

**PETROLOGY AND GEOCHEMISTRY OF RHIZOLITHS FROM
PLIO-PLEISTOCENE FLUVIAL AND
MARGINAL LACUSTRINE DEPOSITS,
EAST LAKE TURKANA, KENYA¹**

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ABSTRACT: Recent studies of rhizoliths from the Koobi Fora Formation (Plio-Pleistocene) of East Lake Turkana, Kenya, indicate that their shapes vary with the depositional environment of their host sediment. Vertical rhizoliths are associated with channel-bar and overbank deposits of fluvial origin. These rhizoliths represent the tap roots of phreatophytes that lived in well-drained, upland settings. Horizontal rhizoliths predominate in facies ascribed to beaches, lagoons, and floodplains associated with ancient Lake Turkana. They are produced by water-emergent aquatic macrophytes and coastal grasses that grow in saturated or poorly drained soil environments.

The rhizoliths consist of sparry and micritic calcite cements whose petrography and geochemistry reflect differences in diagenesis between the two types of root systems. The vertical roots contain little organic debris and have poorly developed meniscus and microstalactitic cements. These attributes reflect precipitation of the calcite in well-oxygenated, well-drained vadose conditions. In contrast, the cements of the horizontal root systems lack textures indicative of vadose conditions, contain abundant clay and plant debris, and display Mn concentrations as high as 4.5 cation percent. These features confirm that the horizontal rhizoliths developed in chemically reduced, water-saturated conditions. Bacterial decay of the plant debris maintained reduced Eh conditions while also supplying abundant Mn²⁺ to the pore solutions. Groundwater that had moved through volcanic strata may have also contributed Mn²⁺. The Mn may have been incorporated in the calcite cements through a combined process of chemisorption and ionic substitution of Mn²⁺ as well as by inclusion of manganese oxides.

INTRODUCTION

Rhizoliths, which are structures produced by the activity and decay of roots (terminology after Klappa 1980), have been used by numerous authors as indicators of terrestrial environments and, to some degree, ancient climatic regimes. Recent studies by Klappa (1980), Semeniuk and Meagher (1981), Cohen (1982), and others have demonstrated that careful evaluation of rhizolith morphology may help refine the analysis of ancient depositional environments. However, the usefulness of morphological studies is limited primarily to relatively young, unconsolidated sediments where rhizoliths are often exhumed by erosion of the loose, surrounding material. In older, well-lithified sediments, long periods of compaction and cementation

may obscure many of the original rhizolith features. Because of this, petrographic analyses may become important for paleoenvironmental reconstructions. Apart from the work of Calvet et al. (1975) and Klappa (1980), few studies document the petrographic variability of rhizoliths and how these differences can be used in facies interpretations.

In this paper we focus on the petrographic and geochemical characteristics of calcareous rhizoliths from the Koobi Fora Formation (Plio-Pleistocene) of East Africa. As originally described by Cohen (1982), these rhizoliths show distinctive morphologies that reflect different paleoenvironmental conditions during their formation (reviewed briefly here). This study expands on this earlier work and demonstrates that the carbonate material of the main morphological types contains unique textural and minor-element signatures. Presumably, these signatures also re-

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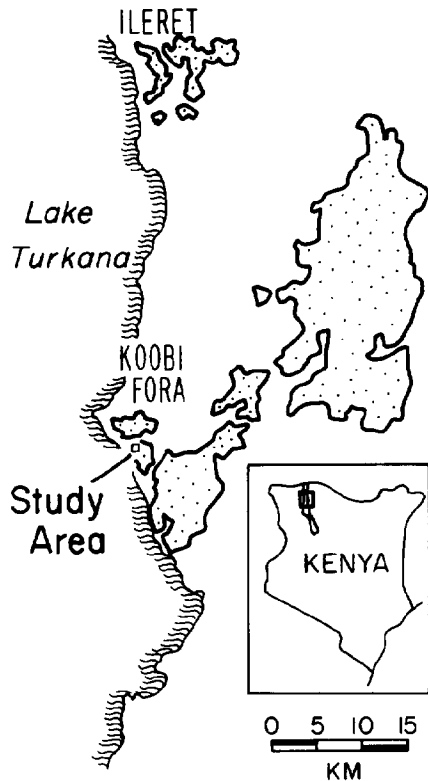


FIG. 1.—Outcrops of the Koobi Fora Formation, East Lake Turkana, Kenya (adapted from Vondra and Bowen 1978).

flect different paleoenvironmental or diagenetic conditions and may prove to be useful in future analyses of other rhizoliths.

STRATIGRAPHIC SETTING

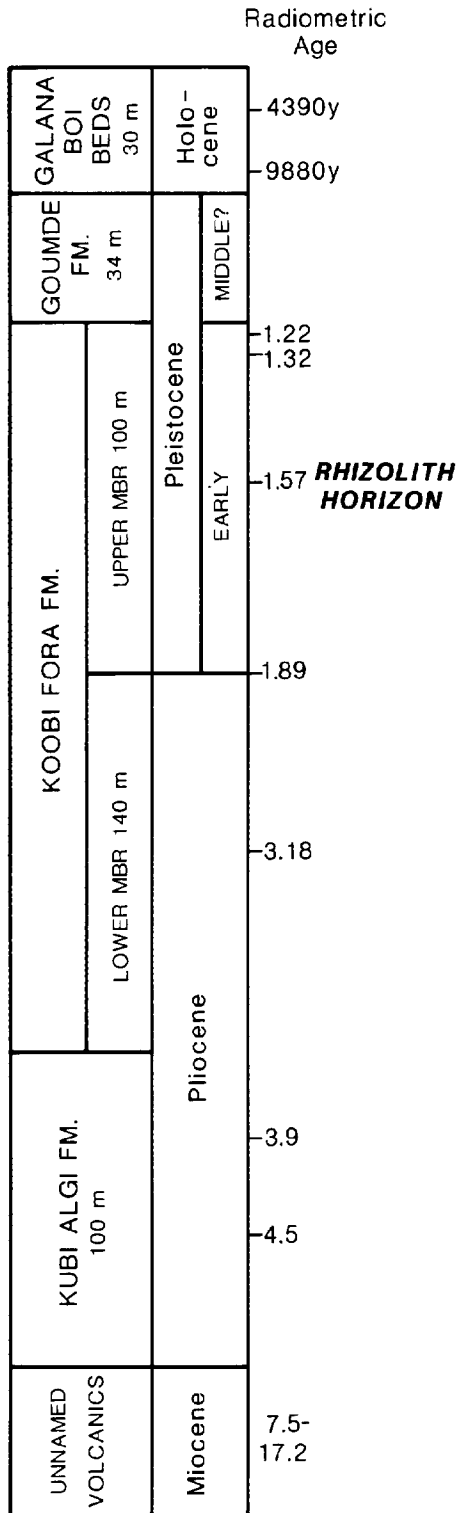
The Koobi Fora Formation crops out discontinuously along the northeast margin of Lake Turkana in northern Kenya (Fig. 1). The formation is part of a 350-m-thick sequence of Plio-Pleistocene sediments that were deposited in a northeastern extension of the Lake Turkana Basin. Widespread attention has been focused on the Koobi Fora Formation because of the important hominid fauna it has yielded (Leakey and Leakey 1978). Climatic fluctuations coupled with pulses in rift-basin tectonism have produced a complex interfingering of lithologies that reflect transgressive and regressive episodes of ancient Lake Turkana. In the northeast-

ernmost Lake Turkana Basin, fluvial and fluviodeltaic sediments interfinger toward the rift basin with marginal lacustrine and lacustrine sediments. Extensive, water-reworked ash units within these deposits allow correlation of isolated exposures (for a complete summary of the regional stratigraphy and depositional systems of the area see Findlater 1976, 1978, and Vondra and Bowen 1978).

The rhizoliths originally studied by Cohen (1982) occur within the middle portion of the Upper Member Koobi Fora Formation (Fig. 2). The member is punctuated at this horizon by a tuffaceous interval, termed the Koobi Fora Tuff Complex, to which Fitch and Miller (1976) have assigned an Ar/Ar age of 1.57 m. yr. Cohen (1982) reconstructed the depositional history of the complex in an area southeast of Koobi Fora (Area 103 of the Koobi Fora Research Project). He described four main lithofacies for the study area. The first consists of silty sand and sandy silt with abundant mammalian footprints and a poorly developed soil horizon. This facies is inferred to have been deposited on a delta plain under subaerial conditions. Overlying the delta-plain facies are tuffaceous sandy silt and cross-stratified sand with molluscan shell lags interpreted to reflect deposition on the shifting interface between delta and coastal-plain environments near the edge of the littoral zone. Laminated and ripple-laminated silts and sandy siltstones overlie the delta littoral margin facies. These units contain abundant concretions, mammal and fish fossils and burrows, as well as an oolitic-pisolitic/biscuit stromatolite bed. This facies is inferred to be a product of deposition in shallow, littoral-lagoonal to proximal, deltaic environments. The uppermost facies measured consists of channelized muddy gravels and sands. The facies represents a fluvial system composed of channel, channel bar, crevasse splay, and overbank depositional environments.

RHIZOLITHS

Through a series of forty 10-m transects, Cohen (1982) documented the stratigraphic distribution and morphological variability of the rhizoliths in the Koobi Fora Tuff Complex. The transects were measured in the channel-bar and overbank deposits of the fluvial facies and the mixed deposits of the shal-



low littoral-proximal deltaic facies. These two facies represent end members of the environmental spectrum in this area. Summarized in Table 1, five main rhizolith configurations were recorded (referred to as root casts by Cohen). All of the rhizoliths are composed of CaCO₃ that occurs as both rhizcretions (accumulations of carbonate around a root mold) and actual root casts (infilling of a root mold by cement and sediment) (after Klappa 1980). The five common morphologies were 1) horizontal, interwoven root mats; 2) horizontal, discrete roots; 3) vertical, discrete roots; 4) diagonal, discrete roots; and 5) root balls.

The different root morphologies of the Koobi Fora Formation were found to vary systematically with their stratigraphic location. Two principal root systems could be separated. The first, the horizontal root system, is composed of the horizontal root mats and horizontal, discrete roots. These root systems occurred in abundance in the shallow, littoral to proximal, deltaic deposits. The second, the vertical root system, consists of both the vertical and diagonal roots. These types occurred commonly in the fluvial deposits. Root balls, which were probably a product of later stage concretionary formation, were not environment-specific.

Actualistic comparisons between modern plant roots of the Koobi Fora area and their fossilized counterparts indicate that the environmental association of the two main root systems is primarily controlled by water availability. In the semiarid climate of East Turkana, plants growing along ephemeral water courses and on floodplains receive an irregular, intermittent water supply during a short rainy season. Plants in this type of environment develop deep, vertical tap roots to exploit perched aquifers or deeper phreatic water sources. In contrast, plants that occur in coastal plains and reed swamps along the lake margin grow in soils that are water-saturated most of the time. Roots of plants in this type of environment tend to form horizontal mats with little deeper penetration. Therefore, by comparison with modern root

FIG. 2.—Generalized stratigraphy of the East Lake Turkana Basin and the stratigraphic position of rhizoliths (from Cohen 1982).

TABLE 1.

Rhizolith Morphology	Description	Facies Association
Horizontal root mats	Interwoven root casts (each less than 5 mm) lying within a larger rhizocretionary root mat. Mats form laterally continuous beds.	Shallow, littoral-proximal deltaic facies: reflect root mats of aquatic macrophytes and coastal grasses.
Horizontal, discrete roots	Irregular, horizontal to subhorizontal root casts and rhizocretions, less than 2 cm in diameter.	Same association as horizontal root mats.
Vertical, discrete roots	Straight, vertical rhizocretions and root casts that reach diameters as large as 10 cm.	Channel-bar and overbank deposits of fluvial environments; reflect deep tap roots of phreatophytes in well-drained, upland settings.
Diagonal, discrete roots	Straight, diagonal rhizocretions and root casts dipping from approximately 15–75°. Occur primarily at points of bifurcation of vertical roots.	Same as vertical roots.
Root ball	Irregular, globular rhizocretions encasing vertical and horizontal roots.	No unique facies association; probably a later-stage diagenetic feature.

systems, the two main rhizolith systems of the Koobi Fora Formation were inferred by Cohen to reflect paleogroundwater conditions: the vertical root systems being produced by phreatophytes in well-drained, upland environments, and the horizontal root systems being a product of coastal grasses and aquatic macrophytes in saturated, marginal lacustrine environments.

PETROGRAPHY AND GEOCHEMISTRY

As Cohen (1982) has shown, the shapes of rhizoliths depend strongly on paleogroundwater conditions. The rhizocretions and root tubules that form around modern roots are commonly seen forming while the root is alive (Klappa 1980; Semeniuk and Meagher 1981). If this was the case for the Koobi Fora root systems, then the textures and chemistries of the carbonates that form the rhizoliths should also reflect the contrasting groundwater conditions. We attempted to test this hypothesis by studying the carbonate cements in thin section and under the electron microprobe.

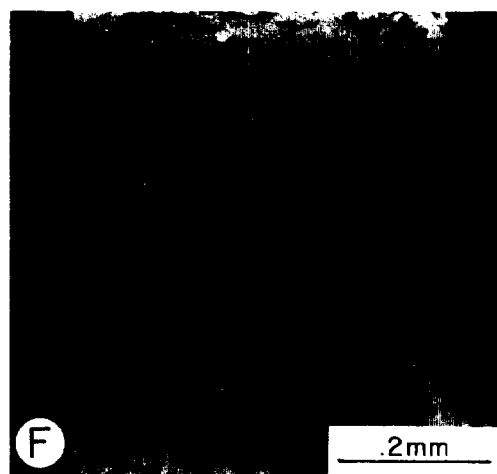
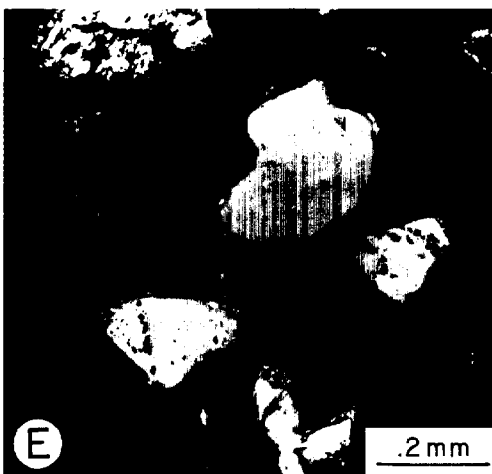
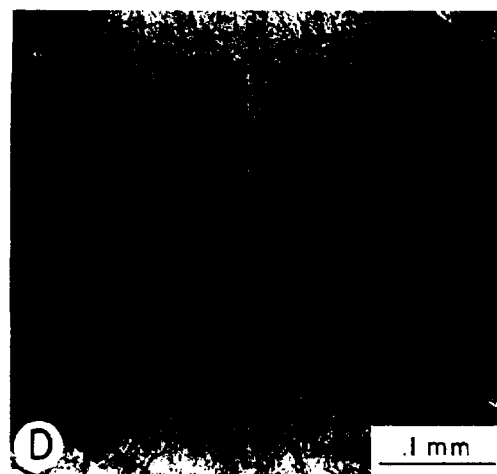
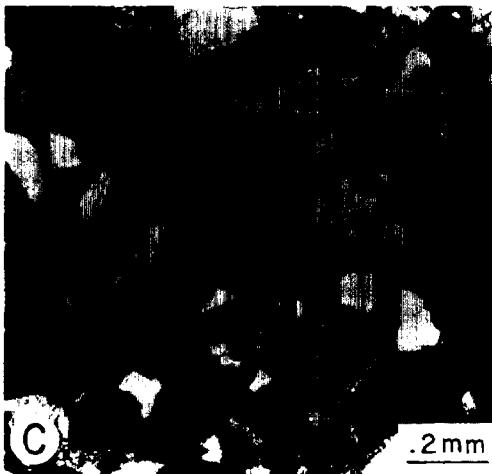
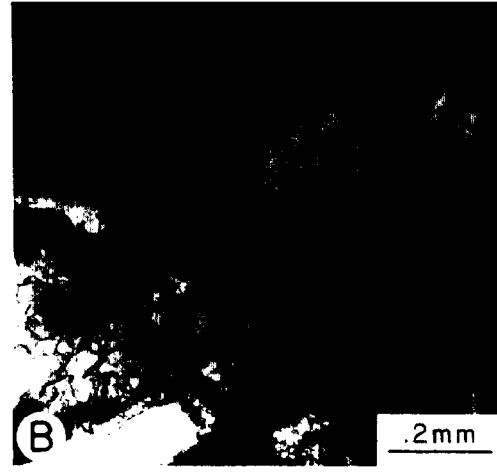
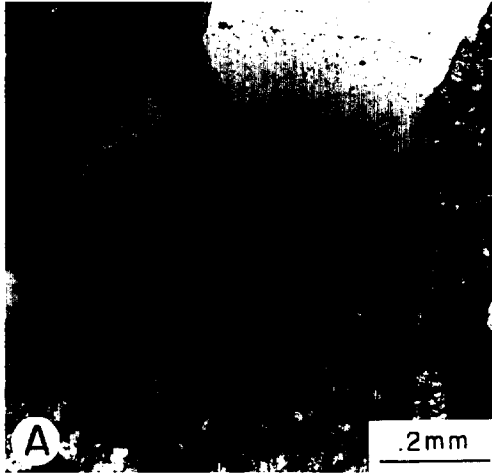
Petrographic Contrasts

The two main rhizolith systems, the vertical root system and the horizontal root system, are composed primarily of micritic and sparry calcite-cemented lithic sands. Little to no relict root material remains. As noted earlier, the carbonate cements usually occur as rhizocretions and root tubules, but also as root casts (infilling of root molds). The two kinds of root systems contrast principally in the distribution of cements and in how they reflect paleodrainage of the soils.

Vertical root system.—This root system forms resistant calcareous rhizoliths which cement medium-grained lithic sands. The volume of carbonate cement that makes up the rhizolith commonly exceeds the original root volume. This records the extent of the area immediately surrounding a root that is affected by life and decay processes.

Three principal cement phases have been documented in the vertical root systems. The first stage is recognized by the development of isopachous rim cements of sparry calcite

FIG. 3.—Photomicrographs of vertical rhizoliths. A) Initial phase of cementation in vertical root system. Shows cements with weakly developed microstalactitic texture. The principal growth direction of these asymmetric cements is consistent within individual samples and is a type of geopetal indicator. Second phase of cementation is micritic material. B) Root sheath of initial phase of cementation. Root sheath has geopetal infill of micrite (second phase) and void-filling spar (third phase). C) Micrite cement that forms the bulk of the rhizocretion. Note two generations of micrite, light (root-infilling) and dark (pore-filling). D) Spar-filled root mold formed after complete decay of rhizome system. E, F) Isolated occurrences of meniscuslike spar cements. Note that cements form discontinuous patches of spar that bridge pore spaces. Cements appear to be superimposed upon early-phase isopachous cements.



on the primary silicate grains. The cements are commonly uniform and fibrous and are a product of noncompetitive growth into open pore spaces. Thin sections cut longitudinally to the rhizolith axis reveal that some of these initial cements have textures that resemble meniscus and microstalactitic phases (Fig. 3a, e, f). Although weakly developed, these textures suggest that early cementation may have involved precipitation in the vadose zone.

Associated with the early cements is the formation of root sheaths or root tubules (Klappa 1980). Shown in Figure 3b, these sheaths are composed of concentric layers of micrite. The sheaths are often filled with sparry calcite and, as in the example shown in Figure 3b, with geopetal infills of micrite. Root tubules or sheaths commonly form around living as well as decaying roots. The formation of the sheath is poorly understood (Klappa 1980) but may involve complex interactions involving microorganisms (bacteria, fungi, blue-green algae), organic acids associated with living and decaying roots, and evapotranspirative uptake and concentration of pellicular water (Johnson 1967; Calvet et al. 1975; Klappa 1980).

The second generation of cementation involved the precipitation of micrite. The micrite occurs as a pore filling that forms the bulk of the rhizcretion (Fig. 3a, b, c, f). The widespread precipitation of the micrite may be associated with both the life and death processes of the rhizome system. Figure 3c shows that the micrite forms multiple phases consisting of light- and dark-colored patches. The darker micrite with floating and point-contacted silicate grains represents precipitation around the rhizome. Its darker color is due to incorporation of pedogenic clays. The lighter-colored, patchy micrite with few silicate grains reflects the original position of an earlier rootlet. After the rootlet's death, the lighter-colored micrite (fewer pedogenic clays) infilled or precipitated in the original void of the root.

As with the root tubules, or sheaths, the origin of the pore-filling micrite is not well understood. As Semeniuk and Meagher (1981) have pointed out, the vertical-tap root systems of phreatophytes can act as a major conduit for water within the vadose zone. These roots, while living, not only draw pel-

licular water out from the surrounding sediment, but draw water upward from the phreatic zone. Moreover, after the death of the root, the void left behind by its decay can act as a conduit for meteoric water. Thus, the area surrounding the root is constantly supplied with water that, under the evaporative influences of the vadose zone, can lead to the isolated precipitation of micrite. Why micrite and not spar is precipitated on this phase is also not clear. This may simply be a product of more rapid rates of precipitation associated with the progressive die-back of the rhizome system (releasing of proteins and sugars and raising the pH). The preservation of the original sparry calcite cements indicates that this is not due to "rhizomicritization" (Klappa 1980) of an earlier cement phase.

The final phase of cementation is associated with the complete decay of the rhizome system. This phase is recognized by the irregular, vermiform patches of spar and the spar-filled root tubules that produce an alveolar texture. As shown in the sheathed root in Figure 3b, this phase involved precipitation within the root tubule after complete removal of the original root. In addition, the presence of the micrite geopetal infills suggest that the spar precipitation postdates the principal phase of micrite formation. The un-sheathed root molds also contain cement textures that indicate a period of spar precipitation following the decay of the rhizome (Fig. 3d). Although the contact between the spar and the surrounding micrite is diffuse, the spar does show an increase in crystal size from the margins to the center of the mold and an abundance of enfacial junctions (Bathurst 1975). This indicates that cementation (rather than aggrading neomorphism of the micrite) filled a void that was formed from the complete removal of the root.

As noted previously, the postmortem root voids can act as a conduit for meteoric waters. The relative impermeability of the surrounding micrite would inhibit the diffusion of water away from the root void, allowing complete saturation and eventual void-filling precipitation of calcite.

Horizontal root systems.—This root system forms less erosionally resistant calcareous

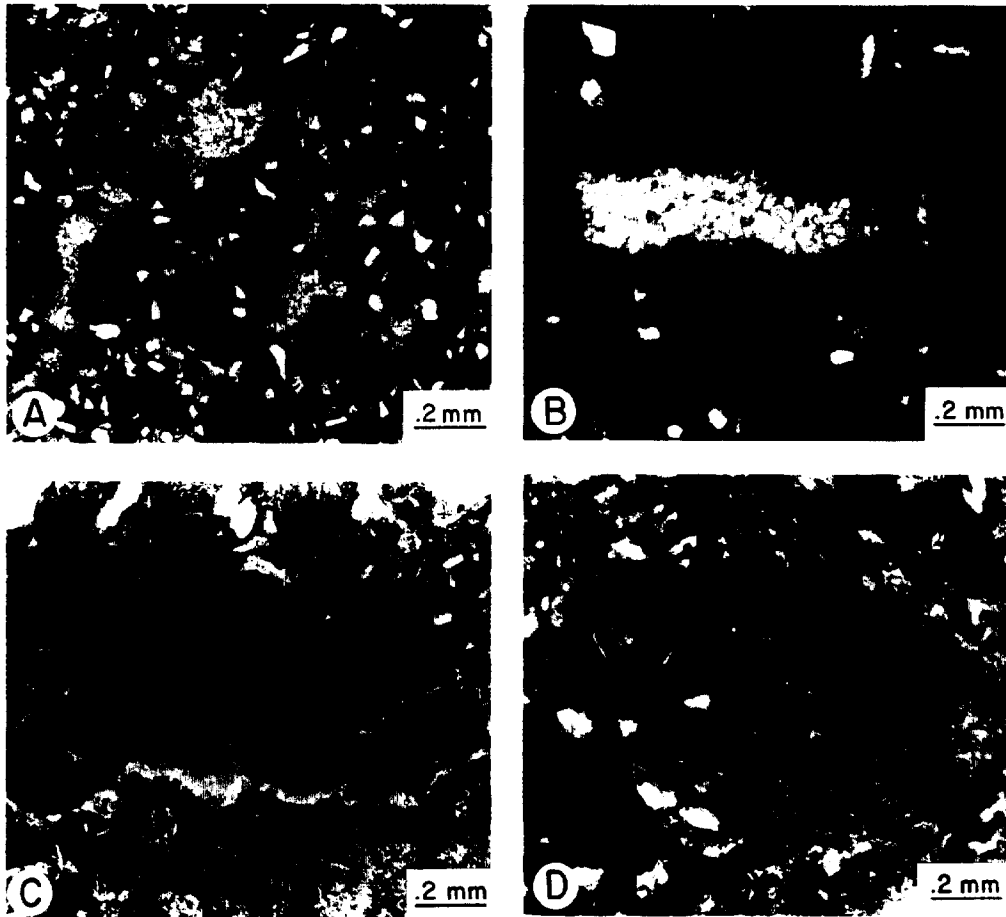


FIG. 4.—Photomicrographs of horizontal rhizoliths. A) Example of micritic cement with later, root mold-filling spar cement. B) Micrite-sheathed root mold with spar infilling. Note abundant manganese oxides. C) Pedogenic clays within micritic cement of rhizolith. D) Manganese oxides infilling a root tubule. Note the concentration of the manganese oxides around the margins of the root sheath.

rhizoliths than usually occur in silts and silty sands. As with the vertical root system, these rhizoliths also cement a larger volume than the original root. In thin section, the horizontal root system consists of a clotted, locally peloidal micrite that cements and etches various silicate grains. Discontinuous, irregular patches of spar occur throughout the rhizolith, giving portions of it an alveolar texture (Fig. 4a).

With the exception of the weakly developed meniscus and microstalactitic cements and isopachous rim cements, the horizontal root system textures are very similar to those of the vertical root system. Specifically, both

types of rhizoliths are dominated by micritic, pore-filling cements. In addition, both sheathed and unsheathed root molds occur that are filled with sparry calcite (Fig. 4b). As with the vertical root system, the micritic material is interpreted to be a feature that is precipitated under the influences of the life-and-decay processes of the rhizome. The mold-filling spar is produced after the root has decayed completely, leaving a sheathed or unsheathed void.

Several petrographic features are unique to the horizontal root systems. The micritic cement of these rhizoliths contains abundant argillaceous material. Isolated patches of clay-

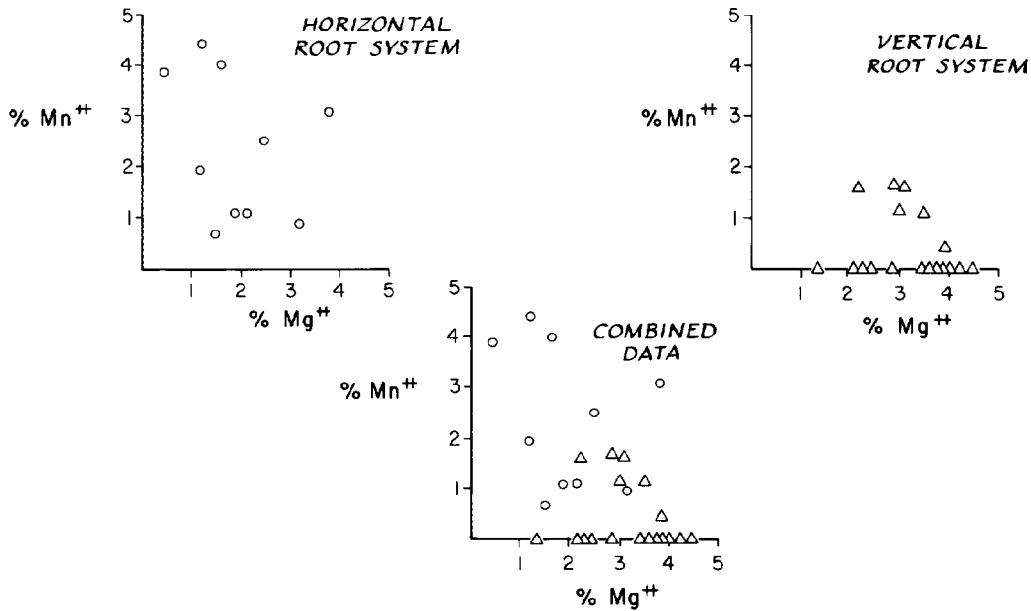


FIG. 5.—Mg²⁺ and Mn²⁺ cation percentages within the calcite cements of the rhizoliths. Data obtained from microprobe analysis. Combined data is plotted to illustrate overlap between two types of root systems.

rich material also occur within the micrite (Fig. 6c), resembling the texture of soils. In addition, abundant plant debris, fish bones, and occasional mollusk shells occur within the micritic cements.

Although present in both types of root systems, discontinuous, pore-filling, opaque minerals are particularly abundant in the horizontal roots (Fig. 4b). They are universally manganese-rich, and are similar to the manganese oxides commonly found in alkaline soils. In addition, these deposits are often concentrated around root tubules (Fig. 4d) and in rare cases infill root molds. The manganese oxides appear to have been coprecipitated with the micrite material. The concentration of Mn in these rhizomes becomes an important distinction between the two types of root systems. The origin of the Mn is probably associated with the decay of the root system and other organic material (next section).

In summary, the horizontal root systems differ petrographically from the vertical system in four principal ways. These are 1) lack of indicators of vadose conditions; 2) the presence of abundant argillaceous, pedogenic

textures; 3) abundant organic debris, especially plant fragments; and 4) significant volumes of manganese oxides. We believe these textures confirm the suggestion of Cohen (1982) that the horizontal root systems developed within or marginal to a saturated, shallow phreatic zone.

Geochemical Contrasts

The previously described carbonate cements were analyzed using an ARL/EMX-SM electron microprobe with a KEVEX EDS system. Spectra were collected for 200 seconds using an accelerating voltage of 15 KEV, a 300nA beam current and a 15-micrometer beam diameter. Background-corrected peak intensities were analyzed using MAGIC V and compared with University of California, Davis, standards. Reported analyses are thought to be accurate within $\pm 3-5\%$ of the amount given.

The rhizolith cements consist entirely of calcite. However, Mn and Mg were found to be common, minor elements with each reaching values as high as 4.5 cation percent. The Mn and Mg contents also seem to be closely related to the type of root system sam-

pled. The horizontal root system cements (Fig. 5) contain highly variable concentrations of Mn and Mg, with neither element exceeding 4.5 cation percent and, more importantly, never falling much below one percent. In contrast, the vertical root system has much lower average concentrations of Mn within its cements. Mn contents are commonly below the levels of detectability with the technique used. No systematic variations in Mn and Mg content were recognized for the different cement phases within an individual root system.

Origin of Mn-rich calcites.—Manganese is a transition element capable of multiple valency. The sensitivity of Mn solubilities and valence states to Eh/pH fluctuations makes the element useful for documenting the differences in the solution chemistries that led to rhizolith development.

Manganese is a commonly reported trace element in marine carbonates. Theoretically, Mn can substitute up to 40% by weight in the calcite structure (Berry and Mason 1959). However, most reported Mn contents range from several hundred to several thousand ppm (Pingitore 1978). Our Mn values given for the Koobi Fora rhizoliths are much higher than those commonly published in the literature. This suggests that two problems need to be answered in understanding the differences within the root system chemistries. These are 1) defining a source and environmental conditions for the high Mn activities, and 2) describing the geochemical processes responsible for the incorporation of high levels of Mn in calcite.

Source and transport of Mn^{2+} .—The solubility of Mn within natural waters is dependent upon its oxidation state and the roles of complexing with other ions or organic matter (Hem 1963; Stumm and Morgan 1970). At low Eh and pH conditions, Mn will exist in a divalent state with correspondingly high solubilities. With an increase in Eh, rapid oxidation and precipitation remove Mn from potential reactions. Increases in pH above approximately 8.5 cause intermediate manganese complexes to form in which Mn^{2+} is adsorbed on manganese oxides. These complexes react rapidly and precipitate as $MnCO_3$, MnS , and $Mn(OH)_2$ (Hem 1963).

Organic and inorganic complexes greatly affect the solubility of Mn^{2+} . High sulfate and

bicarbonate activities can act to slow oxidation reactions by the formation of soluble complexes with Mn^{2+} (Hem 1963). In addition, organic ligands commonly form complexes with Mn that also raise solubilities. The presence of organic matter is also important because tannins (digallic acids), which are commonly released by plants, are capable of maintaining manganese in the Mn^{2+} state (Hem 1964). This is accomplished primarily by a lowering of the pH of the surrounding solutions. Moreover, Mn is strongly controlled by the breakdown of organic material. During anaerobic decay of plant material, Mn that was concentrated intracellularly in plants is released in the Mn^{2+} state. In organic-rich lacustrine sediments, this process can lead to a 100-fold concentration of Mn^{2+} over that found in surrounding lake waters (Hem 1964, 1965). This same process is also important in alkaline soils.

The horizontal root systems of the marginal lacustrine environment form an ideal setting for the concentration of Mn^{2+} during rhizolith formation. Abundant plant debris was noted in the thin-section study. Breakdown of this organic material would have acted to supply Mn^{2+} as well as maintain it in its reduced state by lowering Eh and pH in pore waters. Cohen (1982) noted that coastal grasses and water-emergent aquatic macrophytes were primarily responsible for the horizontal root systems. According to Oborn (1964), the aquatic macrophytes, in general, contain much more intracellular Mn than land plants, adding to the concentration of Mn in this environment. In addition, the presence of abundant organic material will generate organic ligand complexes with Mn, slowing oxidation rates and enhancing the concentration of Mn^{2+} . Finally, the life cycle of the root, which controls rhizolith precipitation, also would contribute to Mn^{2+} concentration. The decay of an individual root would release Mn^{2+} , lower the Eh in the area surrounding the root and form abundant organic ligands for complexing. The presence of manganese oxides surrounding root tubules and, in some cases, infilling root molds partially reflects this (Fig. 4c).

Additional sources of Mn^{2+} include the lake waters and groundwaters that constantly influence the forming rhizoliths. Although Mn^{2+} levels can become high in stratified lakes due

to anoxic bottom waters, the surface waters are usually low in Mn^{2+} due to aeration. This is true for most of the present East African Lakes (Talling and Talling 1965). Groundwater, however, can be a major supplier of reduced Mn^{2+} . In his study of travertine deposits, Ichikuni (1973) found that they commonly had high levels of Mn incorporation in the calcites. In most cases the groundwater supplying the travertines contained high levels of Mn^{2+} due to passage through a volcanic aquifer. H_2S , if present, acts as a reducing agent that retards oxidation of Mn^{2+} in these waters. The sediments of the East Turkana Basin are interstratified with and rest on top of widespread volcanic formations. The groundwater systems that surface near the lake margin pass through large volumes of volcanic material that may be an important source of Mn^{2+} .

As a side note, groundwater may also play an important role in supplying Ca^{2+} for the precipitation of the horizontal rhizolith cements. Cohen (1982) has noted that in present day Lake Turkana the concentration of Ca^{2+} is exceptionally low. The reason for this is that the high pH of the lake has led to very high carbonate and bicarbonate activities, causing most free Ca^{2+} to be precipitated immediately. The mixing zone where phreatic fresh water meets alkaline lake waters may be ideal for the rapid precipitation of rhizolith cements. This mixing zone occurs in the general proximity of the horizontal root systems. In addition, the groundwaters and carbonate precipitation may act to buffer alkaline lake waters, reducing the rate at which Mn^{2+} is oxidized.

Chemistry of precipitation.—Figure 6a,b shows photomicrographs of carbonate cements that fill a root void. The cements display oscillatory zoning that is caused by variations in concentration of Mn within the calcite. The darkest portions of the zone have Mn cation percentages as high as 4.5. This may reflect a variety of chemical processes that include simple ionic substitution of Mn for Ca, chemisorption, or the inclusion of separate-phase manganese oxides as crystal inclusions.

It should be noted that calcite tends to act as a Mn^{2+} sink during both precipitation and recrystallization. Partitioning coefficients

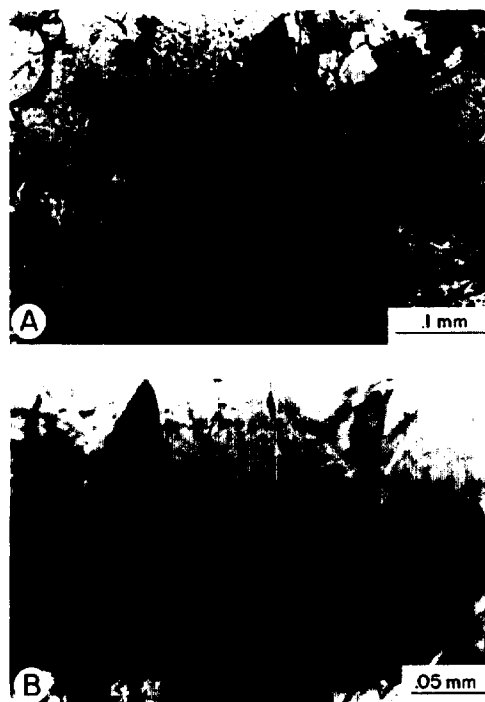


FIG. 6.—Photomicrographs of oscillatory zoning in calcite crystals in the horizontal root system. The darkened portions of the zones are due to chemisorption and/or ionic substitution of Mn. Note the asymmetry of the zonations.

calculated for this system are variable, but Pingitore (1978) suggests that the figure of 15 calculated by Bodine et al. (1965) is a good estimate. This figure reflects a strong preference of Mn^{2+} for the calcite structure. Thus, although Mn^{2+} activities will ultimately control the amount of Mn^{2+} incorporated within the calcite, there is a tendency for Mn enrichment of the crystal relative to the surrounding fluid. It is unlikely that the oscillatory zoning of the calcite crystals is simply a product of Mn^{2+} partitioning during calcite precipitation. The asymmetry of the oscillations suggests progressive enrichment in the calcite crystal during each crystallization episode. This is the opposite of what would be expected if this were a closed geochemical system (an unlikely occurrence in shallowly buried, marginal lacustrine sediments) where the Mn^{2+}/Ca^{2+} ratio of the fluid would decrease steadily during precipitation, leading

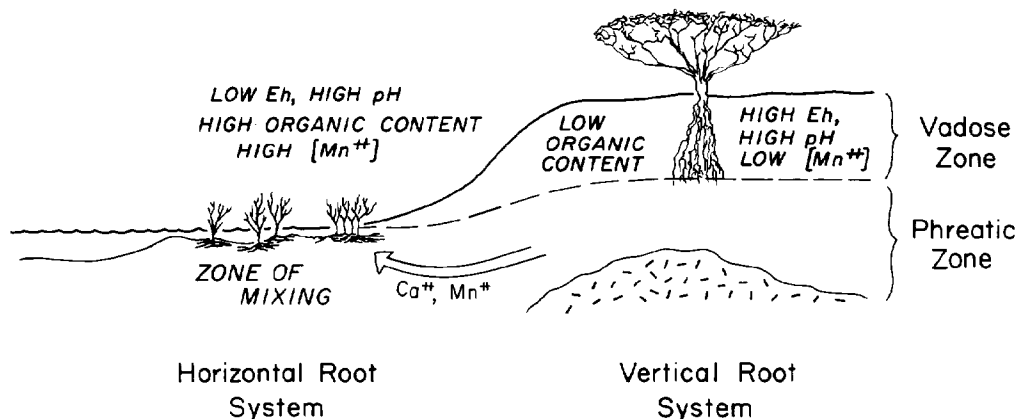


FIG. 7.—Generalized and schematic model for the petrographic and geochemical differences between the vertical and horizontal root systems.

to a decrease in the amount of Mn^{2+} incorporated in the crystals through time.

The incorporation of the Mn^{2+} in the calcite may be more complicated than a simple ionic substitution of Mn^{2+} for Ca^{2+} . Soil research has shown that Mn^{2+} is readily adsorbed by $CaCO_3$ and $MgCO_3$ (Boischot et al. 1950). Through a series of experiments, McBride (1979) demonstrated that the process of chemisorption is one of the principal controls on the distribution of Mn within calcareous soils. His research showed that apparent stoichiometric ionic displacement of Ca^{2+} by Mn^{2+} takes place at the surface of the calcite crystal. This does not involve direct replacement, however, but a process that includes adsorption of Mn^{2+} through the formation of $MnCO_3$ at the calcite surface. This releases a proton which reacts with the calcite to release a Ca^{2+} ion. This is apparently a rapid process which may significantly affect equilibrium conditions during calcite formation.

As noted previously, the maximum values of Mn within the calcite cements occur within the dark, cloudy crystal terminations. The darker color suggests that the Mn may be occurring within the crystal in the oxidized state. Therefore, the progressive enrichment associated with the darker color at the crystal rim may reflect an increase in the amount of manganese oxide inclusions (examination of these samples with SEM and energy dispersive X-ray element mapping did not provide conclusive evidence that a separate-phase

manganese oxide occurs within the darker zones; however, it did not rule out the possibility that the oxides are present but too small to discriminate with the SEM).

There is no direct evidence in the crystals (such as those shown in Fig. 6) for any single process that dominated the formation of manganese-rich calcite cements. All that the oscillatory zoning conclusively shows is that the supply of Mn and its activities (and solubilities) fluctuated within the pore solutions that affected the rhizoliths. Indeed, multiple processes may have led to the formation of this zoning. For example, the clear crystal cores probably reflect incorporation of Mn^{2+} in the calcite cements through ionic substitution or chemisorption (the clarity being due primarily to the occurrence of Mn^{2+} within the crystal lattice). If either the Eh or pH rose, oxidation of the solution Mn^{2+} would have caused rapid precipitation of the less soluble manganese oxides. Where coprecipitated with the sparry calcite cements, the manganese oxides may have been incorporated as discrete crystal impurities, raising the Mn concentration to very high values. The gradational and sharp transitions between clear and cloudy portions of individual crystals presumably reflect differing rates of change in the solution chemistries. These variable changes could occur during an influx of high-Eh meteoric waters, an influx of alkaline lake waters, or through seasonal desiccation of the root zone.

In summary, the geochemical difference between the two types of root systems is most

strongly recorded in the amount of Mn incorporated in the calcite cements. The high Mn content of the horizontal root system cements is a product of unique geochemical conditions and abundant Mn supply. Specifically, the horizontal rhizoliths formed under the influence of low Eh, Mn-rich fluids associated with the breakdown of abundant plant debris, and, possibly, a groundwater supply of Mn^{2+} . The vertical root systems have low values of Mn in their cements. This reflects the better oxygenated, organic-poor, diagenetic conditions of an upland vadose environment.

SUMMARY

A general model for the development of the different root system characteristics is presented in Figure 7. The vertical root systems contain five distinctive features in their cements: 1) rare microstalactitic and meniscus cements, 2) isopachous rim cements around silicate grains, 3) low organic content, 4) low Mn^{2+} substitutions in calcite, and 5) low manganese oxide content.

Cohen (1982) suggested that the vertical root systems were formed by the tap roots of phreatophytes. The petrographic/geochemical data confirm this suggestion by indicating cementation in the well-drained, well-oxygenated conditions of the vadose zone. In contrast, the horizontal root systems differ in the following ways: 1) abundant organic material, 2) high Mn^{2+} content of the cements, and 3) high manganese oxide content.

The horizontal roots were inferred by Cohen (1982) to be a product of root development in or near a shallow water table or in marginal lacustrine environments. The textures and compositions of these rhizoliths suggest that they formed in an organic-rich, saturated soil or sediment environment. In this setting, Mn^{2+} was supplied by groundwaters (which also supplied Ca^{2+}) as well as by the breakdown of plant debris. High Mn^{2+} activities were enhanced by the low Eh conditions of this environment. Mn incorporation in calcite cements may have taken place through a combined process of chemisorption and ionic substitution of Mn^{2+} for Ca^{2+} and incorporation of manganese oxides as crystal impurities. Rates of Mn precipitation

were controlled by fluctuations in pH, Mn^{2+} supply, or the decay of the rhizome system.

The results of this study suggest that the petrographic and geochemical characteristics of rhizoliths may be useful in refining paleoenvironmental interpretations. The broader application of this technique awaits further testing both in ancient rhizoliths and in those forming today.

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