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FORMATION AND DEVELOPMENT OF CALICHE PROFILES IN EOLIAN DEPOSITS: SAN SALVADOR, THE BAHAMAS

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Abstract

Caliche crusts, exemplified by well-indurated laminated micritic (calcrete), occur in many of the soil profiles and paleosols on San Salvador exhibiting a high preservation potential. Caliche consists of horizontal to subhorizontal accumulations of very fine-grained low-magnesium calcite. Profile development is initiated soon after dune stabilization in semi-arid and arid climates as the product of a hydrologic regime wherein evaporation rates exceed precipitation rates. Initially, the weathering profile is quite porous and permeable, allowing rapid influx of meteoric water. Vadose diagenesis leaches some eolianite grains, saturating meteoric waters with respect to low-magnesium calcite and concomitantly precipitating micrite as generally laminated particle coatings that form caliche ooids and pisoids (glaebules). Continued micrite precipitation cements carbonate particles and plugs pores, thus greatly decreasing the porosity and permeability within the weathering zone. Meteoric water ponds above the plugged horizon causing precipitation of laminated caliche crusts. The displacive nature of micrite crystallization separates particles that were once in grain-to-grain contact.

A fully developed caliche profile usually includes, from bottom to top,: 1) unaltered carbonate grainstone, 2)weathered massive chalky caliche, 3) nodular caliche containing more or less abundant caliche pisoids, 4) platy caliche, 5) laminated caliche crusts. This profile may be covered in places by a loose pisolitic soil that commonly contains cobble- to boulde-sized lithoclasts.

Incomplete caliche profiles result from the insufficient duration of weathering or erosion. Multiple caliche profiles occur where soil material has been transported downhill or where an existing profile is overridden by a migrating dune sequence. Laminated caliche is often disrupted so as to form breccia and non-peritidal tepee structures. Other features associated with subaerial exposure and soil profiles include whole shells of the terrestrial gastropod Cerion cocoons and rhizoliths.

Introduction

Subaerial exposure of a carbonate rock unit produces two distinct types of weathering profiles, which are related to different climatic conditions and hydrologic regimes. There are karst surfaces and caliche profiles. Karst is a product of meteoric flushing where the removal of carbonate occurs within the rock. Solutional activity and related karst features on San Salvador have been described by Mylroie (1982). Formation of caliche, on the other hand, results from the net migration of carbonate within the soil profile with very little material being lost by flushing. Calcium carbonate is removed from the uppermost section of the profile and deposited as caliche slightly lower in the profile. Caliche is developed in all carbonate facies exposed on San Salvador, including reef, shallow subtidal, beach, and eolian facies. However, caliche is best exposed in association with eolian dunes, where the caliche tends to form a protective crust that follows surface topography or occurs as a paleosol crust within the eolian sequence. This paper treats the general nature, formation, and development of caliche profiles and relates this information to the caliche phenomenon observed on San Salvador.

Precipitation of Micrite

San Salvador caliche (calcrete) profiles with distinct laminated crusts and extensive lateral development have been described by Adams (1980). Those of other Bahamian islands have been described by Kornicker (1958) and Newell and Rigby (1957). Similar caliche profiles have been described from other parts of the world, e.g., the Florida Keys (Multer and Hoffmeister, 1968), Barbados (James, 1972), Western Australia (Read, 1974), and South Africa (Knox, 1977).

Caliche profiles occur in both carbonate and non-carbonate host rocks in arid or semiarid environments (Bretz and Horberg, 1949). Caliche formation requires a hydrologic regime wherein the potential loss of water through evapotranspiration is greater than the amount of water introduced by meteoric precipitation. Normally, most vadose water is removed from the profile by evapotranspiration but during particularly wet periods some meteoric water reaches the phreatic zone and replenishes the fresh water lens that lies beneath the coastal dunes on islands like San Salvador. The climate on San Salvador, like that of other Bahamian islands, is subtropical, with seasonal rainy periods. Mean daytime temperatures range from 31 C in the summer to 17 C in December. Total annual precipitation is variable, ranging from a low of 101 cm to a high of 178 cm. Most precipitation occurs between August and December (the hurricane season) with a lesser rainy period during May and June. The rest of the year is characteristically dry, with extended periods of drought (Smith, 1982).

During wet periods, meteoric water percolates through the soil cover into the underlying carbonate rock. Initially, this water is undersaturated with respect to calcium carbonate and is charged with carbonic acid derived from both atmospheric and soil sources of carbon dioxide. Meteoric water dissolves carbonate grains and quickly becomes saturated with respect to low-magnesium calcite but remains saturated with respect to aragonite and high-magnesium calcite (Purdy, 1968). Hence, grains containing metastable calcium carbonate continue to be preferentially dissolved while micritic cement is precipitated from vadose waters.

The formation of micrite is attributed by Warren (1983) to fluctuations in the volume of vadose water attached to the grain surfaces. This thin film of adherant water is what remains on the surface of grains after the gravitational water has drained. Evapotranspiration reduces the volume of water that coats the grains and increases the concentration of dissolved calcium carbonate in solution. Concurrently, the volume of free gas in the pore space increases, changing the partial pressure of carbon dioxide and causing precipitation of micritic cement (Reeves, 1976). This mechanism accounts for the formation of meniscus cements in the vadose zone of eolianites. However, in some unlithified grainstones episodic precipitation of micritic cement may coat the constituent grains so as to form caliche ooids (Fig. 9). Similarly, small poorly lithified clasts of grainstone may be coated by laminated micrite to form caliche pisoids (glaebules). Typically, these pisoids range in size from 2 mm to 6 cm in diameter and contain laminated micritic laminae that are as much as 0.3 cm thick. The internal morphology of caliche pisoids is quite variable and has been described in detail by Calvet and Julia (1983). The precipitation of micritic cement is displacive in nature and separates grains that were originally in point contact with one another. Watts (1978) attributes this phenomenon to the force of crystallization caused by the precipitation and growth of interlocking crystals of micrite.

Caliche Profile

Caliche is defined by Esteban (1976) as a "...vertically zoned, subhorizontal to horizontal carbonate deposit..." where calcium carbonate is concentrated during weathering. Several types of caliche occur within distinct horizons of the same weathering profile. A fully developed profile has been described by Esteban (1976) as containing four different varieties of caliche types. Including (1) massive-chalky, (2) nodular, (3) platy or sheetlike, and (4) laminated crust which is also known as caliche hardpan or calcrete. The vertical sequence of caliche types within the profile may be quite variable both in thickness and sequential development. The boundaries between caliche horizons are usually gradational, with the exception of laminated caliche, the upper and lower boundaries of which are quite sharp. Read (1974) describes a generally similar profile, with one major exception. He does not differentiate between nodular and platy caliche, and lumps these horizons together under the term "massive caliche". In the vertical sequence two relationships are consistently developed. These are (1) massive-chalky caliche, which overlies the unaltered parent rock (Esteban and Klappa, 1983), and (2) "loose pisolitic soils" (Read, 1974), which cover the caliche-bearing profile in many areas. The thickness and development of individual caliche horizons within the weathering profile may vary greatly along their lateral extent, often within a single exposure (Figs. 1 and 4).

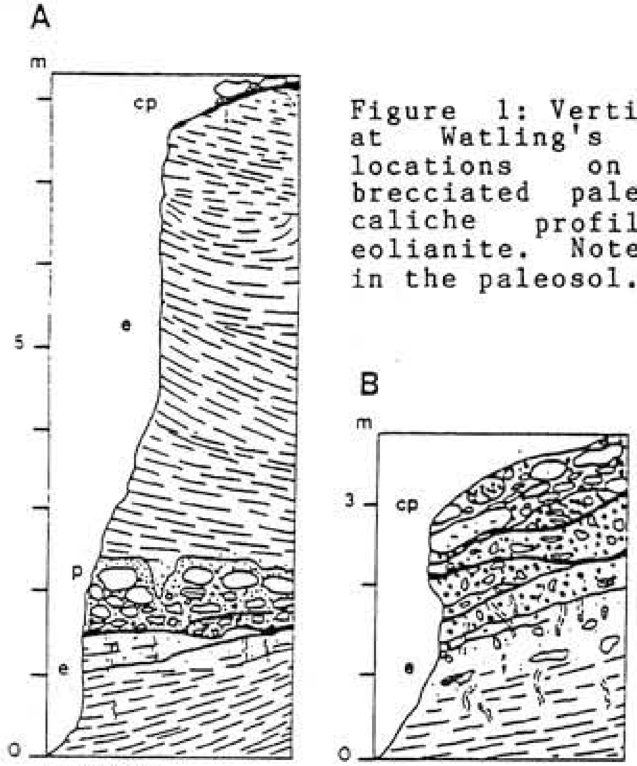

FIGURE 1.

Figure 1: Vertical sections A and B at Watling's Quarry. Note their locations on Figure 3. (p) brecciated paleosol (cp) surficial caliche profile (e) Pleistocene eolianite. Note the karst feature in the paleosol.

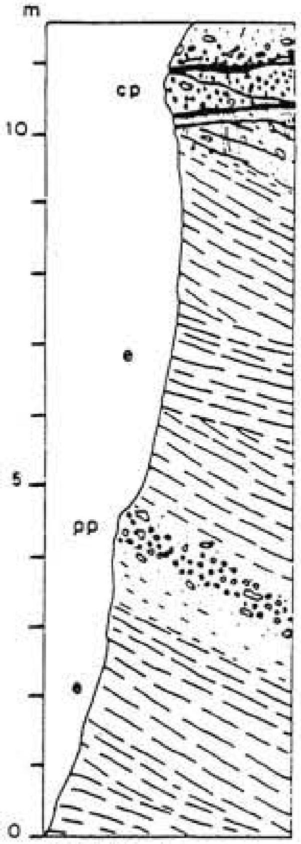

FIGURE 2.

Figure 2: Vertical section measured 30 meters south of the northern end of The Bluff. Note pisolitic paleosol (pp) and thick caliche profile along crest of the dune.

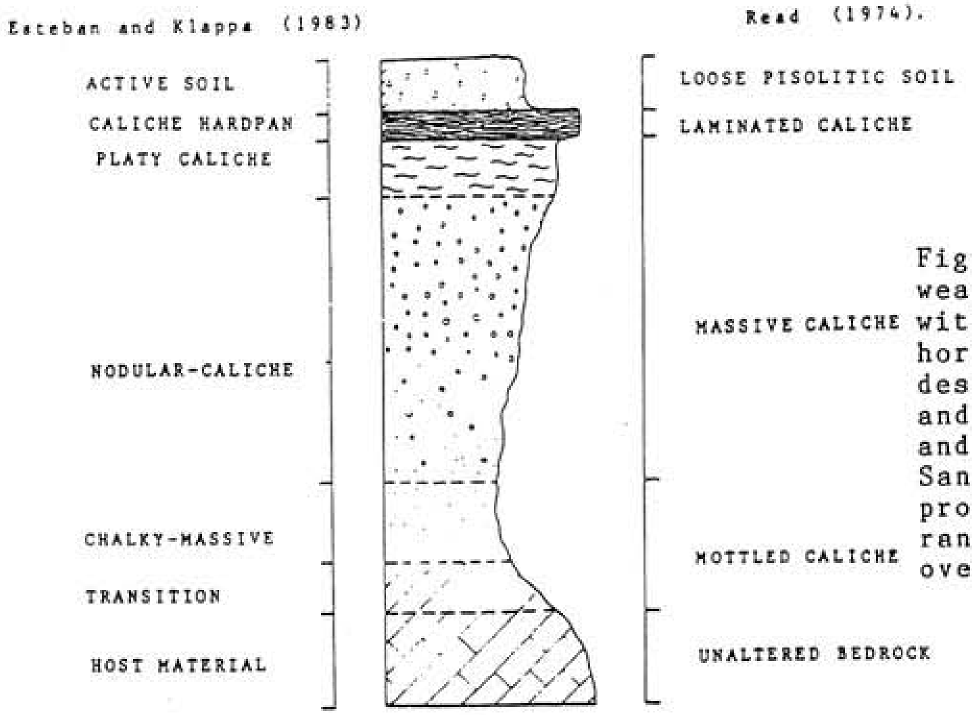

Figure 3: Idealized weathering profile with caliche horizons as described by Esteban and Klappa (1983) and Read (1974). On San Salvador, profile thickness ranges from 0.3 to over 2 meters.

Pisolitic Soils

At many locations on San Salvador loose pisolitic soils cover the caliche profile. This soil covering is thin to absent in many interior regions of San Salvador but is thicker and more consistently developed in certain areas along the east coast of the island. A thin organic-rich "black loam" is typical of soil in the interior of the island whereas thicker reddish brown soils are typical for the more coastal regions (Smith, 1982). Unfortunately for study purposes much of the original top-soil has been removed in historic times by culturally induced erosion.

Caliche-bearing soils are nonbedded, contain abundant caliche ooids, caliche pisoids, and boulder - to cobble-size lithoclasts. These lithoclasts range in size from 5 cm to more than one meter, contain altered eolianite, and are commonly coated by a thin nonlaminated micritic rind similar to that described in Florida by Multer and Hoffmeister (1968). On San Salvador the biologic activity associated with these soils supplies an abundance of organic plant detritus, whole shells of the pulmonate snail Cerion, and a lesser abundance of calcified cocoons. Preliminary studies of the insoluble residue component within the loose soil indicates the presence of clay minerals, quartz and amorphous ferric hydroxides. These insoluble residues are composed of very fine-grained material transported to San Salvador by the wind from distant siliciclastic source terrains. A similar conclusion has been made for the insoluble mineral fraction of paleosols on Bermuda (Ruhe et al., 1961).

Figure 4: Watling's Quarry. Sections A and B record locations of measured sections shown in Figure 1. Quarry wall is approximately 8 meters high. Contact of red paleosol and overlying eolianite is marked by (p). Base of caliche profile is marked by (cp). The caliche profile thickens downslope.

Figure 5: Resistant caliche surface on Crab Cay. Cliffs stand about 6 meters above mean sea level.

Figure 6: Pisolitic paleosol exposed along northern end of The Bluff. Hammer for scale.

Figure 7: Brecciated caliche profile exposed on Crab Cay. Clasts are supported by matrix of reddish brown soil. Hammer for scale.

Figure 8: Small tepee structure developed in brecciated caliche at headland on east end of French Bay. Pencil marks scale.

Figure 9: Photomicrograph of caliche ooids. Plane-polarized light. laminated micrite coats constituent grains. Note micritic coating on mollusk shell.

Figure 10: Photomicrograph showing skeletal grains, some of which have been recrystallized, surrounded by a micritic matrix. Plane-polarized light.

Figure 11: Rhizolith networks on Crab Cay. Note laminated caliche horizon capped by lithoclasts and caliche nodules. Rhizoliths are surrounded by structureless chalky limestone.

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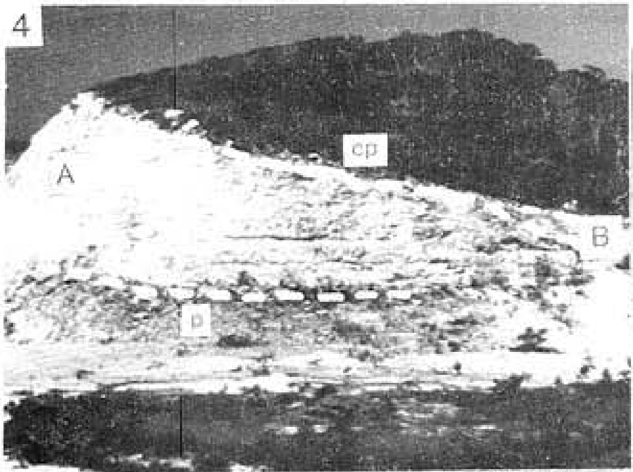

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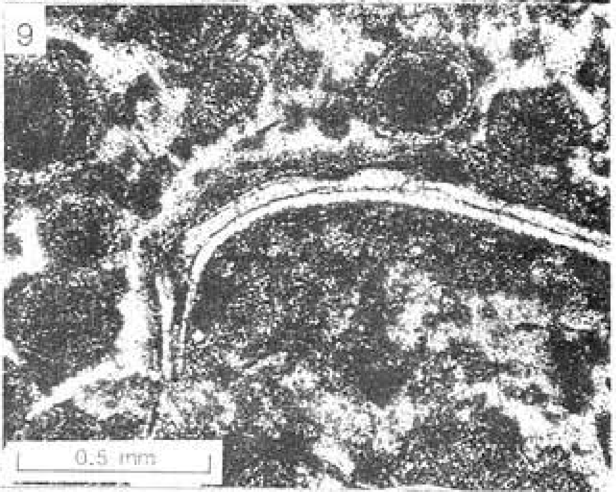

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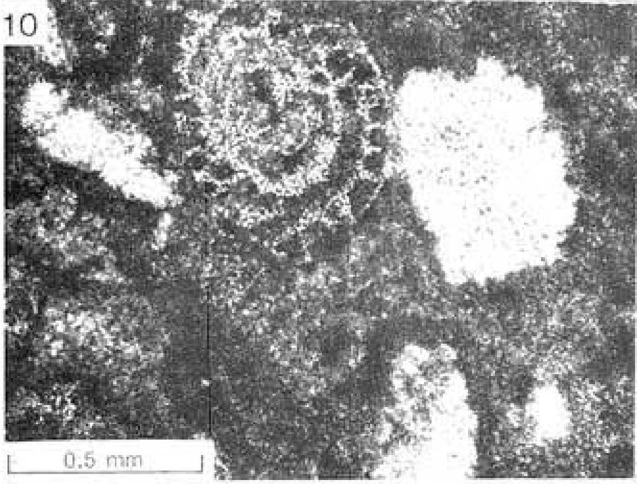

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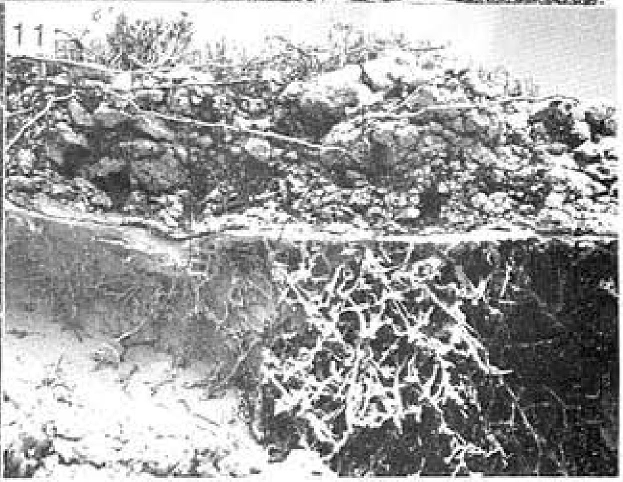

Laminated Caliche Crusts

On San Salvador, Laminated caliche crusts are generally well indurated and more resistant to weathering than the underlying carbonate rocks and thus are a prominent stratigraphic feature where exposed (Fig. 5). If the surface of a well-indurated laminated caliche surface has not been breached hollow rhizoliths, fractures, or karst conduits, the crust will act as an aquaclude having the porosity, permeability and compressive strength of a concrete highway (Gile, 1961). An impermeable caliche crust, once formed, limits the amount of meteoric water that can percolate into the underlying profile and greatly reduces the rate at which further diagenesis can occur in the underlying carbonate. Caliche crusts generally range in vetical thickness from 1 mm to several tens of centimeters. These crusts range in color from very light orange to reddish brown and are very finely laminated. Individual laminae range in thickess from 0.03 to 0.2 mm and are distinguished from one another by differing trace amounts of ferric hydroxide pigment. Thin sections of laminated crusts generally contain a scattering of highly micritized grains within the "groundmass" of caliche. Th other grains were apparently shoved aside by the displacive nature of micrite precipitation.

On San Salvador, laminated caliche crusts follow topographic surfaces, line dolines, and tend to thicken within shallow depressions. Thicker caliche profiles are commonly brecciated, a phenomenon that has been attributed to two processes, namely the displacive forces caused by the crystallization of micrite (Watts, 1978), and the physicochemical action of growing roots within the carbonate substrate (Klappa, 1980). The action of plant roots seems to be a most likely mechanism for the observed brecciation of the caliche profile (Fig. 7) and the formation of non-peritidal tepee structures (Fig. 8). Root molds are commonly observed in association with caliche breccias on San Salvador.

Platy and Nodular Caliche

Platy and nodular caliche, in descending order, underlie the laminated caliche horizon and constitute the massive caliche horizon described by Read (1974). Precipitated micrite coats grains and eventually fills pore space, and effectively transforms the original eolianite grainstone texture into a vadose packstone (Fig. 10). Platy caliche forms directly beneath the laminated caliche horizon and is "distinguished by horizontal and subhorizontal platy, wavy or thinly bedded habit, its fracture porosity, and the abundance of alveolar texture, rhizoliths and needle fiber cements" (Esteban and Klappa, 1983). On San Salvador, the platy caliche horizon ranges greatly in thickness and is characteristically thicker than the overlying caliche crust. Platy caliche grades downward into the nodular caliche horizon. In this lower horizon caliche pisoids may be locally abundant but are not developed everywhere on San Salvador.

Chalky Caliche

Where present on San Salvador, chalky caliche underlies the massive caliche horizon. Where exposed the chalky horizon is characteristically weathered, punky, and structureless. The chalky appearance of this sediment is attributed more to the soft friable nature of the sediment than to grain size. Massive chalky caliche is best developed where the eolianite appears to have been extensively bioturbated by roots and is associated with rhizoliths. A similar massive chalky carbonate sediment has been described in the Yucatan where the rock is locally called sascab (Isphording, 1977).

Transition Zone

A transitional zone occupies the interval between the overlying caliche profiles and the underlying unaltered host eolianite on San Salvador. This zone is characterized both by the presence of sedimentary features clearly associated with that of the underlying host rock and by the alteration associated with vadose diagenesis. Read (1974), describes this zone as the "mottled caliche" horizon because the chalky carbonate rock that grades downward into the relatively unaltered eolianite contains irregular patches of massive caliche. In the lower part of the weathering profile micritization preferentially takes place along fractures and bedding planes so as to form thin nonlaminated micritic stringers that extend as much as several meters below the laminated caliche horizon.

Profile Development

On San Salvador, profile development begins with the formation of thin soils on unconsolidated eolianite. Soils form soon after dune stabilization through the interaction of physical, chemical, and biologic processes in the subaerial environment. In the initial stages of caliche development the profile has high porosity and permeability. Meteoric water percolates with relative ease through the profile and preferentially dissolves the unstable carbonate components while micrite is precipitated concomitantly as laminar coatings on particles. Initially, cementation of loose grains is prevented by mechanical instabilities within the profile that are caused by soil creep and bioturbation. With continued precipitation of micrite coatings, the grains will finally be joined together so as to produce massive caliche (Read, 1974). Further precipitation of micrite fills pore space and greatly reduces the porosity and permeability of the caliche profile. This region has been termed the "plugged horizon" (Gile et al., 1966) and represents the zone of most frequent wetting. Formation of an impermeable zone along the top surface of the massive caliche allows a thin film of meteoric water to pond, causing precipitation of laminated micrite. At any particular location the thickness of a laminated crust is related to the frequency and duration of meteoric water ponding. If a mature San Salvador caliche profile remains near the surface for an extended period of time it may undergo extensive brecciation by plant growth and erosion, with downslope movement of material by soil creep.

Continued dissolution and reprecipitation of calcium carbonate in a disrupted profile may lead to the development of a reworked, recemented, caliche breccia (Esteban and Klappa, 1983). On San Salvado such a recemented caliche breccia is exposed in the paleosol that lies on the floor of Watling's Quarry (Fig. 1).

Variations in Caliche Profiles

Incomplete profiles occur when the duration of weathering has been insufficient for complete profile development and local topography is too steep or mechanically unstable for lithification (Stuart et al., 1961). On San Salvador a distinct pisolitic paleosol exposed at The Bluff represents incipient formation of a caliche profile that has not weathered sufficiently to form a mature caliche profile with laminated crusts (Figs. 2 and 6). Erosion preferentially removes the uppermost portion of the caliche profile from topographic highs and transports this soil material downslope. Multiple profiles occur where older eolianite deposits are overridden by a younger dune sequence, or by the transportation and accumulation of soil material (Read, 1974). Laminated caliche may develop in these newly deposited sediments, thus forming multiple anastomosing crusts. Such complex crusts are well exposed in the dune ridge at Watling's Quarry (Figs. 1 and 4). At that locality, laminated caliche is developed discontinuously but thickens on the flank of the dune where multiple laminated caliche crusts are developed.

Rhizoliths and Other Related Features

Biologic activity within San Salvador soil profiles has given rise to a number of distinct organosedimentary structures and textures that are diagnostic features of subaerial exposure and soil formation. Rhizoliths, which are prominent features in many caliche profiles on San Salvador, are formed by a number of different mechanisms of calcification such as cementation around roots during growth and decay, cementation within the void left after root decay and petrification of roots by micrite. Klappa (1980) defines five basic types of rhizoliths which include: (1) root molds, (2) root casts, (3) root tubules, (4) rhizocretions s.s. and (5) root petrifactions. Root molds are sinuous cylindrical pores left after the root has decayed. Root casts are sediment- or micrite-filled root molds. Rhizocretions s.s. are concretionary deposits of micrite that form around living or decaying roots. Root tubules are cylinders of cement encasing root molds. Root petrifactions result from the precipitation of micrite that encrusts, impregnates or replaces organic matter.

Rhizocretions are light-colored branching tubular structures composed of micrite-cemented grains and occur locally in great concentration. The mold that remains after root decay may become filled with brown to reddish brown micrite that forms distinctive root casts. On San Salvador, rhizoliths are composed of low-magnesium calcite and range in diameter from several millimeters to several centimeters. The diameter of rhizoliths (the rhizocretion plus the root cast) approximates the cross sectional area of the original root and the lateral extent of the root hairs (Klappa, 1979). San Salvador rhizoliths may extend from several centimenters to several meters into the underlying rock, and commonly exhibit a distinctive branching morphology. The diameter of rhizoliths characteristically decreases downward with each branching. An excellent example of his branching morphology is beautifully exposed at Crab Key where intricate rhizolith "networks" are exposed (Fig. 11). At this locality some rhizoliths contain live or decaying roots. Care must be taken to distinguish between rhizoliths and animal burrows. Curran (1984) has established criteria by which to distinguish the structures caused by roots and those caused by animal burrowing.

On the microscopic scale, certain features occur in San Salvador caliche profiles that indicate subaerial exposure. There are (1) alveolar texture (term introduced by Esteban, 1976), (2) random needle fibers of low-magnesium calcite (term introduced by James, 1972) and (3) Microcodium, now thought to be the result of symbiosis between the cortical cells of plant roots and soil fungi (Klappa, 1978).

Concluding Statement

On San Salvador both caliche profiles and karst surfaces record periods of subaerial exposure in the sedimentary record. The laminated caliche crusts have high preservation potential and have become incorporated into the geologic record on the island, recording periods of subaerial exposure under arid and semi-arid conditions. Karst features and caliche profiles are caused by different climatic conditions and hydrologic regimes but commonly occupy the same surface. This superimposed relationship should be useful in determining the climatic and diagenetic history of San Salvador.

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