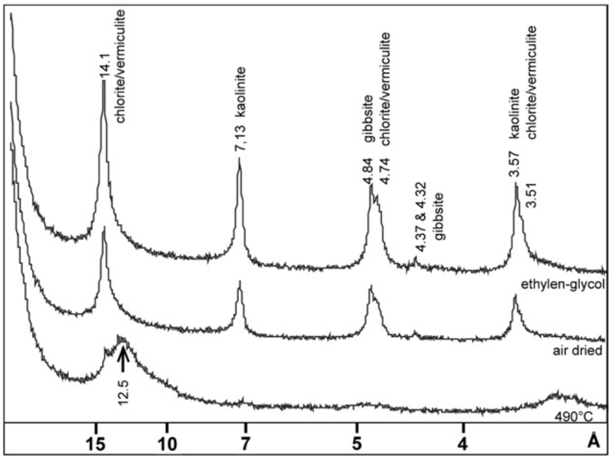


**Figure 6.** X-ray diffraction patterns on the oriented < 2 μm fraction after the application of Rich (1968) and Tamura (1957) tests. Sample no. 2 from ST site. Because diagrams remain unchanged after applying the tests for removing interlayered aluminium hydroxydes from swelling clays, the 12–14 Å minerals of Bermuda paleosols are inferred to be random interlayered chlorite/vermiculite and not HICs.

detritical grains of volcanic origin. The minerals characteristic of mature profiles present in Bermudan paleosols probably result from the pedological weathering of the albitized basalt. The alteration of volcanic albite classically produces kaolinite, if hydrolysis is partial, or gibbsite or nordstrandite, if it is complete.

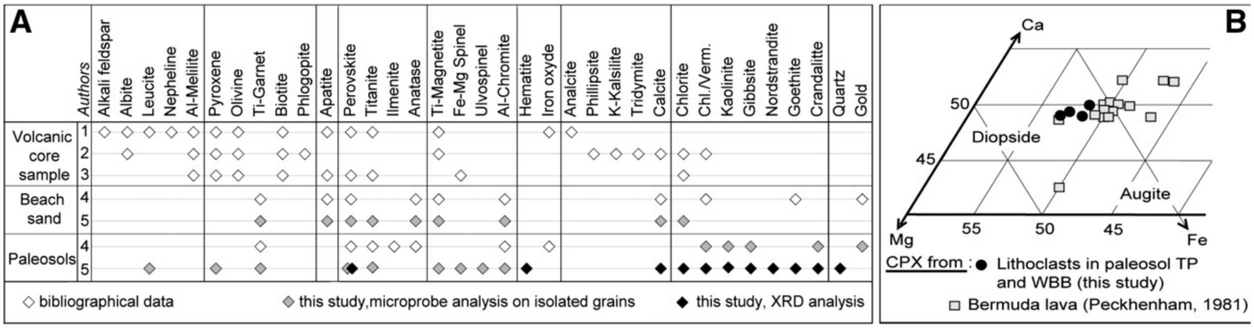
The quartz content in Bermuda paleosols often has been discussed. Our study shows that the quartz content is very variable, being more a function of site than of age. Furthermore, the quartz sources can be multiple. Former authors attribute it to avian transport from North America (Rueger, 2004), or to atmospheric dust input (Herwitz and Muhs, 1995; Herwitz et al., 1995). However, the large size of quartz grains implies that aerosolic dust only represent a negligible part of the quartz input. Thus, the hypothesized avian origin is reliable, as already discussed by Foreman (1951). Neither of these hypotheses can be rejected, but we can suggest another possible source. Our observations show that quartz grains typically are associated with volcanic lithoclasts in the paleosol matrix. There is no reason to consider birds selective in the mineralogical assemblage they carry. Peckenham (1981) reports the formation of quartz in the volcanic seamount, through the alteration of titanite. Titanite may form quartz and perovskite under an increasing $CO_2$ fugacity. The complexity of the Bermuda volcanism probably is underestimated and the existence of still unknown, more acidic intrusions that could possibly contain quartz has already be envisaged (Foreman, 1951, Vogt and Jung, 2007).

The high phosphate content in Bermuda paleosols was classically attributed to guano deposits (Ruhe et al., 1961). If the inputs of both quartz and phosphate in soils were related to avian activity, both minerals should be associated in paleosols, which is not the case (Fig. 5). Volcanic material is a likely additional source of phosphate because crandallite is known to result from intense weathering of apatite (Nriagu and Moore, 1984), and apatite is one of the main accessory mineral of the Bermuda lava (Pirsson, 1914b, Peckenham, 1981).

In conclusion, we propose that the major fraction of the parent material of most Bermudan paleosols originates from the altered lavas forming the volcanic substrate of the archipelago. The paleosol source rock comes from a complex volcanic seamount that underwent numerous phases of lamprophyre injection and alteration. Aumento and Gunn (1974) report more than 1000 volcanic units in strata of the 800 meters. Thus, the exact source rock of the paleosols is not determinable and probably evolved with time and according to the local igneous composition of the Bermuda seamount. This variation of the source rock probably is a key for understanding variations in paleosol mineralogy. Local variations may thus be highly influenced by the nature of the parent material. The presence of highly weathered material in recent paleosols probably is related to important reworking processes that are still active at COI beach. This suggestion clearly differs from early hypotheses linking the non-carbonate minerals of these paleosols to airborne dust. These hypotheses do not account for the occurrence of chlorite and chlorite/vermiculite, the addition of phosphatic material, and the relatively large quartz grains in these layers.

### *The undetectable airborne dust components*

The North Atlantic Oscillation (N.A.O.) is responsible for the alternation in wind direction over Bermuda, and thus for fluctuations in the origin of airborne dust. During the summer, mineral dust, composed of illite (up to 60%), kaolinite and quartz with minor proportions of chlorite and feldspars (Glaccum and Prospero, 1980), is brought from the northern part of the Sahara desert (Prospero, 1996). During the winter period, mineral dust originating mainly from the mid-continent North America, and composed of quartz, dolomite, and feldspar, with illite, smectite, chlorite and interlayered clay minerals in the fine fraction (Pye et al., 1995), is transported to Bermuda with the prevailing the westerlies (Chen and Duce, 1983; Prospero, 1996). Today, the Saharan dust input is estimated to be ten times greater than the American one (Prospero, 1996), and global fluxes of atmospheric dust



A

| | *Authors* | Alkali feldspar | Albite | Leucite | Nepheline | Al-Melilite | Pyroxene | Olivine | Ti-Garnet | Biotite | Phlogopite | Apatite | Perovskite | Titanite | Ilmenite | Anatase | Ti-Magnetite | Fe-Mg Spinel | Ulvospinel | Al-Chromite | Hematite | Iron oxyde | Analcite | Phillipsite | K-Kalsilite | Tridymite | Calcite | Chlorite | Chl./Verm. | Kaolinite | Gibbsite | Nordstrandite | Goethite | Crandalitte | Quartz | Gold |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Volcanic core sample | 1 | ◇ | ◇ | ◇ | ◇ | ◇ | ◇ | ◇ | | ◇ | | ◇ | ◇ | ◇ | | | ◇ | | | | | ◇ | ◇ | | | | | | | | | | | | | |
| | 2 | | ◇ | | | ◇ | ◇ | ◇ | | ◇ | ◇ | | | | | | ◇ | | | | | | | ◇ | ◇ | ◇ | ◇ | ◇ | ◇ | | | | | | | |
| | 3 | | | | | ◇ | ◇ | ◇ | | ◇ | | ◇ | ◇ | ◇ | | | | ◇ | | | | | | | | | | ◇ | | | | | | | | |
| Beach sand | 4 | | | | | | | | ◇ | | | ◇ | ◇ | | | ◇ | ◇ | | | ◇ | | | | | | | ◇ | | ◇ | | | | ◇ | | | ◇ |
| | 5 | | | | | | | | ◈ | | | ◈ | ◈ | ◈ | | ◈ | ◈ | | | ◈ | | | | | | | ◈ | ◈ | | | | | | | | |
| Paleosols | 4 | | | | | | | | ◇ | | | | ◇ | ◇ | ◇ | ◇ | | | | ◇ | | ◇ | | | | | | | ◈ | ◈ | ◈ | | | ◈ | | ◈ |
| | 5 | | | ◈ | | | ◈ | | ◈ | | | | ◈ ◆ | ◈ | | | ◈ | ◈ | ◈ | ◈ | ◆ | | | | | | ◆ | ◆ | ◆ | ◆ | ◆ | ◆ | ◆ | ◆ | ◆ | |

◇ bibliographical data ◈ this study,microprobe analysis on isolated grains ◆ this study, XRD analysis

**Figure 7.** Comparison of the mineralogical assemblages from the volcanic substrate, the volcanic beach sands from site WBB and from paleosols. Chlo./verm.: chlorite/vermiculite. (1) Pirsson (1914b); (2) Aumento and Gunn (1974); (3) Peckenham (1981); (4) Blackburn and Taylor (1969); (5) this study. Most of the minerals found in the paleosols can be found in the seamount mineral assemblage. Site WBB beach sands present a peculiar composition, non-representative of the Bermuda seamount. Their composition also differs from the mineralogical assemblage determined on the isolated lithoclasts found in the paleosol matrix. Beach sand deposits involve a hydrodynamic transport that favors the concentration of high-density minerals such as perovskite, titanite or chromite. (B) Comparison of Al-diopside composition from isolated grains in the paleosols and from phenocrysts in core samples (Peckenham, 1981) plotted in the conventional Wollastonite–Enstatite–Forsterite classification scheme (Morimoto et al., 1988). The clustering of dots shows that the chemical compositions of the clinopyroxene are identical.

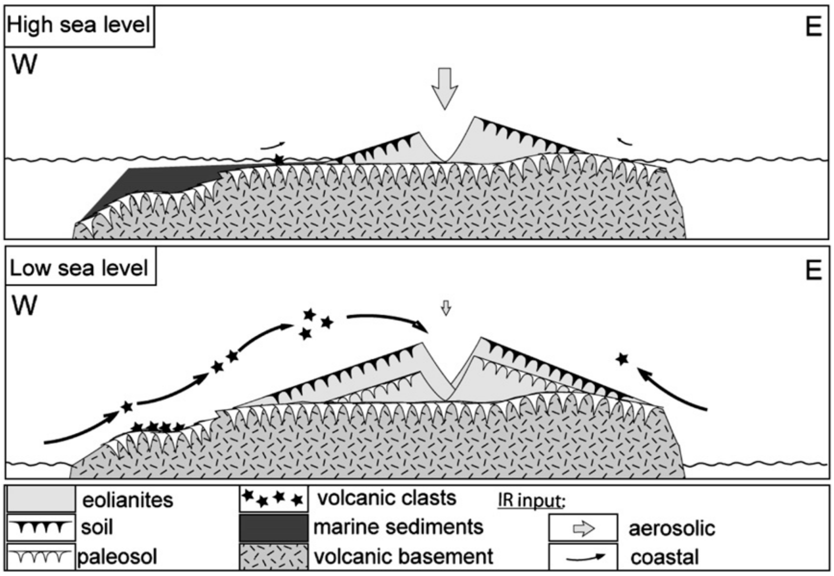


**Figure 8.** Schematic E-W section of the Bermuda archipelago in relation to Quaternary sea-level fluctuations. (A) during sea-level highstands, the seamount is drowned and covered by carbonate sediments. The input of insoluble residues in soils comes mostly from airborne dust (Prospero, 1996). (B) During sea-level lowstands, most of the insoluble residues come from the remobilization of newly emerged volcanic material.

were theoretically stronger during glacial periods (Kolla et al., 1979). Thus, illite-rich (up to 60%, Glaccum and Prospero, 1980) Saharan dust should heavily contribute to the composition of Bermudan paleosols. However, there is no correspondence between the mineralogy of the illite-rich airborne dust, and that of the chlorite-rich Bermudan paleosols (Figs. 5, 6 and 7). We propose that the input of atmospheric dust to Bermudan paleosols was diluted in a much greater local contribution of parent material from the altered volcanic substrate, to the point of being undetectable by XRD analysis. Indeed, Boardman et al. (1995) estimated 0.08 g/cm²/$10^3$ yr was the average dust flux over the Bahamas during the very last Quaternary climatic cycle. The mineralogical composition of the recorded dust is mainly composed of quartz, dolomite and feldspars. We consider this record to represent an integration of the North American and African airborne dust which is consistent with Muhs et al. (2007) studies on the eolian dust input in the western Atlantic. The 0.08 g/cm²/$10^3$ yr estimated flux of atmospheric dust is 4 to 5 times lower than the insoluble residue flux calculated for Bermudan paleosols, which approaches 0.36 g/cm²/$10^3$ yr (Table 3). Moreover, this value is probably underestimated because we hypothesized that all the insoluble residues are preserved in the paleosols, which is dubious considering the effect of weathering and erosion processes. Nonetheless, it implies that the dust-derived insoluble residues probably are a minor component of Bermuda paleosols. The main insoluble residue source for these paleosols, the local chloritized basalt, represents a far greater contribution than total airborne dust. The latter are therefore mainly undetectable with the XRD method.

**Table 3**
Total Insoluble Residues (IR) deposit over Bermuda recorded in paleosols. (*) the IR flux recorded in paleosols is calculated from 21 selected locations excluding colluvium, solution pipe and karstic deposits, as well as Qtu/Qw and Qtl/Qw profiles which involved unclear dating (see Fig. 2 for site location). Time interval is estimate on the basis of stratigraphic data from Vacher et al (1995). GBRT: Grape Bay Railway Track. Reworked material is not considered when identified. (**) Phosphate minerals are not considered because of their possible avian origin.

| | GBRT | Bermuda paleosol (mean values*) |
|---|---|---|
| thickness (cm) | 70 | 49 |
| total IR (%) (**) | 32 | 36 |
| accumulated IR (g/$cm^2$/$10^3$ yr) | 0.45 | 0.36 |

### *The apparent maturity of Bermuda paleosols*

The Bermuda paleosols are mainly issued from the alteration of the basalt, not from that of underlying carbonates. Instead, grains from the volcanic source rock are blown from a proximal source during glacial low-stands of sea level (Fig. 8). This phenomenon, regularly repeated, leads to the "rejuvenation" of the soil source rock. The allochtonous input balances and even exceeds pedological weathering, which results in the preservation of isolated lithoclasts and of volcanic minerals, mainly chlorite and chlorite/vermiculite, in the paleosol matrix. The source rock "rejuvenation" buffers the pedological weathering and limits its impact on development of soils structure. It minimizes development of a deep soil column with distinct horizons and explains why minerals characteristic of highly pedogenized profiles coexist with fresh weakly weathered minerals.

Our new interpretation of the parent material of Bermuda paleosols further contributes to resolve a long lasting paradox regarding their maturity. Actually, the Bermuda paleosols are thicker and more clayey than Bahamas paleosols (Foos and Bain, 1995; Boardman et al., 1995; Herwitz and Muhs, 1995). Because of their low $SiO_2/Al_2O_3$ ratio (Table 2) and the absence of mica/illite, they have been described as equally, or even more mature than their southern counterparts in the Bahamas and Barbados (Ruhe et al., 1961; Herwitz and Muhs, 1995), which contradicts known paleoclimatic patterns. This paradox is now explained by the difference in the parent material of these respective paleosols. Volcanic material from the Lesser Antilles mainly composes Barbados paleosols, which cannot be compared with the Bermuda paleosols where volcanic contributions differ (Muhs et al., 2007). However, Bahamian paleosols are mostly derived from the alteration of the illite-rich Saharan dust (Muhs et al., 1990; Boardman et al., 1995; Foos and Bain, 1995; Muhs et al., 2007), whereas Bermuda paleosols result from the alteration of chloritized and albitized alkaline volcanic material devoid of mica/illite, and they are characterized by a low initial $SiO_2/Al_2O_3$ ratio (this study). This parent material favored the formation of aluminum-rich paleosols with kaolinite, gibbsite, and crandallite generally thought to be characteristic of tropical weathering. Thus, the nature of source rocks allows us to minimize the importance of the weathering processes that affected Bermudan fossils soils. The preferential input of volcanic material during low sea level, during which carbonate production is insignificant (Fig. 8), drastically reduces the carbonate input inland, and thus favors the required decarbonatation.

## Conclusion

Our results demonstrate that the volcanic seamount of Bermuda is likely the major source of the non-carbonate minerals occurring in the paleosols exposed on the archipelago. The input of volcanic material onto the islands essentially occurs during sea-level lowstands, when volcanic rocks are exposed and subjected to erosion and transport by waves and wind. This local contribution is so important that long-distance atmospheric input of dust (e.g. from the Sahara) is diluted and probably difficult to detect by the XRD method. This new hypothesis strongly differs from previous studies that suggested a Saharan origin of the parent material for these pedogenic units (Bricker and Mackenzie, 1970; Herwitz and Muhs, 1995; Herwitz et al., 1996). The new hypothesis also resolves the paradox pertaining to regional differences in maturity. The current study of Bermuda paleosols, also provides an alternative explanation for quartz content and the surprising local presence of chromite, through demonstration of a link to Bermuda volcanic intrusions. The discrimination of long distance atmospheric transport versus local transport of volcanic components in Bermuda paleosols may require the application of advanced geochemical methods such as Rare Earth Elements (REE) analyses, which was successfully applied by Muhs et al. (2007) on the Caribbean paleosols of Quaternary age.

Moreover, as the island is mainly composed of eolianites, slopes are widespread and colluvium deposits affect numerous profiles (Hearty, 2002). The reactivation of old pedological units is probably underevaluated in Bermuda and, considering the mineralogy of the profile developed on the basaltic substrate reworking of this substrate probably significantly impacted Quaternary paleosols.

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