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Root calcrete formation on Quaternary karstic surfaces of Grand Cayman

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ABSTRACT

The rugged karst terrain developed on the dolostones of the Miocene Cayman Formation (Fm) on Grand Cayman includes numerous large cavities that formed through the activity of tree roots. The surfaces of those cavities are coated with laminated calcrete crusts up to 8 cm thick that are formed of an alteration zone, an accretionary zone, and final infill of the cavities. These crusts are formed of various laminae, including dolostone with root traces, alveolar septal structures, peloids, micritic and microsparitic laminae, micrite with bioclasts, and pisoliths. Features such as microborings, spores, needle-fiber calcite and micro-rods are common in all parts of the calcrete crust. Calcrete formation was initiated as the roots and associated microorganisms generated the cavities. Later on trapping and binding processes and organically induced precipitation of carbonate allowed the formation of the accretionary (mostly laminar) part of the calcrete. The last phases of crust formation took place when ponded waters filled the cavities. The calcrete crusts developed on the Cayman Formation dolostones record a very specific setting for calcrete formation and constitute a good example of non-horizontal calcrete crusts.

KEYWORDS **Calcretes. Root. Karst. Cayman Island. The Caribbean. Quaternary.**

INTRODUCTION

Calcretes are near surface, terrestrial, accumulations of predominantly calcium carbonate, that vary from powdery to nodular to highly indurated forms. They result from cementation and the introduction of calcium carbonate into soil profiles, bedrock, and sediments (Goudie, 1973; Wright and Tucker, 1991). Also known as caliches, they have been the subject of numerous studies over the last two decades because they are important indicators of (a) subaerial exposure (Esteban and Klappa, 1983), (b) semiarid to arid climate climatic conditions (Goudie, 1983; Alonso-Zarza 2003), (c) stable geomorphic surfaces (Machette, 1985), and/or (d) non-active areas in alluvial systems (Wright and Alonso-Zarza, 1990). Although found in many different geological settings, calcretes are typically associated with soil profiles in surficial or subsurficial locations. It should be noted, however, that nonpedogenic and phreatic calcretes have also been recognized (Arakel, 1991; Mack et al., 2000). Calcrete formation is controlled by the interplay of a wide range of biological and physico-chemical processes – a fact that is amply demonstrated by the wide variety of microfabrics associated with calcretes (Wright, 1994). Calcrete microfabrics commonly preserve evidence of the role that various organisms have played in their formation.

Calcretes developed on different Caribbean island record the subaerial processes that formed in association with recent soil formation. In this paper we examine the development of calcrete on the dolostones of the Cayman Fm on Grand Cayman. In so doing it is possible to assess the roles of pedogenic and biological processes in calcrete formation and their significance to subaerial diagenesis processes. Much of the calcrete development is found in large, steep to vertical karstic-tree root cavities. They offer a unique opportunity to examine calcrete development on non-horizontal surfaces that are located within the host rock rather than on its upper surface. The close association of laminar calcretes with roots has led to their designation as rhizogenic calcretes (Wright et al., 1995) or rootcretes (Jones, 1992). Only exceptional development of calcretes within oblique fractures or root cavities has been considered (Calvet and Juliá, 1983).

GEOLOGICAL CONTEXT

The central part of each of the Cayman Islands is formed of massive Tertiary limestones and dolostones that belong to the Bluff Group (Jones, 1994; Fig.1). This core is unconformably onlapped by the Ironshore Fm, which is formed of poorly lithified limestones that were deposited at various times throughout the Pleistocene (Jones, 1994; Vézina et al., 1999). The Bluff Group is formed of the Brac Fm (Late Oligocene), the Cayman Fm (Middle-Late Miocene), and the Pedro Castle Fm (Late Pliocene) (Jones, 1994).

Grand Cayman has a relief of less than 20 m with large parts of the island being less than 10 m above sea level. Hard, finely crystalline dolostones that belong to the Cayman Fm are exposed over most of the eastern half of Grand Cayman (Jones, 1994, his fig. 2.3). In contrast, much of the western half of Grand Cayman has limestones of the Ironshore Fm and/or Holocene swamp deposits at the surface. In this area, hard dolostones of the Cayman Fm are restricted to an elevated ridge that parallels the south coast along with isolated exposures in the southwest corner and at Hell. Surface exposures of the Pedro Castle Fm are restricted to the south part of the island in the vicinity of Pedro Castle (Jones, 1994, his fig. 2.3). When exposed at the surface, the hard, finely crystalline dolostones of the Cayman Fm are typically characterized by rugged phytokarst development (Folk et al., 1973; Jones, 1994) that is characterized by rugged, sharp-edged pinnacles separated from each other by deep crevices and potholes that are commonly less than 1 m wide (Jones, 1994, his fig. 2.12). The little soil that is present is generally concentrated in the potholes and crevices. Areas with extensive soil cover are rare and localized.

Most of the eastern part of Grand Cayman, which is the least developed part of the island, is covered with dense tropical vegetation despite the sparse, poorly developed soil. Hardwood forests that included mahogany, red birch, ironwood, cedar, and fig originally covered much of the eastern part of Grand Cayman. Today, much of the original forest is restricted to small patches and other areas have been replaced by thatch palms, manchineal, and logwood, vines, climbing cacti, and maidenplum (Bradley,

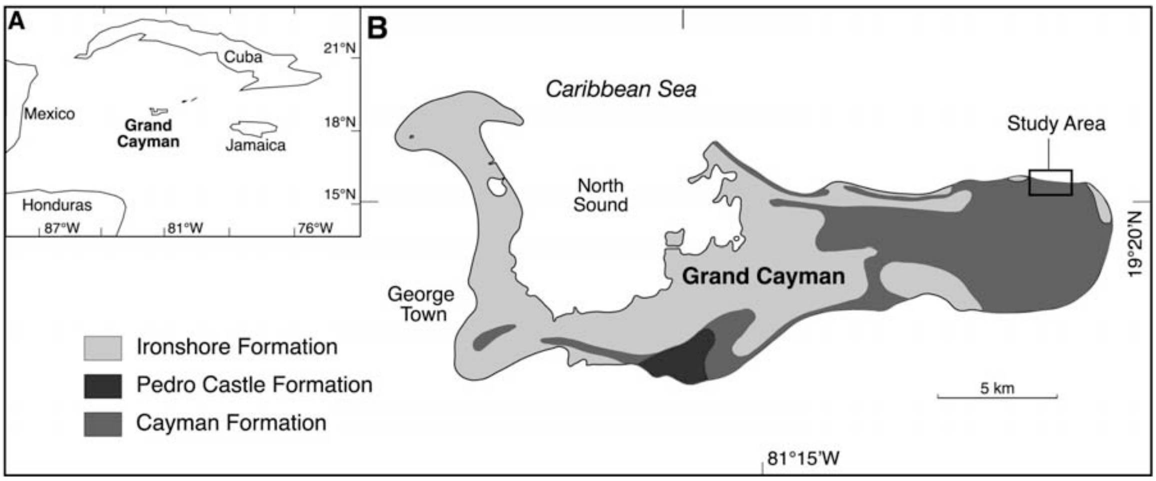

FIGURE 1 | **Map showing the location of Grand Cayman Island and the study area.**

1985; Brunt, 1994). Although some of these plants are rooted in the soils in the potholes, others are rooted directly into the bedrock. Some of the large trees, for example, have roots that extend down into the bedrock for in excess of 6 m. Presumably, the large taproots penetrate down to areas where they can access the groundwater.

The rocks around the plant roots have been subjected to considerable diagenetic alteration (e.g., Jones, 1989). In many areas, it is readily apparent that the roots have brecciated the host rock to the extent that large isolated fragments of the dolostone are completely enmeshed by roots and root hairs. The size and morphology of the cavities associated with the plants are highly variable and a function of the size and morphology of the root system. Cavities up to 2 m in diameter are commonly associated with trees that have large tap-roots, numerous secondary roots, and large masses of rootlets and root hairs (Fig. 2). Conversely, the smaller roots of other plants (e.g., bushes, grasses) only give rise to small cavities that have a relatively simple tubular morphology. Many of the root cavities are filled with brecciated fragments of the bedrock and various accumulations of terra rossa soils.

DESCRIPTION OF ROOTCRETE

On the Cayman Islands, rootcretes are common features of the dolostones of the Cayman Fm. The highly irregular, sharp to diffuse boundary between the rootcrete and the dolostone (Fig. 2A) indicates that the host rock

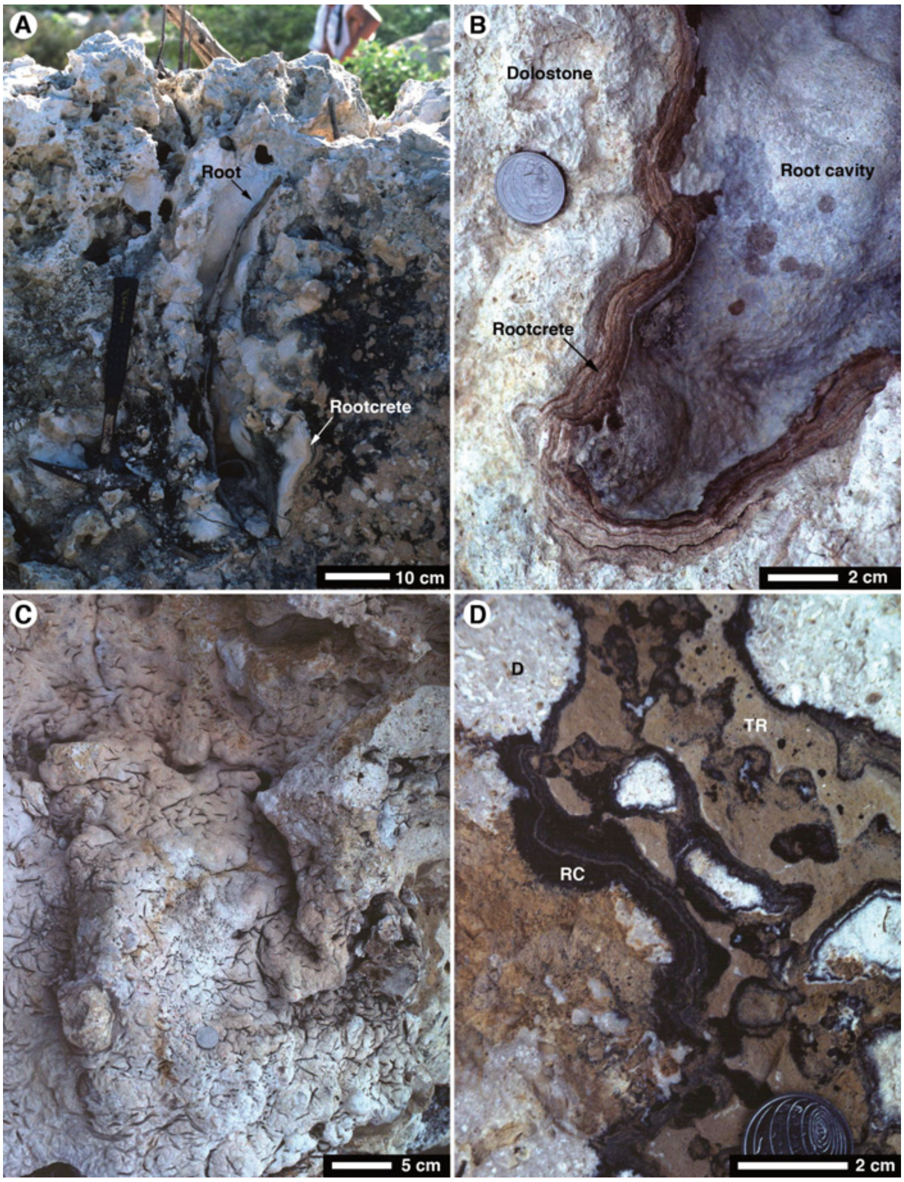

FIGURE 2 **Field photographs of root calcretes in the Cayman Formation, northeast part of Grand Cayman. A) Root calcrete surrounding tree roots in dolostones in upper part of Cayman Formation. B) Brown, thinly laminated root calcrete lining cavity created by tree roots. C) Cavity facing surface of root calcrete showing small grooves that were once filled by tree rootlets and root hairs. D) Root cavity in dolostone lined with manganese-rich root calcrete (RC) and filled with lithified terra rossa (TR).**

underwent dissolution and/or corrosion which are the result of the phytokarst development indicated above. The rootcrete typically displays a wavy profile and the calcrete commonly penetrate to different depths, within the host rock (Fig. 2B and 2C). The walls of the root cavities are commonly lined with laminated crusts, up to 2 cm thick, that have been referred to as rootcretes (Jones, 1992). These dense crusts, commonly highlighted by concentrations of black Mn oxides, appear to have been formed as a result of the alteration of the bedrock by processes that were mediated by the plant roots. Compared to the host dolostones of the Cayman Fm, the rootcretes have significantly lower porosity and permeability. Indeed, it is possible that the rootcretes act as impermeable linings that allow rainwater to be held in and around the plant roots following periods of rain. A thin layer, enriched in red clays commonly highlights the boundary between the host rock and rootcrete. Elsewhere, a discontinuous film of Fe-Mn oxide-hydroxides stain is present in the host rock (Fig. 2D). Small dedolomitised patches and small patches of calcite spar cements are found in the dolomite close to the boundary with the calcrete. The rootcrete is divided into (1) the alteration zone, (2) the accretionary crust, and (3) cavity fill (Figs. 3 and 4).

The Alteration Zone

Two different microfabrics are recognized according to the degree of breakdown of the host dolostone, and to the diameter of the root traces.

Reworked dolostone with fine root traces

This beige to pink zone is found under the laminar calcrete and as isolated patches in the host dolostone. Its boundary with the host dolostone is irregular. This zone, formed of a porous mixture of dolomite, clay, and calcite, contains numerous fine root traces. Dolomite crystals (up to 10 μm), which are the dominant component, vary from unaltered rhombic crystals to highly etched crystals that are coated with mucilge, spores and filaments (Figs. 5A, 5B and 5C). The clay seems to coat the dolomite crystals, the calcite, and the organic debris.

Extensive networks of filaments, calcified or not, are present throughout the reworked dolostone. These filaments are 5-10 μm in diameter and hundred of microns long. Root traces, which are cylindrical pores up to 1 mm in diameter and several mm long, are coated by different carbonate laminae. They do not show any preferential orientation. Locally preserved root cells, 15-20 µm in diameter, display a tissue-like pattern (Fig. 5D). Each cell has a nuclei formed of a single calcite crystal that is surrounded by a crystalline cortex, (Fig. 5E). Similar features have also been recognized in Miocene calcretes of the Madrid Basin and interpreted as calcified root cells (Alonso Zarza et al., 1998a). Some filaments occur close to the calcified cells. Alveolar septal structures are also present around the holes.

Indurated dolostone with root traces

This term refers to the indurated dolostones that are characterized by well-developed root structures (Fig. 3A). These root structures, which appear isolated in the dolostone, are probably connected to the laminar calcrete.

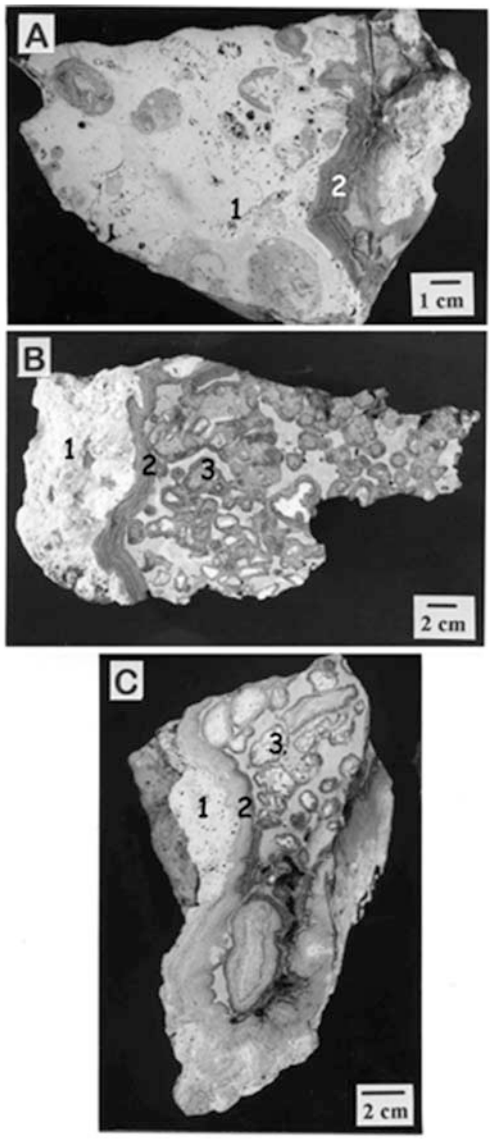

FIGURE 3 | **Hand samples of the rootcretes showing the arrangement of the main zones. A) Rootcrete developed in a relatively narrow cavity. It shows a thick alteration zone (1) and an accretionary, in this case laminar, crust (2). B) Strongly developed pisolithic zone (3) on a thin laminar one (2), most of the nuclei of the pisoliths are fragments of the dolostone. C) Completely filled cavity. It shows an alteration zone (1) and laminar crust (2) coating all along the cavity and a latest infill with pisoliths and dark micrite (3).**

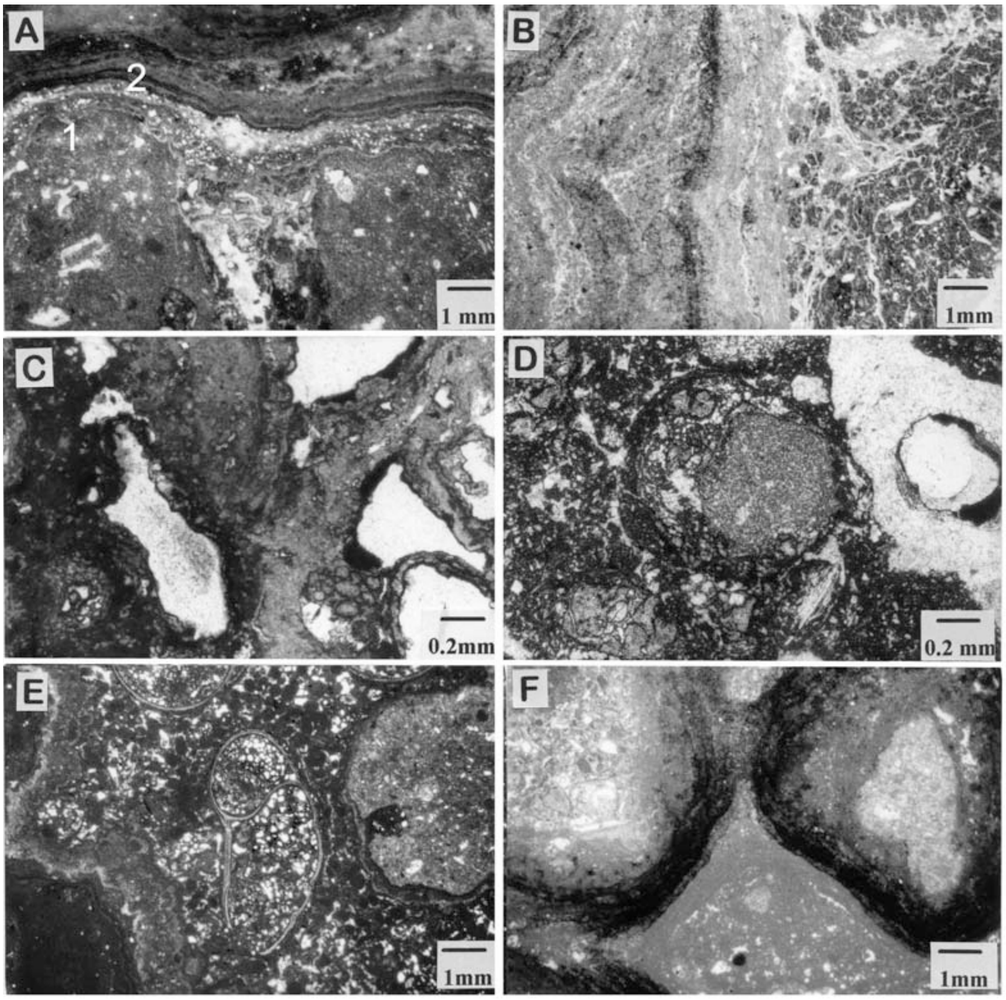

FIGURE 4 **Microphotographs of the calcrete microfabrics. A) Alteration zone (1) and laminar crust (2) made in this case by dolomite crystals with micritic filaments. B) Laminar crust mainly formed by brown coarse micrite-microspar (to the left). The final infill (right) of the cavities consists of very desiccated micrite. C) Alveolar septal structures showing the large pores and the micritic filaments. D) Coated grains (peloids) formed of a more homogeneous nuclei and a very irregular cortex made of micrite filaments, smaller peloids and detrital grains. E) Micrite with gastropods completely filling the cavities. F) Nodular crust coated by dark micrite. Peloidal micrite is the final infill of the cavity.**

The root structures are ~ 1 cm in diameter and up to several cm long. A cross section through such a root shows a more or less circular internal void that is encased by several irregular micritic zones that are outlined by irregular boundaries. The thickest innermost zone, which encases the central void, is formed of dark micrite that has high porosity and alveolar septal structures. Calcified fungal filaments are present in the porous micrite. This zone is encased by a thinner zone of lighter micrite that is characterized by diffuse linear structures that are defined by slightly coarser crystals. The outermost zone of dark micrite is characterized by diffuse laminations.

Several lamination patterns can be recognized in different root traces. Irrespective of such variation, laminae formed of alveolar septal structure are present. The boundary of the root trace with the host dolostone is irregular with micritic stringers, up to 1 mm in diameter, extending into the host rock. Some clays and oxide stains are present along the sharp contact with the dolostone. Etched dolomite crystals are found in the outer laminae of the root trace. Several long and straight randomly orientated micritic filaments are typically present in the root laminae.

Accretionary zone

This zone, which is the most complex in the rootcrete, consists of a laminar and/or nodular crust (Fig. 3). Depending on the size of the original cavity, this zone is up to 8 cm thick.

Laminar crust-calcrete

The laminar crust is 0.2–2 cm thick. This variable part of the calcrete is formed of intercalated laminae that are characterized by different microfabrics. There appears to be a random arrangement of the different microfabrics and it is impossible to describe a type succession. The following microfabrics are found in this crust.

Dolomite crystals and micritic septae

This microfabric, found at the contact or in the nearby dolostone host rock (Fig. 4A), consists of irregular distributed, loose dolomite crystals that are joined together by micrite septae and spores. The amount of dolomite crystals is highly variable, they may form most of the laminae or they may be embedded in a massive micrite, including only a few dolomite crystals. The dolomite crystals, which are of variable size, are highly etched and supported by organic filaments. This microfabric may form the entire laminar calcrete, especially if it is thin. The distribution of loose and etched dolomite crystals indicate that they formed through the erosion and mechanical breaking of the dolostones.

Alveolar septal structures

These structures may be present in all the microfacies; there are some laminae that are formed solely of alveolar structures. Such laminae, which are ~ 5 mm thick and formed of porous micrite, are usually the thickest and most porous part of the crust. The alveolar septa consist of irregular, more or less tubular to spherical voids, that are usually ~ 1 mm wide, and outlined by micritic septae that are ~ 0.1 mm thick (Figs. 4B and 4C). The voids and septa may be included in the micrite groundmass of the laminae or form a complex network that forms the entire laminae. Some of the voids are filled with microspar. The voids and crystals are commonly covered with mucus that precludes accurate description of their morphology and determination of their size. Under the SEM, the alveolar septal structures appear as porous areas (Fig. 5F) with the host micrite covered by microborings and the voids cut or bounded by networks of calcified filaments (Fig. 5G). Some clay rich nodules containing detrital dolomite crystals and some gastropods are found locally in the alveolar microfabrics. In these cases, the internal cavities of the gastropods are filled with an alveolar microfabric. The gastropods and clay rich nodules were probably derived from the upper part of the soil.

Peloidal laminae

Peloids occur in irregular laminae, 1-2 mm thick, locally interbedded with other laminae. The peloids are held in a micrite matrix. These laminae also contain micritic strings, microspar, and in some cases, alveolar septal structures. The irregular spherical peloids, 0.1-0.2 mm long, are formed of dense micrite and, in some cases, minor amounts of clay (Fig. 4D). Some of the micritic peloids are merged and difficult to separate from the micrite matrix. The clay rich peloids, which probably formed by the replacement of soil clay glaebules, typically display circumgranular desiccation cracks with are filled by micrite or layers (about 10 μm long) of calcite fibrous cement (Figs. 5H and 5I).

Micrite

These laminae are formed of calcite crystals, < 1 μm long, that are coated by clays and/or mucus (Fig. 5J). It may contain some alveolar septal structures that are locally outlined by clay and oxide/hydroxide cutans. In the septal alveolar structures the coarser crystalline areas are characterized by diffuse, elongated filaments. The dark micritic laminae may contain etched dolomite crystals, clays, and oxides/hydroxides.

Coarse brown microspar

Brown microspar laminae, up to 6 mm thick, form the most distinctive part of the laminar crust (Fig. 4B). These laminae are formed of anhedral calcite crystals, 4-15 μm long, along with minor amounts of small, etched detrital dolomite crystals. Different crystal size (Fig. 5K), different clay content, Mn staining (detected by the microanalyses under SEM), and/or the presence of dark micrite and peloids define the different laminae. Mn-staining, which is most common in the outermost laminae, is irregular and locally forms strings. It probably follows primary organic remains. Calcified filaments, alveolar septal structures and pockets containing micritic and clay peloids are present. Spherulites of LMC with a radial fabric, up of 40 μm in diameter, are common in some of the laminae. Calcified spores commonly form the nuclei of the calcite crystals (Fig. 5L).

Dense micrite with bioclasts

This relatively rare fabric, typically found in laminar crusts > 1 mm thick, usually has highly irregular boundaries and usually consists of dense brown to gray micrite with scattered ostracods. Etched dolomite crystals, derived from erosion of the cavity walls, are present in the micrite. The most striking features of this microfabric are the spar-filled cracks. The irregular cracks that contain disaggregated fragments of micrite and ostracods and some desiccation cracks commonly recognized in of palustrine carbonates (Freytet and Plaziat, 1982).

Pisolithic crust

Pisolithic crusts tend to overlie the laminar crust (Figs. 3B and 3C), and/or occupy in the central parts of the root-karst cavities. This crust is formed of various types of pisoliths, including granular to homogenous micrite. The pisoliths, ~ 1 cm in diameter, have an inner nucleus formed of dolomite and/or peloidal micrite that is encased by an outer laminated cortex, up to 4 mm thick. The cortex typically displays the same microfabrics as those in the laminated crusts. Some pisoliths, however have a composite nucleus and complex laminae development.

Cavity Fill

It occurs filling the porosity left by the laminar and pisolithic crusts (Figs. 3B and 3C), and probably corresponded to part of the space occupied by the root that decomposed. It consists of masses of micrite with some etched dolomite crystals and quartz grains and gastropods (Fig. 4E). Traces of kaolinite have been found under XRD. The micrite may be very homogeneous, but usually

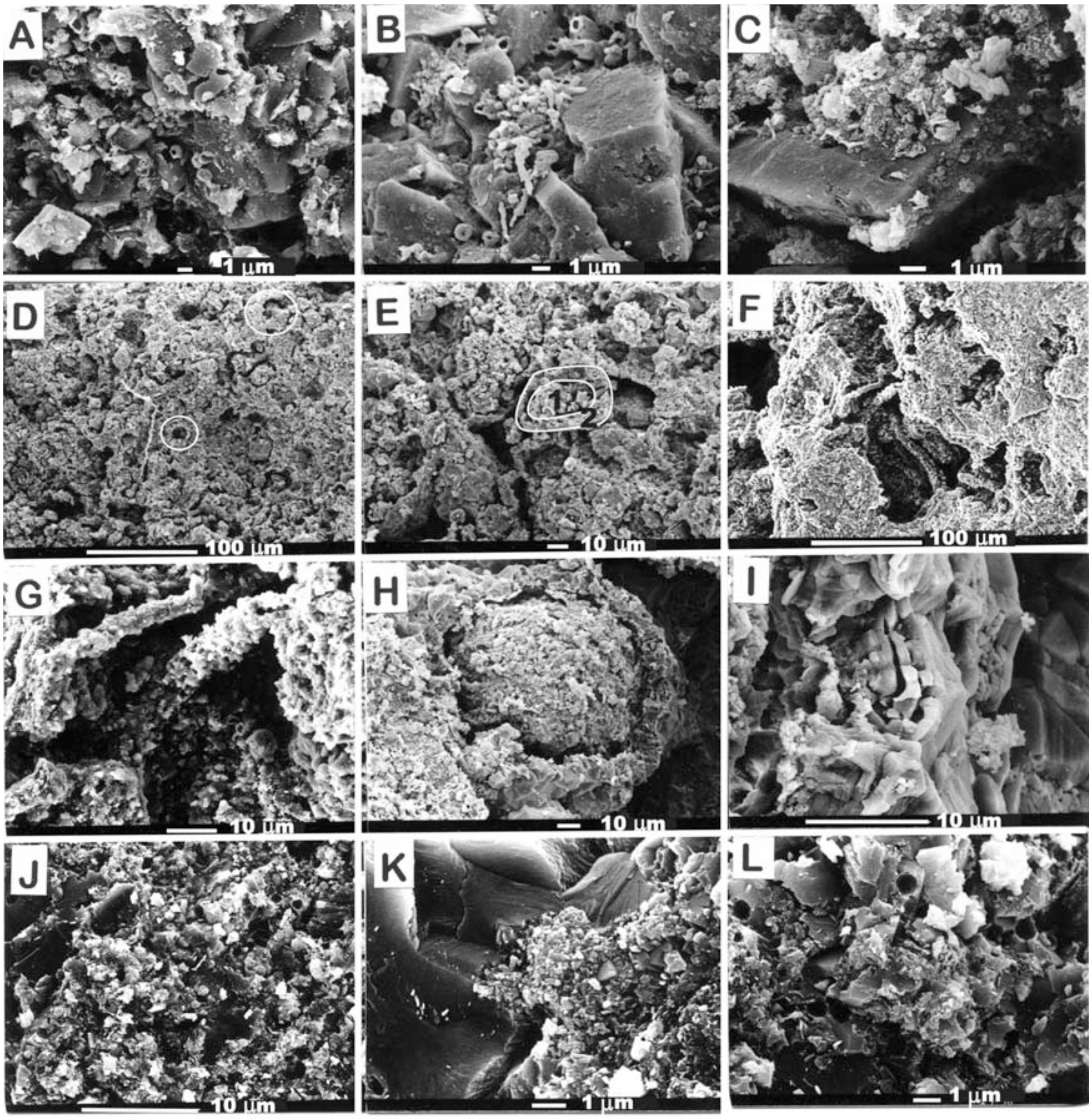

FIGURE 5 **SEM images. A) Weathered dolostone showing spores and mucus between the dolomite crystals. B) Weathered dolostone. Organic structures amongst dolomite crystals are causing their partial dissolution. C) Loose dolomite that is being etched by organic structures. D) General view of calcified root cells (some are encircled) forming mosaic with suggest a tissue like pattern. Calcified filaments also occur. E) Detailed view of the calcified cells formed of a central nuclei (1) that consists of a calcite crystal and an outer cortex (2). F) General view of alveolar septal structures. Microborings and calcified filaments are also shown. G) Detailed view of calcified filaments within the alveolar septal structures. H) View of a micritic peloid. The inner part is formed of calcite and some clays. The cortex is formed of calcite crystals growing amongst debris of clay and micrite. I) Detailed view of the crystalline cortex of the peloid. J) General view of the micritic microfabric showing small size calcite crystals some clays and spherical pores. K) Irregular contact between the micrite and microspar laminae. L) Micrite-microspar laminae. Some of the larger calcite crystals contain spores.**

it shows desiccation cracks from irregular to circungranular, and micritic peloids (Fig. 4F). This gives rise to a granular microfabric similar to that recognised in some palustrine settings and suggesting that at some stages water could be ponded within the cavities.

Other features

Although evident in all parts of the rootcrete, microborings, calcified spores, and needle-crystals, are most common in the laminar crust.

Microborings

Microborings, which are most common in the alveolar microfabric, are up to 300 mm long and ~ 1 mm in diameter. They do not follow any preferential direction and are distributed homogeneously throughout the calcrete (Fig. 6A). They are usually straight (Figs. 6B and 6C), although some curved ones are present (Fig. 6D). The microboring may be empty, coated by mucilage, or lined by calcite crystals that are up to 1 mm long. Some of the microborings also contain spores and needle fiber calcite crystals (Fig. 6C). The microborings are very similar in size and morphology to the porosity left by filaments (Phillips and Self, 1987) or root hairs.

Spores

Spores, which are spherical to slightly polygonal bodies bodies, 0.5 to 1 μm in diameter (Fig. 6E), have calcite walls that are 0.1 m thick. Their outer surfaces of the wall are rough, whereas large and thin ridges coat the inner surface. Small pores, 0.05 μm in diameter, are commonly evident on their surface. They are considered to be spores because of their general morphology and similarity to the spores described by Jones (1992). The spores are found throughout the rootcrete. In the weathered dolostone, they tend to be clustered between or on the surface of the dolomite crystals (Figs. 6D and 6E). In some areas, crystals of microspar calcite encase the spores (Fig. 6F).

Needle fiber calcite

Needle fiber calcite crystals are concentrated mainly in the areas with alveolar septal structures, where they lie on larger calcite crystals, on mucus, on spores and/or conidia, on filaments, and in the microborings. Fibers, ~ 0.3 μm long and 0.08 μm wide (Figs. 6H and 6I), are found around the microborings, forming irregular aggregates up to 4 μm in diameter, and on the surfaces of spherical bodies and calcified filaments. Larger fibers, typically ~ 2 μm long and 0.1 μm wide, are usually located in the pores of the alveolar septal structures, in the outermost part of the microborings walls, and in the microborings (Figs. 6C and 6G). Needle fiber calcite crystals, which are common in calcretes (Verrecchia and Verrecchia, 1994), have been attributed to biogenic and non-biogenic origins. The close association of the fiber crystals with organic structures in the Cayman rootcretes suggests a biogenic origin, possibly related to the bacteria or fungi. It is also possible that some of the smallest aggregates of needles or micro-rods (Figs. 6H and 6I) may have formed in association with decaying microorganisms such as bacteria (Loisy et al., 1999). Nevertheless, it must be acknowledged that the different crystals sizes could be due to physicochemical processes.

INTERPRETATION

Recent calcretes from Grand Cayman provide evidence of the importance of macro and microorganisms in the weathering and formation of carbonate deposits under subaerial conditions. Cavities formed by plant roots became lined with rootcretes as a result of numerous complex and interrelated physiochemical and biochemical processes. The presence of laminated root traces in the dolostone, and the occurrence of needle fiber calcite, spores, and mucus between the dolomite crystals, shows that roots created space for themselves by breaking down the host dolostones. Moreover, dolomite crystals derived from the host rock were trapped and bound onto the weathering surfaces by the microorganisms. The dolomite crystals in the weathered zone and the rootcrete are etched and covered with spores, mucilage, filaments, and needle fiber crystals. The microbes and their associated mucus may have been responsible for the physical and/or mechanical alteration for etching of the dolomite.

Alveolar, micritic and microspar laminae form the accretionary zone where precipitation of carbonate around the rhizosphere was the dominant process. Although laminae formed of alveolar septal structures are found throughout the calcrete, they are most common close to the weathered areas. Alveolar septal structures have been attributed to the calcification of root structures and their associated fungi (Wright, 1986). In the Cayman examples, the close association of alveolar septal structures with filaments, spores, and needle fiber calcite indicates very active areas of the rhizosphere. These laminae represent the true “rootcrete” laminae.

Micrite laminae are interbedded with all of the other microfabrics found in the calcretes. These laminae may represent episodes or areas where root activity was reduced and precipitation of micrite was possible. The presence of mucus and filaments in these laminae suggests that biochemical processes may have been more important than physicochemical processes in their precipitation.

Microspar laminae are commonly the last microfabric in the laminar crust, usually in contact with the nodular crust or the cavity fill. These laminae commonly alternate with the micritic laminae. The numerous filaments, microborings, and spores found in these laminae suggest that they may have formed through microbial activity. Most of the calcite crystals in these laminae have a spore as their nuclei (cf. Jones, 1992). The presence of calcified cell roots, however, suggests that some of the laminae or crystals may have formed due to root activity. The microsparite laminae seem to have formed through the direct activity of organisms, even though it is not always possible to determine the exact type of organism involved.

Micro-scale erosion and reworking are indicated by the distribution and composition of the peloidal laminae. The fact that some peloids seem to replace and grow on clay glaebules indicates that some components did not originate in the Cayman Fm. It is important, however, to note that they also include clays that probably adhered to them as they were moved around in the cavities. Root penetration and movement in the cavities could favor peloid formation and their arrangement in the laminae. Formation of peloids in relation with roots and associated microorganisms is a common feature of calcretes (Calvet and Juliá, 1983; Jones and Squair, 1989) and palustrine environments (Freytet and Plaziat, 1982; Alonso-Zarza et al., 1992). Their occurrence indicates multiple phases of soil formation and/or erosion.

Micrite with bioclasts laminae are interbedded with the different laminae but mostly filling small irregular surficial cavities. Locally, the micrite is cut by root traces. The presence of this microfabric in the laminar crust indicates that water could accumulate in these root cavities enabling the precipitation of micrite and creating a suitable microenvironment for gastropods. As describe above (general

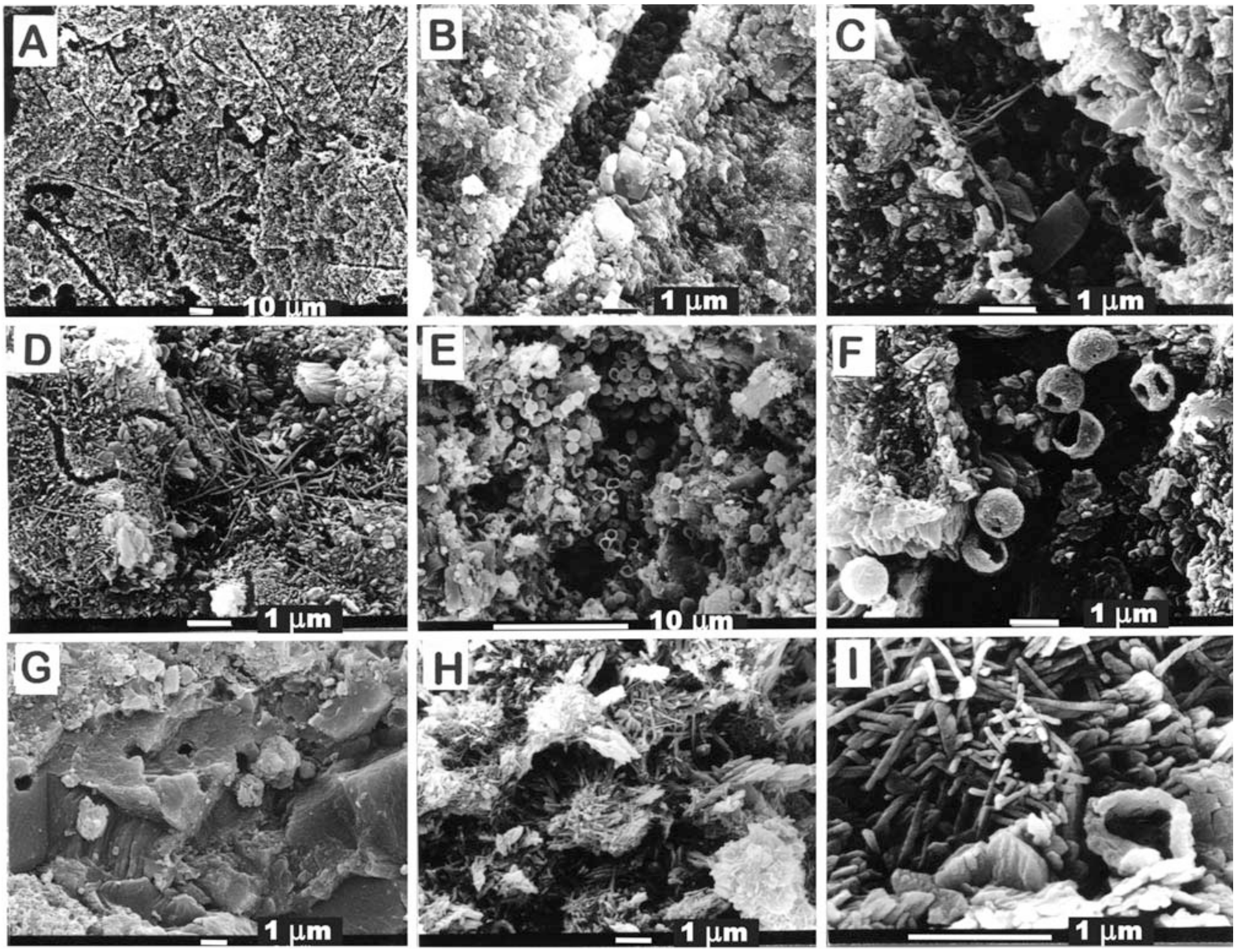

FIGURE 6 **SEM images. A) Microborings showing a very homogeneous distribution along the calcrete, in this case micritic microfabric. B) Straight microboring outlined by coarse calcite crystals. C) Microboring showing a partial infill of calcite needles and euhedra calcite crystals. D) Needle calcite crystals of different sizes they are associated with curved microborings. E) Spores occurring in the porosity of the alveolar septal structures. F) Detailed view of the spores, they tend to occur in groups. G) Spores in the coarser calcite crystals. H) Messes of needles giving places to the formation of irregular bodies of 1-2 µm size. I) Needles on organic structure either filaments or spores.**

description of the rootcretes) the laminar crusts acted as impermeable linings favoring rain water accumulation within the cavities and subsequent micrite precipitation.

When present, the pisolithic crusts indicate a change in the stability conditions of the cavities. They formed when fragments of the host-rock fell into the root cavities. These fragments can be coated by roots and associated microorganisms and thus the different microfabrics previously described can form on them.

The last phase of crust formation included filling of the cavities between the pisoliths or between the walls. Some of these cavities may have been formed when the roots were lost to decay. The characteristics of these fills suggest that the micrite may have been precipitated from water that was ponded in the cavities. So they were like very small lakes that when desiccated show the same features as palustrine limestones.

DISCUSSION

Rootcretes developed on dolostones in the Cayman Fm include components and microfabrics that are similar to laminar calcretes that are found in surficial conditions and classically considered as the “K” horizon of soils (Gile et al., 1965). The fact that the calcretes line the root cavities shows that such crusts can form in non-horizontal and shallow subsurface areas and are not necesssarily restricted to more or less flat subaerially exposed surfaces. Although rare, there are other examples of calcretes that penetrate bedrock obliquely (Calvet and Juliá, 1983) or almost vertically (Rossinsky et al., 1992). Most laminar crusts, however, are developed as hard horizons in soil profiles (Gile et al., 1966; Machette, 1985) and are associated with root activity (Esteban and Klappa, 1983; Wright et el., 1995; Alonso-Zarza, 1999). Verrecchia et al. (1995) have shown, however, that some types of laminar crust may form on the soil surface and in direct contact with the atmosphere with cyanobacteria being the dominant organisms involved, but bacteria can also play an important role. Algae and fungi are also known to contribute to the formation Holocene calcareous crusts (Kahle, 1977). The Cayman rootcretes are yet another example of the development of laminated crusts.

The arrangement of the microfabrics in the laminar crust shows that they developed through the interplay of many different processes that operated simultaneously or at different times. In the initial stages, dissolution and mechanical reworking produced cavities of variable morphology and provided a rooting area for plants and associated microorganisms. Once the root systems were established in the cavities, alveolar septal structures, peloids and microspar microfabrics formed. In the Cayman examples, calcification of roots rarely leads to the formation of calcified cells like those the described by Alonso-Zarza et al. (1998a) and Kosir (2004). The presence of micrite and micrite with bioclasts suggests that some of the cavities may have been periodically filled with water following periods of heavy rain. The last phase of crust formation is recorded in the red micritic and microsparitic fills of the cavities.

The varied and complex arrangement of fabrics in the Cayman rootcretes shows that their formation was controlled by complex processes that included mechanical breakdown of the bedrock, dissolution (chemical and biochemical), precipitation of calcite (in relation with root and microorganisms and also in ponded waters), and emplacement of reworked material. These processes are the same as those involved with the formation of thick calcrete profiles on more or less flat surfaces (Wright et al., 1995; Alonso-Zarza et al., 1998b). In the latter settings, calcrete crust formation requires relatively long periods of very low sedimentation rate and stable terrestrial landscapes. The presence of these thin rootcretes lining cavities is a clear evidence of exposure surfaces, even in the absence of any other features. This is important because the rootcretes may be preserved even in situations were most of the subaerial crusts and other surface indicators of exposure have been lost through erosion (Rossinsky et al., 1992). It is also interesting to consider that these rootcretes formed on a karstic surface that cover large areas of the Cayman Islands, so very probably the calcretes represent more arid conditions and are indicators that the dominant wetter climate conditions responsible for the karst formation were at times interrupted by short more arid periods.

CONCLUSIONS

Dissolution in relation to the initial stages of cavity formation and mechanical activity of roots and associated microorganisms entering the cavities are the main processes with which calcrete formation started. Both processes operated on a macro and micro scale as seen by the mechanical generation of fragments and dolomite crystals of different size, by the presence of cm-scale root haloes, and microorganisms in the host dolostones. Etched dolomite crystals are found in the host rock and in the initial calcrete laminae indicate dissolution processes linked to the activity of microorganisms (fungi or bacteria). These crystals were trapped and bound into the laminae crusts by root hairs and microbial filaments. These processes initiated rootcrete formation and favored the rooting of larger plants. Subsequent, trapping and binding processes and organically-induced precipitation of carbonate led to the formation of the accretionary (mostly laminar) part of the calcrete. In the last stages of crust formation the surficial cavities could be filled by rain waters that occupied the root cavities.

The formation of the calcretes took place in an unusual setting when compared with the "classical calcrete" profile (Gile et al., 1965, 1966; Machette, 1985), that usually develops on flat surfaces with morphological stable landscapes. The Cayman rootcretes formed in cavities and it is therefore difficult to treat them as the K horizon of a soil (Gile et al., 1965). Like the "classical" calcrete profile, these rootcretes have a weathering zone that reflects the breakdown and disgregation of the host dolostone. Unlike the classic calcrete, the Cayman rootcretes have (sub)vertical and laminae that follow the contours of the cavities that they line. These calcretes probably represent a relative short period of time when drier climatic conditions inhibited karstic development but encouraged development of thicker calcrete profiles.

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