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Cover photo: *Diploria strigosa*, the common brain coral, preserved in growth position at the Cockburn Town fossil coral reef site (Sangamon age) on San Salvador Island. Photo by Al Curran.

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BAHAMIAN PALEOSOLS: IMPLICATIONS FOR STRATIGRAPHIC CORRELATION

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ABSTRACT

Megascopic and mineralogic examination of Bahamian paleosols from San Salvador and Andros Island was performed in order to evaluate the potential of paleosols as stratigraphic aids.

Based on megascopic criteria, four fundamental types of paleosols are recognized in the Bahamas, including laminated crust, homogeneous crust, breccia-conglomerate, and homogeneous matrix types. Analogs of all paleosol types are found forming today. Paleosol types probably differ as a result of overlying soil and local topographic differences rather than from different climates at formation. Therefore, megascopic distinction of paleosols is not of stratigraphic use.

Paleosols can be classified by insoluble residue (IR) mineralogy using the presence or absence of two minerals: illite and boehmite. Paleosols with both illite and boehmite rarely are found in the Bahamas. Boehmite-rich paleosols result from a more humid environment with extensive leaching; while illite-rich paleosols result from less extensive alteration conditions and more closely resemble the mineralogy of IR brought to the Bahamas as dust. IR mineralogy of paleosols appears to be a function of climatic variation through the late Quaternary, although local environments undoubtably affect diagenetic conditions. Use of IR mineralogy as a stratigraphic aid is hindered by paleosol erosion and redeposition which produces a paleosol not representative of its climate of formation. Based on stratigraphic relationships and IR mineralogy, five different paleosols have been recognized on San Salvador.

INTRODUCTION

Paleosols are recognized as subaerial exposure surfaces and have been widely described in association with Holocene and Pleistocene limestones (Ruhe and others, 1961; Multer and Hoffmeister, 1968; James, 1972; Read, 1974; Harrison, 1977; Watts, 1980; Coniglio and Harrison, 1983) as well as limestones of the Phanerozoic (Walls and others, 1975; Harrison and Steinen, 1978; Riding and Wright, 1981; Prather, 1985). In addition to petrographic studies, Gile and others. (1966) and Robbin and Stipp (1979) documented accumulation rates of caliche profiles. The origin and diagenesis of insoluble residue in bauxite have been studied in Jamaica (Hose, 1963; Sinclair, 1967). Caliche crusts, calcareous laminated crusts, calcrete, and duricrusts also indicate exposure surfaces of carbonate accumulations which are directly or indirectly associated with soil horizons. In this paper, the term paleosol will refer to all of these products that are formed in association with an exposure surface.

Early recognition of laminated caliche crusts in the Bahamas (Newell and Rigby, 1957; Kornicker, 1958) has been amplified by Brown (1984) who described fully developed megascopic features of caliche profiles of San Salvador, Bahamas. Hale and Ettensohn (1984) described microscopic features of paleosols of San Salvador and attributed their origin to pedogenesis. Modern Bahamian soils have been classified based on color and organic content (Little and others, 1977). The mineralogy of insoluble residue of modern soils of Eleuthera and New Providence Islands includes kaolinite, chlorite, quartz, gibbsite, boehmite, iron oxides and amorphous aluminum oxides, (Ahmad and Jones, 1969).

PURPOSE OF STUDY

The stratigraphy of the Bahamas has been studied in detail only for New Providence Island and San Salvador islands (Garrett and Gould, 1984; Carew and Mylroie, 1985). The difficulty in studying Bahamian stratigraphy is due to the lack of outcrops, the lithologic similarity of deposits, and the difficulty in radiometric dating of the rocks. Also, because many Quaternary highstands of sea level have been of short duration (a few 1,000's of years) and have all been within a few meters of present sea level (Boardman and others, 1984; 1986), lateral accretion of facies as opposed to vertical "layer-cake" accretion has confused the stratigraphic relationships.

Carew and Mylroie (1985) proposed a stratigraphic section for San Salvador which uses both lithologic criteria and paleosols as aids in differentiating three Quaternary limestone formations (Owl's Hole Formation, Grotto Beach Formation, and Rice Bay Formation). However, there is an apparent discrepancy between the number of paleosols used by Carew and Mylroie (1985) and the number of exposure surfaces that should be present in their stratigraphic section.

A reasonable assumption is that every sea-level highstand is associated with the development of an additional lithologic package which is separated from other packages by a subaerial exposure surface. There have been at least 10 highstands of sea level (Shackleton and Opdyke, 1973; Boardman and others. 1984) since the deposition of sediments comprising the Owl's Hole Formation (>700,000 years ago; Carew and Mylroie, 1985). Since there have been only three lithologic packages, designated as formations, identified on San Salvador, this either means that each highstand does not always produce a lithologic package, that erosion has significantly erased the rock record, that exposure surfaces are not effectively recognised or some combination of these.

Can paleosols be differentiated based on their own characteristics? Insoluble residue brought to the Bahamas as dust during the late Quaternary has varied in mineralogy and quantity (Eaton, 1986). Thus paleosols accumulated at different times may be differentiated from one another and be of use as stratigraphic aids.

The purpose of this study is to determine to what extent paleosols can be distinguished from each other and thus used as independent aids to stratigraphy on San Salvador and between Bahamian islands. Megascopic criteria and mineralogy of insoluble residue are two parameters examined.

METHODS

A total of 124 paleosols and 9 modern soil samples were studied from sites on San Salvador and Andros Island, Bahamas (Figs. 1 and 2). Additional samples were recovered from Little Bahama Bank, Bahamas. Multiple samples were taken, when appropriate, to examine vertical and lateral continuity of paleosols. Polished sections of 100 paleosols were examined.

Samples were dissolved in acetic acid (15%) to extract insoluble residue (IR). Mineralogy of IR was determined by x-ray diffraction after removal of organics with 30% hydrogen peroxide (Tessier and others, 1979). All samples were X-rayed after being treated with glycol, heated to 400°C, and to 550°C. Clay mineral identification was determined following the guidelines of Brown and Brindley (1980) and Starkey and others, (1984). Relative proportions of IR were determined by comparing areas of the primary peaks (e.g. Brindley, 1961; Biscaye, 1965).

RESULTS AND DISCUSSION

Megascopic Description

Classification. Bahamian paleosols are typically red to brown, laminated to non-laminated, micritic deposits. Paleosols vary from crusts less than one to greater than six cm thick (like those of Multer and Hoffmeister, 1968) to indurated or non-indurated earthy deposits as much as a meter thick. Four fundamental types are recognized: laminated crust, homogeneous crust, breccia-conglomerate, and homogeneous-matrix (Fig. 3a-d).

Laminated crusts are the most abundant paleosol in the Bahamas. Laminae, colored red, tan, and brown, vary from 0.1 to 1 mm thick, are often regularly spaced, and pinch and swell in association with micro-topographic highs and lows. Lamination may be simple or complex (Fig. 4a). Laminated crusts are usually not associated with breccia-conglomerate and homogeneous-matrix paleosols.

Homogeneous crusts (microcrystalline rind of Multer and Hoffmeister, 1968) vary from a few mm to one cm thick. They may be found individually or associated with other

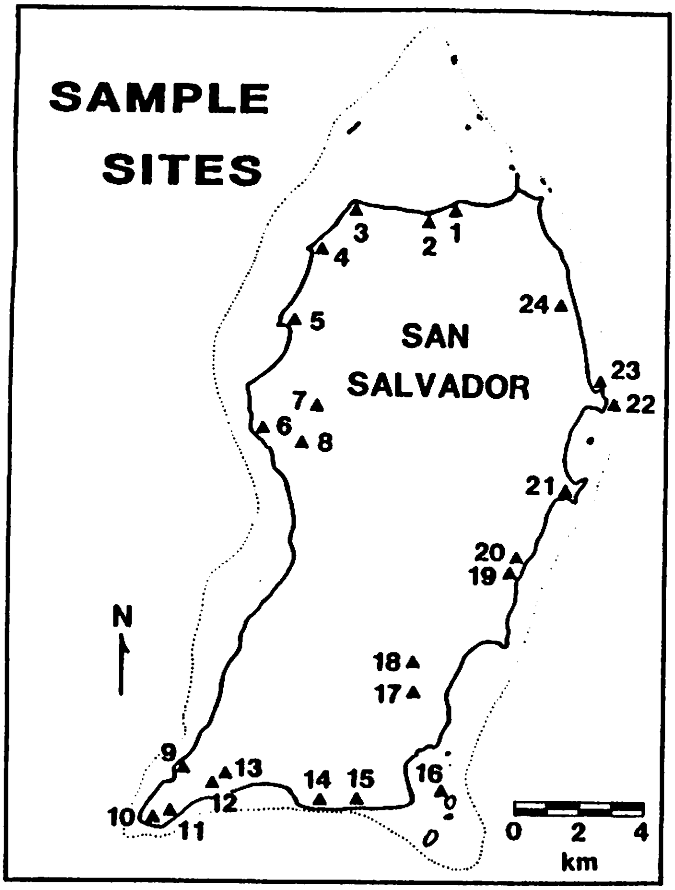


Fig. 1. Sample sites, San Salvador.

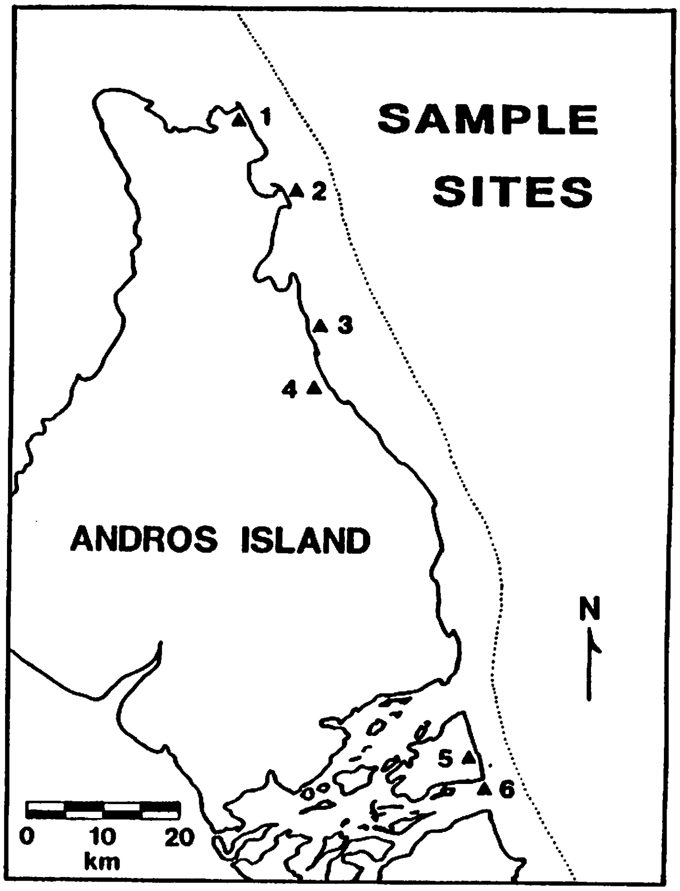


Fig. 2. Sample sites, Andros Island.

paleosols or soils (Fig. 4b).

Breccia-conglomerate paleosols (Fig. 3c) and soils (Fig. 4b) have large clasts (>2mm; Gile and others, 1966) that vary from subangular to pisolitic in nature; whereas homogeneous-matrix paleosols (Fig. 3d) do not have these large clasts. These paleosols are the thickest, varying from several centimeters to a meter thick.

Stratigraphic Implications. Megascopic distinction between paleosols is not a useful stratigraphic aid in the Bahamas. All four types of paleosols are recognized capping the presumed Grotto Beach Formation at localities on San Salvador (Sue Point, site 5; Grotto Beach, site 9; French Bay cliffs, site 11; and Crab Cay, sites 22 and 23). The Owl's Hole Formation paleosol at the type locality (site 10) is distinguished from its presumed equivelant at Watling's Quarry (site 12) by its brown color (as opposed to deep red at Watling's Quarry), by its rhizoliths, and by its lack of clasts. All four of these paleosol types have modern analogs in the Bahamian region (Robbin and Stipp, 1979; this study). These observations confirm that paleosol type is a function of the overlying soil (Multer and Hoffmeister, 1968) as well as moisture balance (Harrison, 1977), rather than any unique reflection of climatic variations throughout the Quaternary.

Insoluble Residue Mineralogy

Mineralogic Classification of Soils and Paleosols. Quartz and kaolinite are nearly always the most abundant minerals in samples collected. Other common minerals include boehmite, illite, chlorite, interstratified chlorite-vermiculite, and montmorillonite. Minor minerals in most samples include gibbsite, hematite, K-feldspar, plagioclase, and goethite.

Based on our studies, soils and paleosols can be classified by the relative abundance of two minerals: illite and boehmite. The majority of samples contain either illite or boehmite; while 13% of the samples studied did not contain either of these minerals (Fig. 5). Very few samples contain both minerals, and those that do may represent two or more different soils. Interstratified chlorite-

Fig. 3a. Laminated crusts.

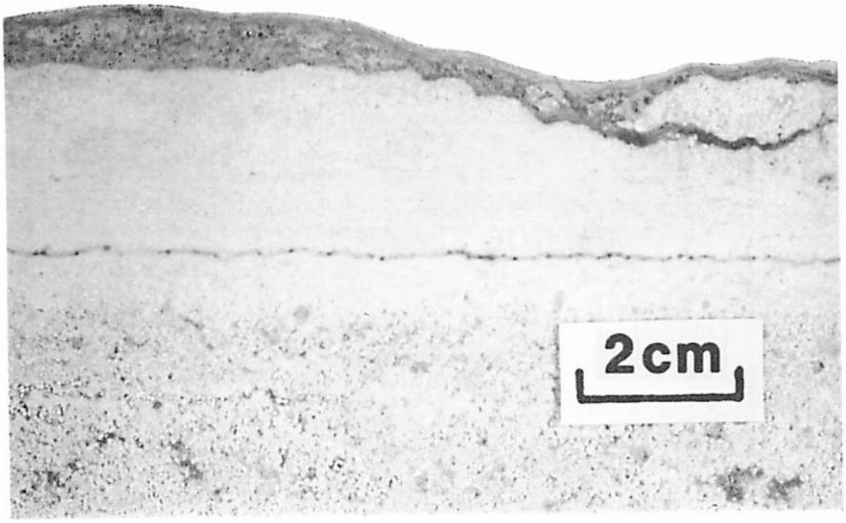


Fig. 3b. Homogeneous crust.

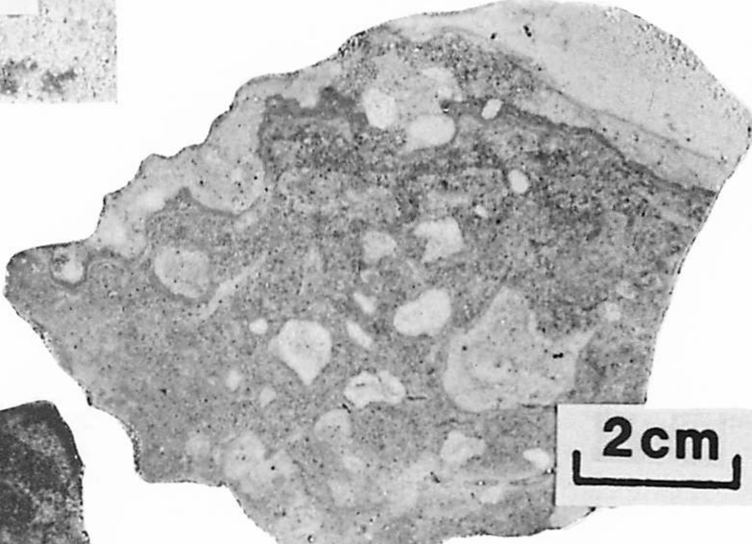


Fig. 3c. Breccia-conglomerate.

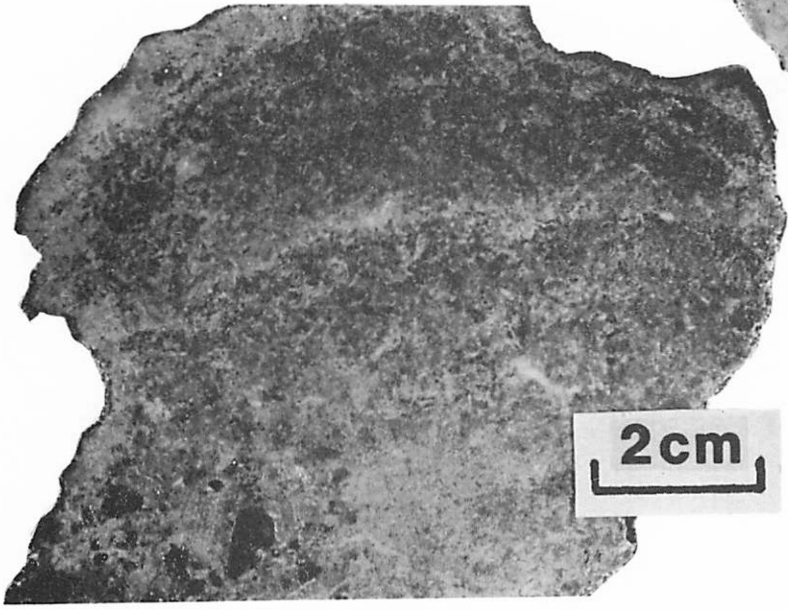


Fig. 3d. Homogeneous-matrix.

Fig. 4a. Polished slab illustrating periods of accretion and dissolution of a laminated crust (the "Thumb", site 19, San Salvador).

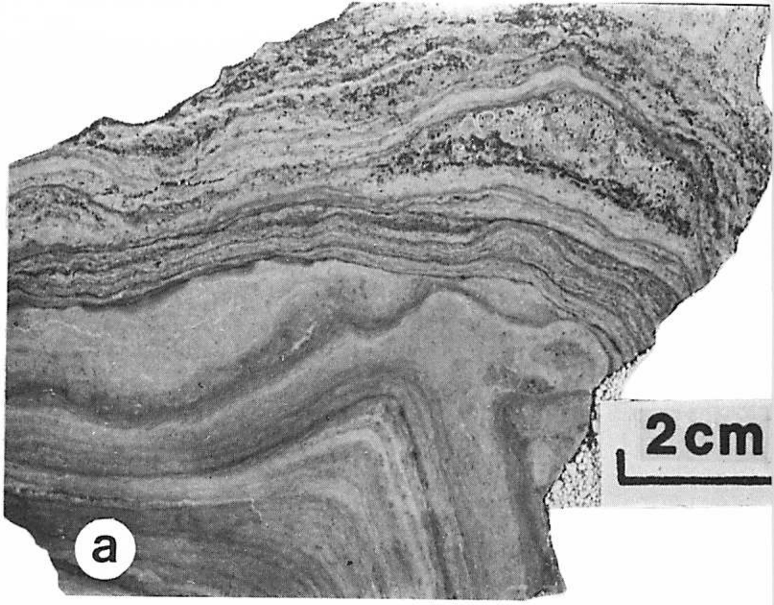
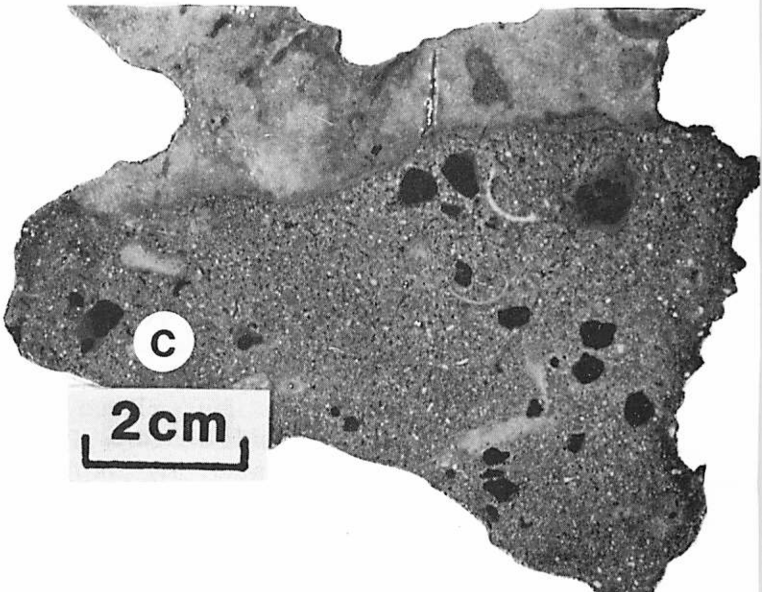


Fig. 4b. Homogeneous crust overlain by a breccia-conglomerate soil (cable cut north of Cockburn Town, San Salvador).

Fig. 4c. Multi-generation paleosol (Singer Bar Point, San Salvador).



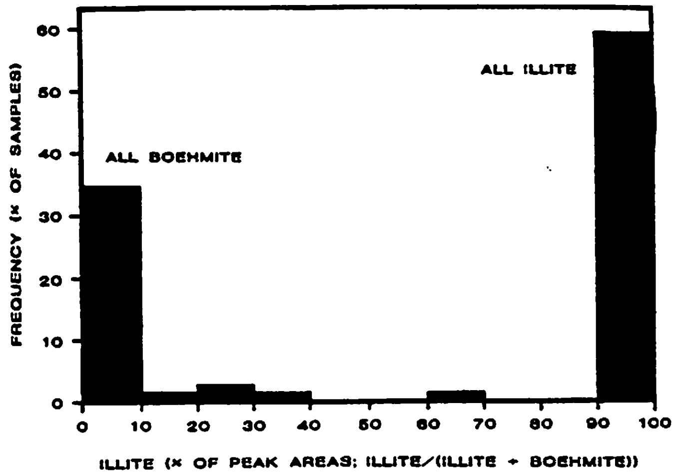


Fig. 5. Frequency diagram showing the distribution of illite and boehmite. Numbers are the ratio of the peak area of illite to the combined peak area of illite plus boehmite. Samples with neither mineral are not included. Most samples contain either illite or boehmite. The few samples which contain both minerals probably represent mixing of two or more soils.

vermiculite is found only with soils that are boehmite-rich.

Singer Bar Point, San Salvador (Fig. 1, site 1), also known as Dump Point, is an excellent example of a multi-generation paleosol (Fig. 4c). It contains dark red $CaCO_3$-free clasts composed of boehmite, gibbsite, and goethite within a red boehmite-rich paleosol. Minor amounts of magnetite are also identified within the clasts.

Localized occurrences of paleosols dominated by apatite have also been found in the Bahamas (i.e. Coconut Grove, Andros Island) and are believed to be indurated cave deposits and therefore not easily applicable to stratigraphic correlations within the Bahamas.

Geographic and Stratigraphic Distribution of Paleosols. On San Salvador, boehmite-rich paleosols are found on the northern end of the island (Fig. 6) with the exceptions of site 13 (near an inland pond) and site 19 (the "Thumb" locality). This geographic segregation of paleosol mineralogy on San Salvador is not apparent on Andros Island (Fig. 7).

Paleosols capping units from different localities on San Salvador but placed in the same formation (Carew and Mylroie, 1985) do not always have the same IR mineralogy. Watlings Quarry (site 12) and Owl's Hole (site 10), both designated as the Owl's Hole paleosol, have different mineralogies. Watling's Quarry is illite-bearing, and the Owl's Hole locality contains neither illite nor boehmite. The type section for the Grotto Beach Formation (site 9) has an illite-rich paleosol capping the Cockburn Town Member. Although no paleosol is found directly above the Cockburn Town type locality, samples a few 100 meters to the north are either boehmite-rich or contain neither illite nor boehmite. Other outcrops with overlying paleosols that are also assigned to the Cockburn Town Member include Sue Point (boehmite-rich paleosol) and Crab Cay (illite-rich paleosol).

Are these differences in IR mineralogy of presumed correlative paleosols due to (1) subenvironmental variations on San Salvador over time, (2) errors in the proposed stratigraphy of San Salvador, or (3) some other controlling factor?

The influence of subenvironments (i.e. ridge tops vs. valleys, vegetated vs. non-vegetated) undoubtably plays some role in IR mineralogy in the Bahamas, though probably a relatively minor one. If it is assumed that the paleosols at Owl's Hole (neither illite nor boehmite) and Watling's Quarry (illite-rich) are the same, the difference in mineralogy may exist because the soils formed in different subenvironments. The extensive vegetation that is evident from the rhizoliths of the Owl's Hole locality may have created a diagenetic environment that extensively leached illite, which is a mineral continuously brought to the Bahamas as dust (Eaton, 1986). Deep red clays and laminated crusts along the fringes of brackish Stout's Lake (San Salvador) contain significantly higher proportions of illite compared to all other samples collected. This may reflect a geochemical environment where illite weathering is minimal, perhaps due to the lack of organic activity and its relationship with the lake itself. However, considering the relatively low relief of the island and the relatively close proximity of sample sites, it is unlikely that subenvironmental variation could produce both illite-rich and boehmite-rich soils at the same time or could produce an illite-rich soil at the same time as a soil with neither illite nor boehmite (e.g. Watling's Quarry and Owl's Hole localities).

If different climatic periods are responsible for producing paleosols of different IR

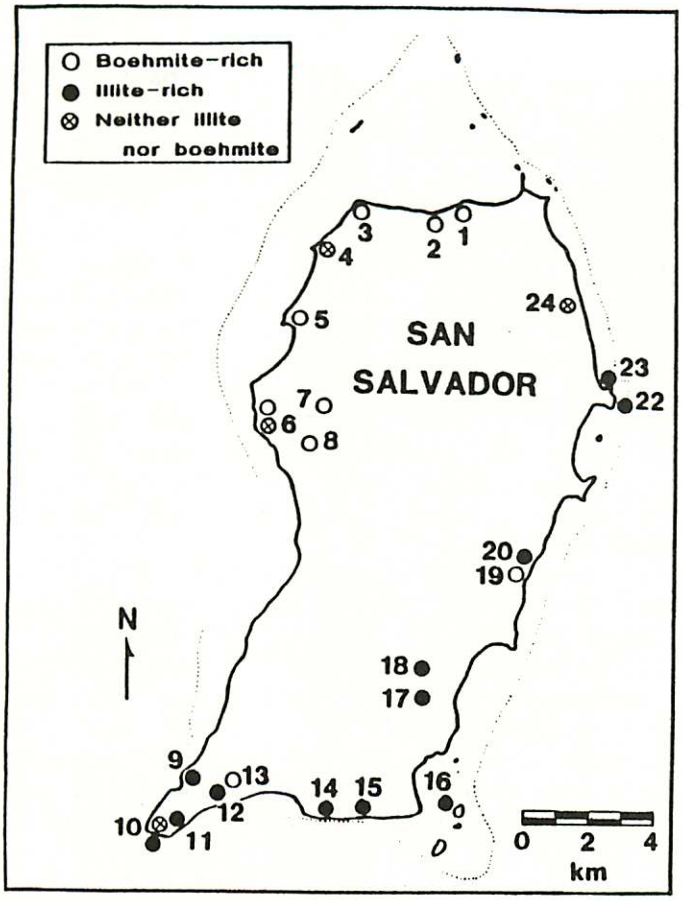


Fig. 6. Insoluble residue mineralogy distribution, San Salvador, Bahamas.

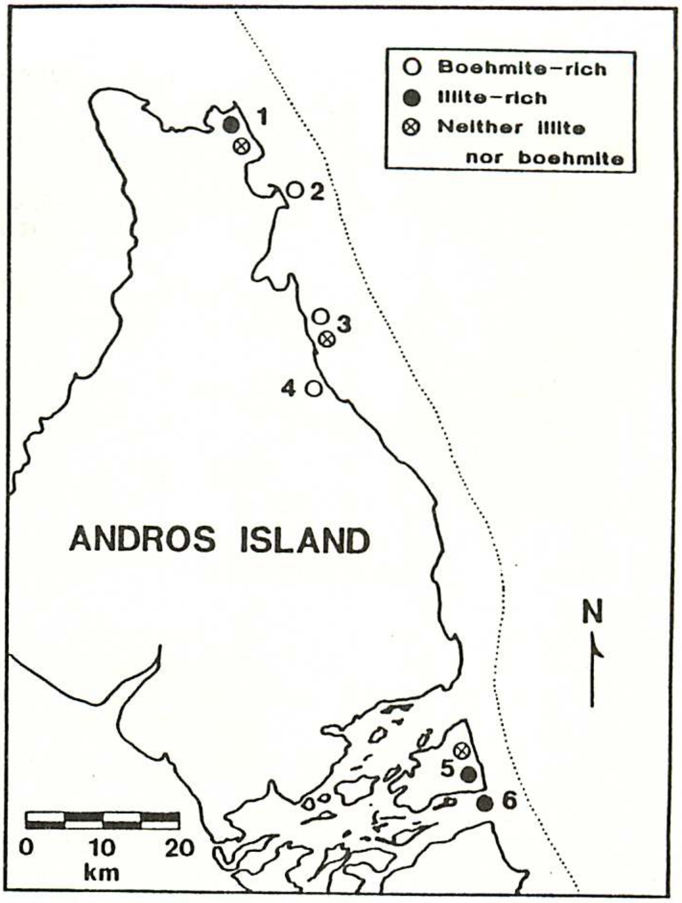


Fig. 7. Insoluble residue mineralogy distribution, Andros Island, Bahamas.

mineralogy, paleosols may in fact have relevance as stratigraphic markers. The extensive weathering indicative of boehmite formation is probably the result of a more humid climate than that required for illite preservation. Therefore, boehmite-rich paleosols of the northwestern region of San Salvador probably formed during a different time period than much of the rest of the island.

However, other evidence indicates that the distribution of IR is not only a function of duration of exposure and climate. The mixing of paleosols/soils of different ages clearly occurs. Modern soil samples taken on both Andros Island and San Salvador have the same mineralogy as their locally occurring paleosols (either illite- or boehmite-rich). This strongly suggests that modern soils are significantly influenced by the reworking of pre-existing paleosols as opposed to present climatic conditions. Thus paleosols differentiated by IR mineralogy may have limited use in stratigraphic correlation in the Bahamas.

The boehmite-rich red clasts within boehmite-rich matrices of the Singer Bar Point and Barker's Point paleosols exemplify this situation. The rounding of the boehmite-rich clasts suggests that weathering of the clasts may have contributed to the boehmite matrix. Whether the climate at the time of paleosol formation was humid enough to induce the formation of boehmite is not clear. It is reasonable to suggest that many of the paleosols in northwestern San Salvador (mostly boehmite-rich) have been influenced by the weathering of an earlier paleosol. However, since we find few mixed illite-boehmite paleosols indicative perhaps of a multi-generation soil (illite-rich and boehmite-rich), the clasts themselves and the encompassing paleosol may represent two separate, more humid periods of soil formation.

We suggest that there have been at least five different soil-forming periods. This contrasts with the two distiguished by Carew and Mylroie (1985). Paleosol localities representing these different periods include:

1) The Owl's Hole paleosol (site 10) which contains neither illite nor boehmite.

2) The lower prominant Watling's Quarry paleosol which is illite-rich (= Grotto Beach paleosol?).

3) The upper Watling's Quarry paleosol in which insufficient sample was available to determine mineralogy.

4) The Singer Bar Point clasts which are boehmite-rich and of which their source is not known.

5) The Singer Bar Point matrix with clasts which are boehmite-rich.

CONCLUSIONS

Paleosols can be distinguished by megascopic criteria and IR mineralogy. Megascopic distinction has not proven to be useful in stratigraphy; whereas insoluble residue (IR) mineralogy does add useful insights to stratigraphy.

Based on stratigraphy and IR mineralogy, five different paleosols are recognized on San Salvador. This mandates further evaluation of the proposed stratigraphy (Carew and Mylroie, 1985) which only indicates two paleosols. Using IR mineralogy as a stratigraphic aid is limited because of present and past paleosol recycling which produces paleosols not representative of the climate of formation. More detailed examination of IR mineralogy of paleosols may prove useful in future revisions of San Salvador stratigraphy.

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