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Rhizoliths in ancient eolianites

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Abstract

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Rhizoliths are abundant within Permo-Pennsylvanian eolian rocks of southeastern Utah. They are also present at the tops of several eolian sand bodies within the Pennsylvanian Fountain Formation of southeastern Wyoming and at a single stratigraphic level within the Jurassic Navajo Sandstone of southeastern Utah. Ranging in diameter from less than 1 mm to 15 cm, these cylindrical structures are composed of siliciclastic-free micrite and calcite spar. Cylinders ramify throughout the uppermost 2–3 m of thin, flat-topped sand bodies. Large cylinders are compound rhizoliths and display alveolar fabric, a feature resulting from rootlet calcification that is characteristic of modern and ancient calcretes. Development of rhizoliths required flat, geomorphically stable substrates for plant growth, highly permeable surficial sediments, and sources of calcium ions. The restriction of rhizoliths to planar deflation surfaces suggests that plants were unable to colonize or stabilize eolian bedforms. Paleozoic rhizoliths appear to be restricted to coastal areas with onshore winds. Associated evaporites suggest an arid to semi-arid paleoclimate. Rhizoliths formed when carbonate allochems derived from an upwind epeiric sea were dissolved and calcite reprecipitated around plant roots. Quaternary rhizoliths are best developed in similar sedimentologic and geographic settings. The abundance of rhizoliths and carbonate allochems in Quaternary and late Paleozoic low-latitude coastal dunes suggests that they are genetically related to glacio-eustatic sea-level fluctuations.

Introduction

Wind is the dominant agent of sediment entrainment only in environments where uncohesive sediment is available and vegetative cover is incomplete. The high density of vascular plants in modern terrestrial environments restricts the eolian domain to shorelines, deserts and periglacial settings. Land plants evolved during the Silurian. What does the post-Silurian stratigraphic record reveal concerning the interaction of plants and eolian processes through time? Stems, foliage, and reproductive parts of plants growing in eolian sand are rarely fossilized in situ; most organic remains are rapidly decomposed after burial in these permeable, thoroughly oxidized sediments. Rhizoliths, organosedimentary structures produced by plant roots, are, however, abundant in Quaternary eolian sands (Klappa, 1980). Within permeable host sediments and regions with a negative water balance, calcification can apparently keep pace with decomposition. Because they are composed of low-Mg calcite and are generated within pre-existing sediments, these structures have excellent preservation potential (Klappa, 1980). Large, abundant rhizoliths are characteristic features of calcareous dune sands of Quaternary age. The texture, composition and climatic setting of calcareous dune sands provide optimal conditions for the development of rhizoliths.

In southeastern Utah, rhizoliths are abundant in a thick sequence of Permo-Pennsylvanian eolian strata and at a single stratigraphic level within the

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Navajo Sandstone. In southeastern Wyoming, rhizoliths of Pennsylvanian age are present in a thin zone of interbedded sandstones and conglomerates near the contact between the fluvial Fountain Formation and eolian sandstone of the Casper Formation. All of these rhizoliths are preserved below planar erosional or deposition surfaces. Although their roots deeply penetrated eolian sand, these plants were apparently incapable of colonizing active bedforms.

Unlike several other kinds of root traces, the calcitic rhizoliths reported here can be easily distinguished from burrows and non-biogenic concretions. The distinctive form and fabric of these structures has remained virtually unchanged since the Middle Pennsylvanian.

The goals of this paper are: (1) to document the form, fabric, and sedimentologic setting of Late Paleozoic and Early Mesozoic rhizoliths in eolianites of the western United States; and (2) to show that the distribution of rhizoliths within ancient eolianites provides important information concerning paleogeography, paleoclimate, and plant paleoecology.

Stratigraphic and sedimentologic setting

On the Monument Upwarp of southeastern Utah, rhizoliths are abundant in eolian rocks ranging in age from Middle Pennsylvanian (Desmoinesian) through Early Permian (Wolfcampian). In the Hermosa and Rico Formations (Fig. 1), thin, flat-topped eolian sand bodies containing rhizoliths are separated by marine carbonates. The overlying Cedar Mesa Sandstone is a stack of thin eolian sand bodies separated by extensive planar erosion surfaces. Like the flat upper surfaces of the sand bodies of the Hermosa and Rico formations, these erosion planes are interpreted to have formed when sand seas were deflated to the level of the groundwater table (Stokes, 1968; Loope, 1985). Rhizoliths are abundant in rocks directly beneath these deflation surfaces. The eolian interpretation of the sandstones is based on the presence of climbing translatent stratification formed by climbing wind ripples (Hunter, 1977) within the large-scale cross-strata (Loope, 1984).

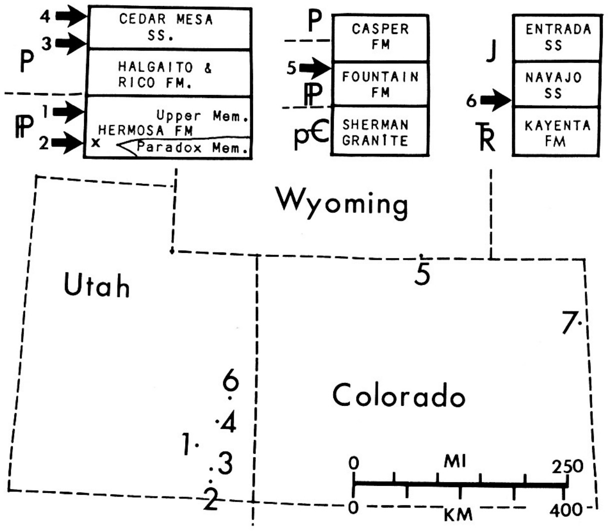

Fig. 1. Stratigraphic position and geographic location of rhizoliths discussed in text. Locality *7* is within the Miocene Ogallala Formation.

The most abundant and best preserved rhizoliths found during seven years of field work in southern Utah are within the upper member of the Hermosa Formation (terminology of Hite and Buckner, 1981); they are best exposed and most accessible on the floor of Dark Canyon, a deep gorge which meets the Colorado River near the head of Lake Powell (Fig. 1, loc. 1). Rhizolith-bearing calcarenaceous sandstones (Fig. 2E) and quartzose calcarenites of eolian origin (Loope and Haverland, this volume) have sharp contacts with underlying and overlying marine carbonates (Fig. 2A and B). Rhizoliths (Figs. 2C, D and 3) occur below the planar erosional surfaces that are present within some eolian units as well as at the tops of the most of these units.

The oldest rhizolith-bearing eolianite located during this study is within a Desmoinesian (Middle Pennsylvanian) sequence exposed along the canyon of the San Juan River (Fig. 1, loc. 2). This 1.5 m-thick calcarenaceous quartz sandstone, and the shelf carbonates that enclose it, are correlative with halite deposits at the center of the Paradox Basin. This thin sandstone and underlying algal carbonate rocks were deposited during eustatic lowstand when reflux of basin brines was minimal (Hite, 1970). The sandstone is part of the stratigraphic interval studied in great detail by Pray and Wray (1963, their unit A-10), who recognized

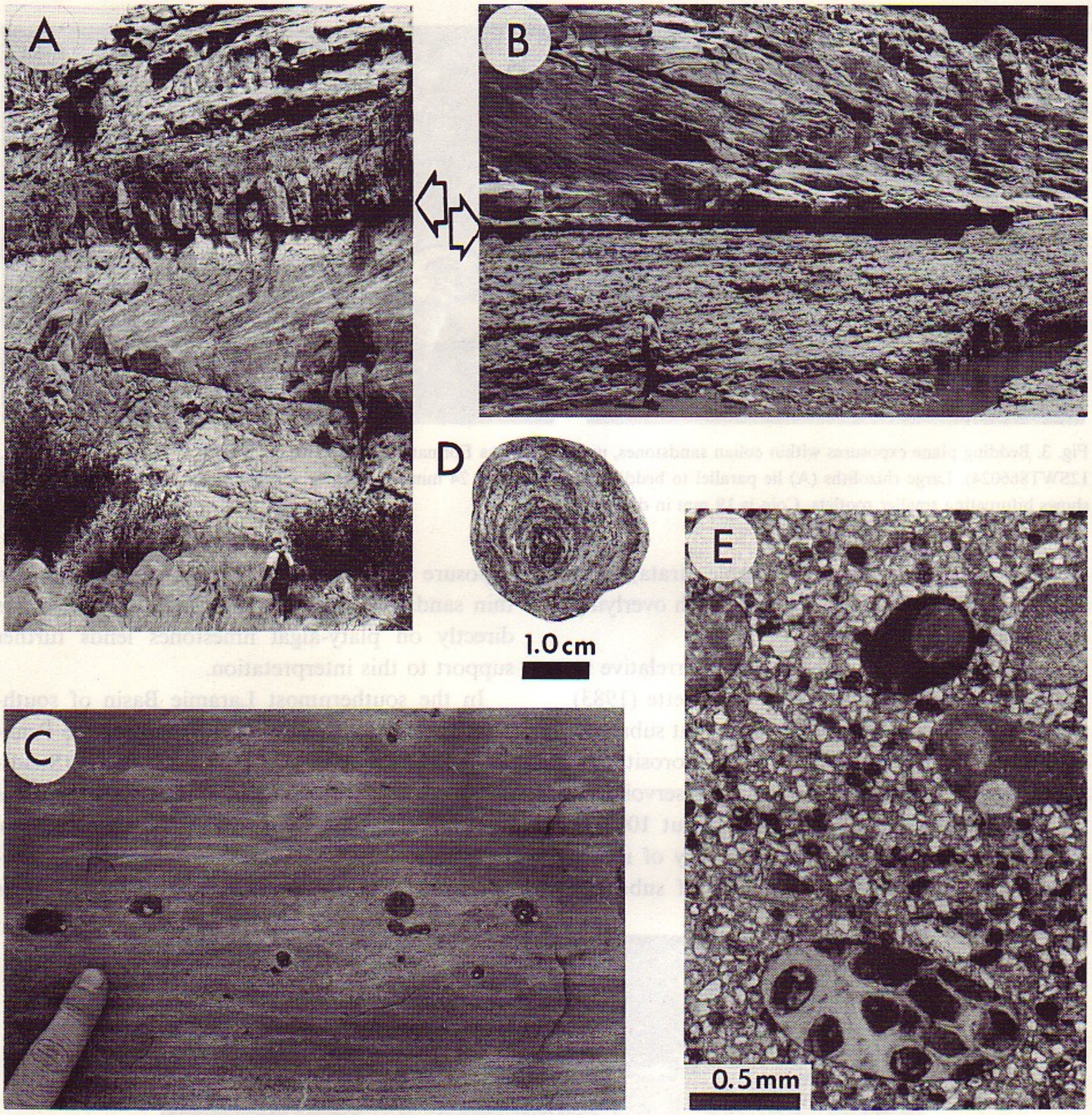

Fig. 2. Upper Hermosa Formation (Fig. 1, loc. 1). (A) Sharp contact (arrow) between large-scale cross-stratified calcarenaceous eolian sandstone and overlying marine grainstone (Fable Valley Quad., 12SWT878021). (B) Sharp contact (arrow) between eolianite and underlying marine wackestone with abundant megafossils and nodular chert (lower Dark Canyon; units 2 and 3; Loope and Haverland, this volume). (C) Transverse sections of rhizoliths in cross-stratified eolian sandstone. Rhizoliths are parallel to plane of lamination and to dip direction of cross-sets. (D) Transverse section of rhizolith showing concentric laminations; structure filled centripetally (cf. Calvet et al., 1975, fig. 5). (E) Calcarenaceous eolian sandstone; carbonate allochems driven onto land by onshore winds. Thin-section contains 39% siliciclastic grains, 36% calcite grains, 25% calcite cement/matrix (unit 8 of Loope and Haverland, this volume).

that its upper and lower contacts could represent disconformities. Cross-stratification in this unit is obscured by biogenic structures. An eolian origin is inferred on the basis of: (1) petrographic similarity of this sandstone to thicker sandstones higher in the section that contain diagnostic eolian sedi-

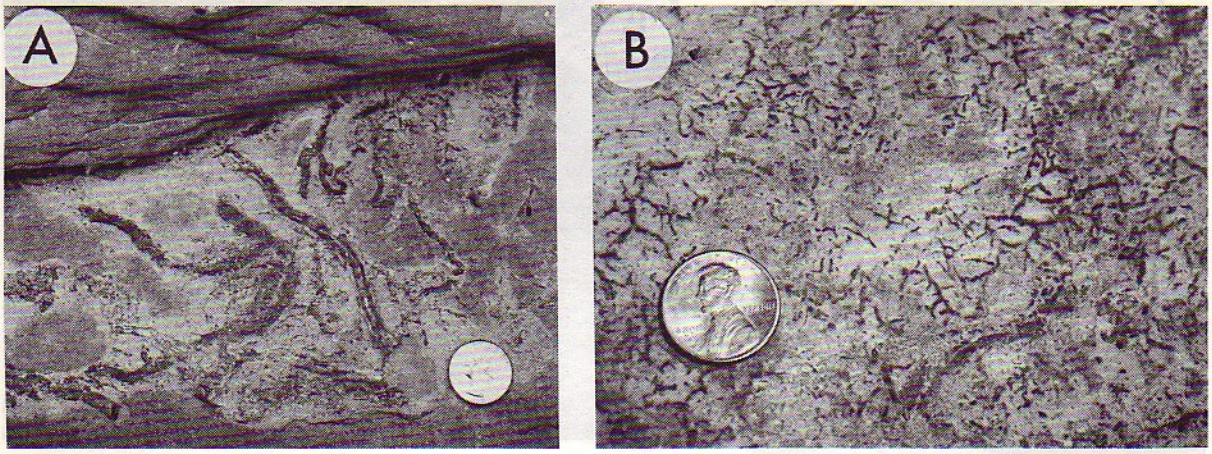

Fig. 3. Bedding plane exposures within eolian sandstones, upper Hermosa Formation (Fig. 1, loc. 1; Mouth of Dark Canyon Quad., 12SWT866024). Large rhizoliths (A) lie parallel to bedding plane. Coin is 24 mm in diameter. Close-up of same bedding plane (B) shows bifurcating smaller rootlets. Coin is 19 mm in diameter.

mentary structures (i.e., wind ripple strata); and (2) the sharp mineralogical contrast with overlying and underlying carbonates.

From a subsurface study of rocks correlative to those in the San Juan Canyon, Choquette (1983) pointed out several lines of evidence that subaerial exposure was an important factor in porosity development in platy-algal carbonate reservoirs of the giant Aneth oil and gas field, about 100 km east of the outcrop area. The discovery of rhizoliths, which are excellent indicators of subaerial exposure (Esteban and Klappa, 1983), within a thin sandstone of probable eolian origin that lies directly on platy-algal limestones lends further support to this interpretation.

In the southernmost Laramie Basin of southeastern Wyoming, eolian sandstones of the Pennsylvanian/Permian Casper Formation (Steidtmann, 1974) overlie arkosic fluvial conglomerates of the Fountain Formation (Knight, 1929). Rhizoliths are abundant in thin, large-scale cross-stratified, fine- to very fine-grained sandstones

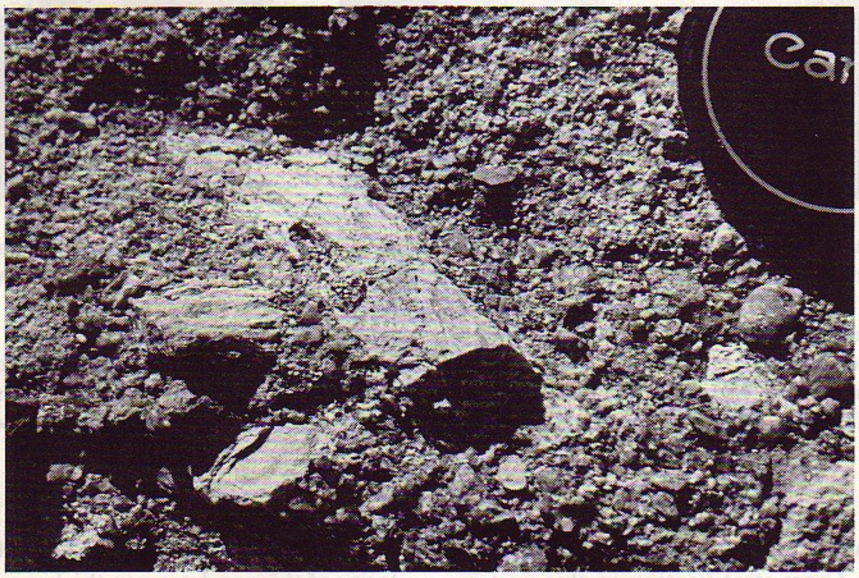

Fig. 4. Fragmented, reworked rhizolith in channel-filling fluvial conglomerate, Fountain Formation (Fig. 1, loc. 5; Sand Creek Pass Quad., 13TDR355385).

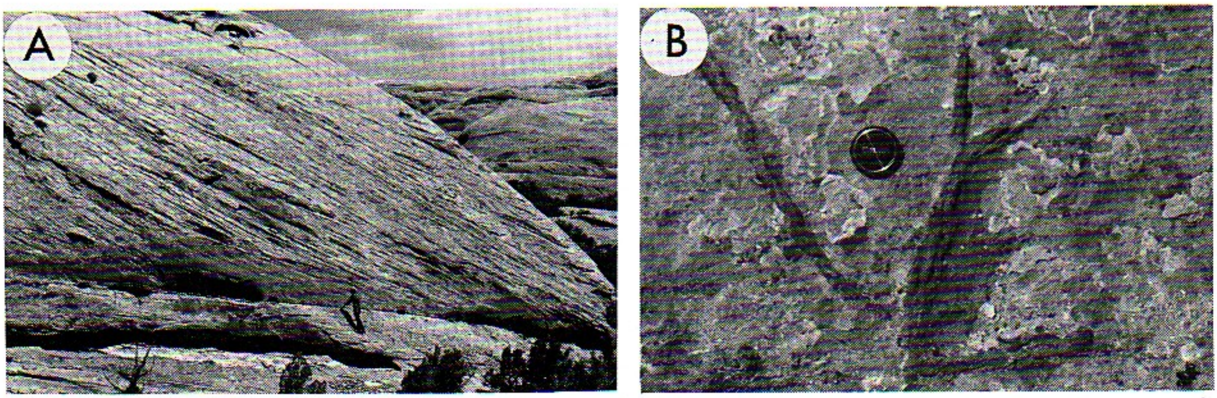

Fig. 5. Rhizoliths in the Navajo Sandstone (Fig. 1, loc. 6; Moab Quad, 12SXT207660). (A) Man points at bedding surface separating flat-bedded, rhizolith-bearing sandstone and large-scale cross-stratified sandstone. (B) Bifurcating rhizolith on subhorizontal surface within flat-bedded sandstone shown in A. Note that, unlike a burrow system, branches are of unequal diameters.

that are interbedded with fluvial conglomerates near the Casper/Fountain contact. Although bioturbation of these thin sandstone bodies prevents identification of distinctive eolian stratification types (Hunter, 1977), the rhizolith-bearing sandstones are tentatively interpreted as eolian on the basis of their texture, the presence of large-scale cross-sets, and their proximity to well-documented eolian strata in the overlying Casper Formation (Steidtmann, 1974; Hunter, 1981). Arkosic conglomerates fill channels cut into the tops of rhizolith-bearing sandstones and contain abundant fragmented rhizoliths (Fig. 4). Rhizoliths are apparently absent from dune and interdune deposits of the main part of the Casper Formation.

Near Moab, Utah, well-preserved calcareous rhizoliths have been discovered at a single level within the Navajo Sandstone (Figs. 5 and 6). As in the Paleozoic examples, these rhizoliths are within bioturbated sandstone beneath a horizontal bedding surface. These rhizoliths are underlain and overlain by large-scale eolian cross-sets and are approximately 15 m above the base of the formation. They lie 5 m above a thin lens of dolomicrite that Gilland (1979) has interpreted as a freshwater lake deposit. Gilland found well-preserved pollen, spores and dinosaur tracks within the lens.

External form of rhizoliths

The features interpreted here as rhizoliths are rods of micritic limestone varying in diameter from less than 1 mm to nearly 15 cm. As in the Pleistocene rhizoliths illustrated by Calvet et al. (1975), contacts between micrite and host sediment are sharp and rods are generally free of clastic grains (Figs. 2C and 6A). After burial, some calcitic rhizoliths are silicified or dolomitized (Fig. 7). In such cases, the sharp contact between the altered rhizolith and the siliciclastic matrix is an important clue to the origin of the structure.

In bioturbated host rocks, no preferred orientation of rhizoliths has been observed. Cylinders of diverse diameters ramify throughout the upper 2–3 m of the sandstone body. In rocks retaining primary structures, rhizoliths are commonly oriented parallel to bedding or lamination (Fig. 3) and are especially abundant in coarser grained strata. Within some cross-strata, rhizoliths are preferentially oriented parallel to the dip direction (Fig. 2C). Glennie and Evamy (1968) and McKee and Bigarella (1972) have noted the tendency of plant roots to grow parallel to lamination in eolian sands. This growth pattern allows maximum exploitation of zones of higher permeability (Glennie and Evamy, 1968).

Within red sandstones of the Navajo, Cedar Mesa and Hermosa Formations, rhizoliths are commonly surrounded by "aureoles" of pale sandstone (Fig. 8). Quartz grains within some "aureoles" are surrounded by lath-shaped calcite crystals (Fig. 6D). From eolian sands of Israel, Amiel (1975) illustrated similar calcite crystals

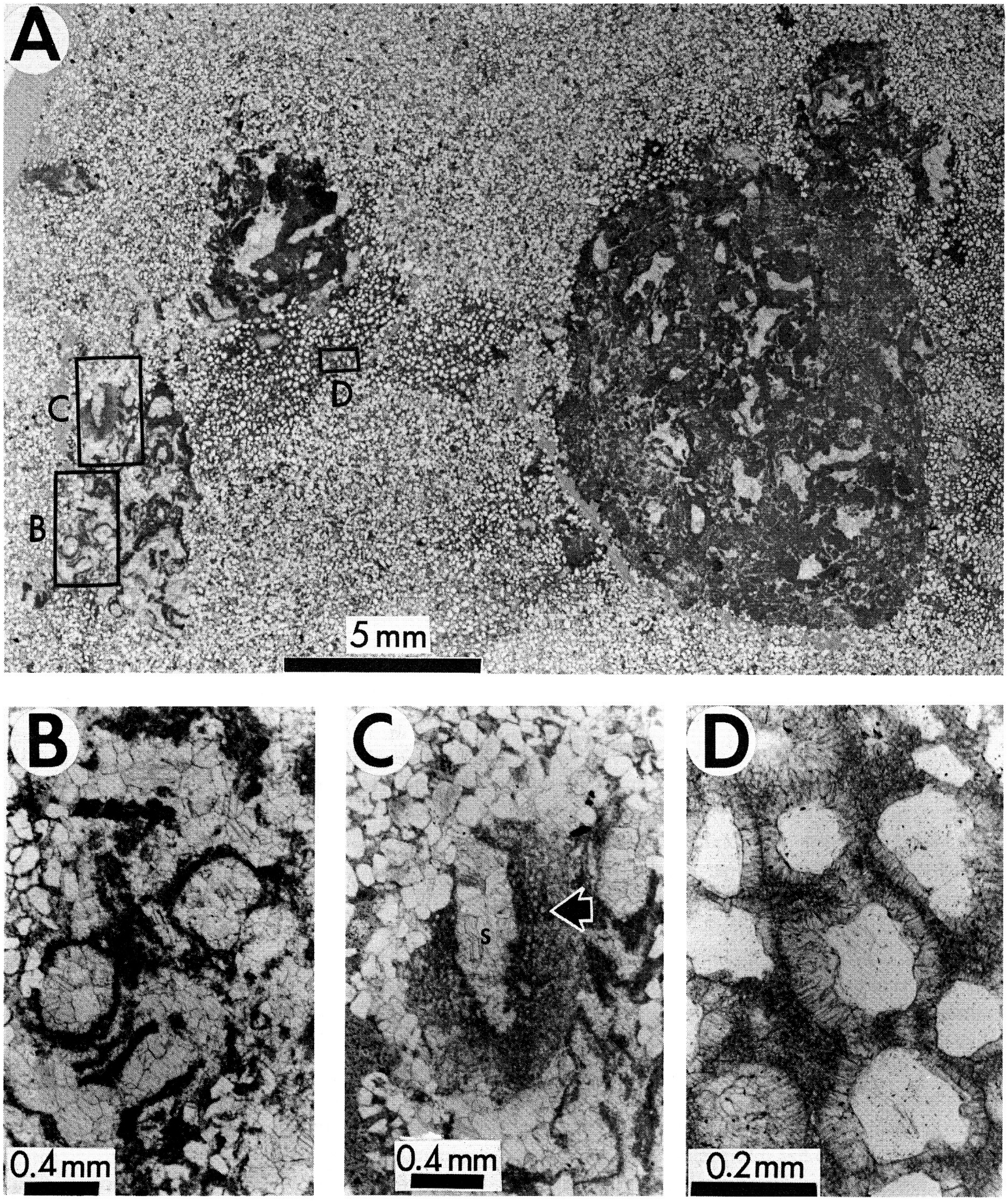

Fig. 6. Rhizoliths in the Navajo Sandstone (same locality as Fig. 5). (A) Large and small rhizoliths in transverse and oblique sections. Note: (1) sharp contacts between quartz sand matrix and rhizoliths; and (2) clotted micrite and spar-filled tubular voids within large rhizoliths. Positive print of thin-section. (B) Alveolar fabric (cf. Esteban and Klappa, 1983, fig. 66) within large rhizolith, produced by calcification and encrustation of small, invading rootlets (micrite) and void filling (spar). (C) Peripheral cellular(?) structure (arrow) and central void-filling spar (*s*) of small rhizolith. In Quaternary materials (Klappa, 1980, fig. 6e, f), only epidermal and cortical cells petrify; central vascular tissue decomposes to form tubular void. (D) Corroded quartz grains encrusted by lath-shaped calcite crystals. Note intergranular micrite. Photomicrographs B, C and D taken in plane light.

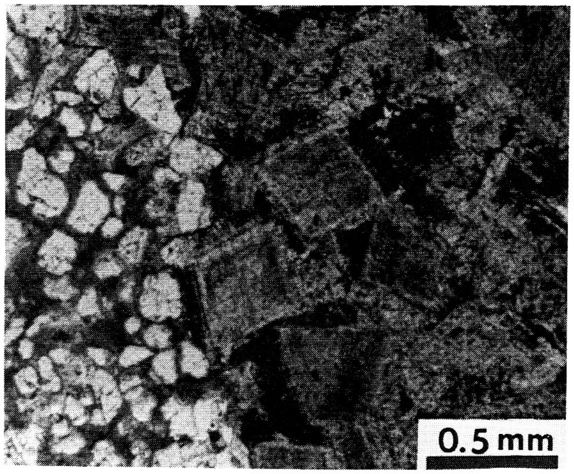

Fig. 7. Sharp boundary between dolomitized rhizolith (right) and siliciclastic matrix, upper Cedar Mesa Sandstone (Fig. 1, loc. 1; Mouth of Dark Canyon Quad., 12SWT713891). Iron oxide on weathered dolomite delineates rhizoliths on outcrop.

Fig. 8. "Aureoles" of bleached sandstone surrounding rhizoliths, Cedar Mesa Sandstone (Fig. 1, loc. 3; Cedar Mesa Quad., 12SWS944257). Note bioturbated matrix.

within columnar structures that surround living roots.

I have not detected tapering in these ancient rhizoliths. Several previous workers (Ball, 1967; Ahlbrandt et al., 1978) have concluded that the taper of plant roots should allow root traces to be differentiated from animal burrows. Although some roots (carrots) have a strong taper, my observations of living roots and Quaternary rhizoliths indicate that in most cases, the taper is imperceptible in segments a few tens of centimeters in length. The degree of taper in plant stems and roots is dependent on the ratio of growth by elongation to growth by thickening. As revealed by growth rings, thickening of roots is slow and erratic compared to thickening of stems; roots

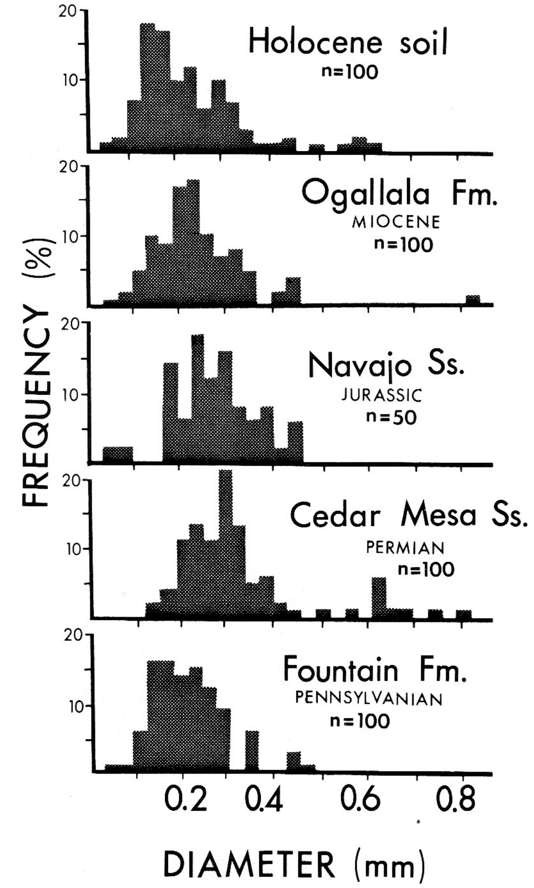

Fig. 9. Size/frequency diagram, diameters of open (modern) and spar-filled (ancient) tubular spaces within large (cm-scale) rhizoliths. Tubes are interpreted as central regions of rhizoliths formed subsequent to death of "mother" root. Holocene rhizoliths are from southern Utah (Moab Quad, 12SXT2279).

commonly taper rapidly near the trunk and retain a nearly constant diameter distally (Wilson, 1970, p. 40). In outcrops of indurated rock where it is difficult or impossible to recover lengthy specimens, taper is not a useful criterion for the identification of rhizoliths.

Internal fabric of rhizoliths

In thin-sections, the fabric of these Mesozoic and Paleozoic rhizoliths is distinctive. The internal structure is remarkably similar to that of Mississippian calcrete reported by Harrison and Steinen (1978) and to the alveolar fabric of Quaternary terrestrial carbonates described by Esteban (1974) and Esteban and Klappa (1983). The clotted micrite matrix of the ancient rhizoliths is interrupted by closely spaced, spar-filled cylindrical pores (Fig. 6A). As in Quaternary material (Esteban and Klappa, 1983), the diameters of the pores generally range between 0.1 and 0.5 mm (Fig. 9). Alveolar fabric is the product of coalesced, small rhizoliths (Esteban and Klappa, 1983). The large rods described here are thus interpreted as compound rhizoliths—the individual cm-scale rhizoliths are themselves composed of aggregations of much smaller rhizoliths. The internal structure of the large rhizoliths is analogous to that of "root rock" (Perkins, 1977). Small rootlets, corresponding in diameter to small, simple rhizoliths (Fig. 10), apparently invaded the space occupied by the larger root after its death. Thin-sections reveal that many Holocene and Miocene rhizoliths are also compound: epidermal and cortical cells of small rootlets are commonly preserved deep within much larger rhizoliths (Fig. 11). Although cellular structure is commonly seen in Quaternary rhizoliths (Klappa, 1980), I have observed only faint suggestions of this pattern in Mesozoic and Paleozoic rhizoliths (Fig. 6C).

The diameters of cylindrical voids composing the alveolar fabrics of Mesozoic and Paleozoic rhizoliths are very similar to those within Miocene and Quaternary rhizoliths (Fig. 9). Reynolds (1975) has demonstrated that 95% of the total root length of some trees is represented by rootlets less than 1 mm in diameter. He found that the smallest roots in douglas fir trees are 0.15 mm in diameter and that the peak of the root length/diameter distribution for this species is 0.3 mm. Reynolds (1975) suggests that this preponderance of small roots may be the result of the adaptation of root systems to rapid changes in soil water availability. He believes that smaller roots are ephemeral and can

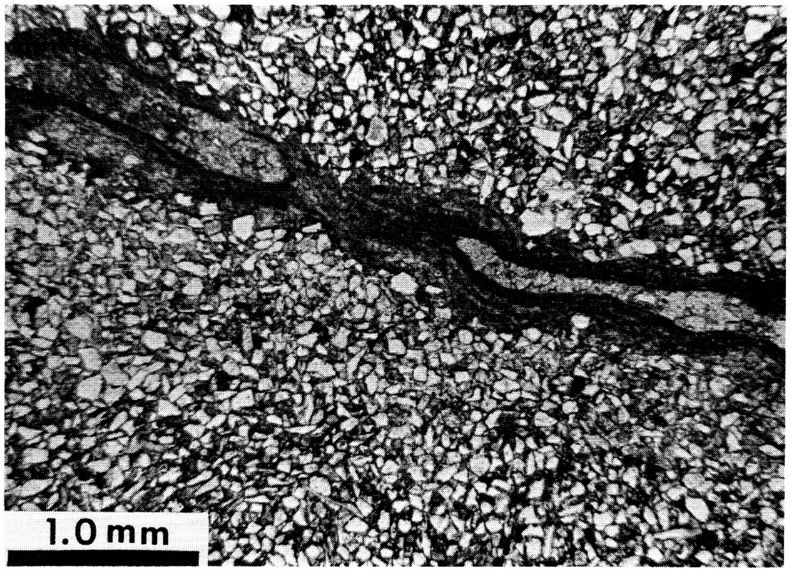

Fig. 10. Small, simple rhizolith identical in scale and structure to those producing alveolar structure within large (compound) rhizoliths. Cedar Mesa Sandstone (Fig. 1, loc. 4; Needles Quad, 12SXT038261). Plane light.

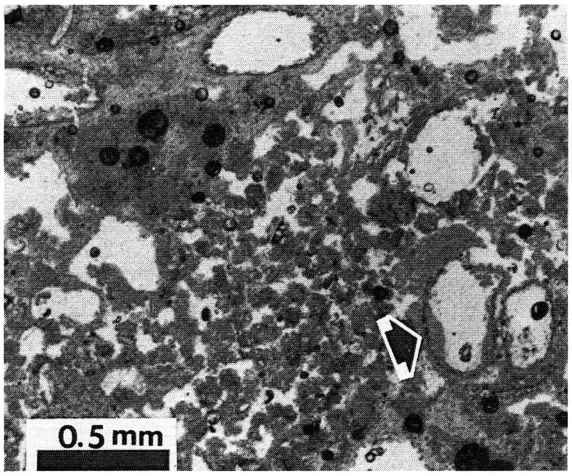

Fig. 11. Photomicrograph of transverse section of large (3 cm diameter) rhizolith from Miocene Ogallala Formation (Fig. 1, loc. 7; south side of Highway 34, east of Wray, CO). Note clotted micrite and transverse, longitudinal, and oblique sections of small rhizoliths with epidermal cell structure preserved by opal (arrow). Plane light.

be compared functionally to the leaves of deciduous trees. The similarity in scale of tubules within Quaternary through Pennsylvanian alveolar fabrics (Fig. 9) suggests that ancient root systems, like modern ones, were dominantly composed of sub-millimeter-sized rootlets.

Host sediments

Quaternary rhizoliths are especially abundant and well developed in calcareous sands with high permeability. Quaternary calcareous dune sands of Australia (Read, 1974; Semeniuk and Searle, 1985), Mallorca (Calvet et al., 1975; Klappa, 1980), California (Johnson, 1967), Mexico (Ward, 1975), Florida (Ball, 1967) and Ontario (Kindle, 1925) contain spectacular developments of rhizoliths. Gill (1975) and Perkins (1977) reported rhizoliths from Pleistocene beach sands as well as from eolian sands. Curran (1984) noted that on San Salvador, Pleistocene rhizoliths are restricted to calcarenite facies and are most abundant in the eolianites.

Although many eolian limestones of Quaternary age have been described, such rocks have not been previously reported from the Paleozoic (McKee and Ward, 1983). Fairbridge and Johnson (1978) have argued that calcareous dune deposits are restricted to coastlines affected by glacio-eustasy. Johnson (1968) suggested that, in response to Gondwana glaciation, calcareous dune sands may have been deposited during the late Paleozoic; he believed that ancient analogs of Quaternary coastal eolianites should be sought in areas of low paleolatitude. Gardner (1983) pointed out, however, that there is little agreement concerning the role of sea-level fluctuations in the origin of Quaternary calcareous eolian sands; she believed Johnson's (1968) suggestion offered little prospect of success.

Fairbridge and Johnson (1978) and Gardner (1983) agree that calcareous dune sands are deposited when strong, persistent onshore winds drive shallow-marine calcareous debris landward. On the basis of data collected from eolian cross-sets, late Paleozoic wind systems in the study area are relatively well known (Poole, 1964). Other studies have delineated positions of basins and persistent topographic highs. Figure 12 shows that the rhizolith-bearing calcarenaceous sandstones and quartzose calcarenites of the upper Paleozoic sequence in southeastern Utah were deposited on the southwestern margin of a shallow epeiric sea —an area where winds were directed onshore.

Carbonate debris within these ancient eolianites was not necessarily derived from strand lines.

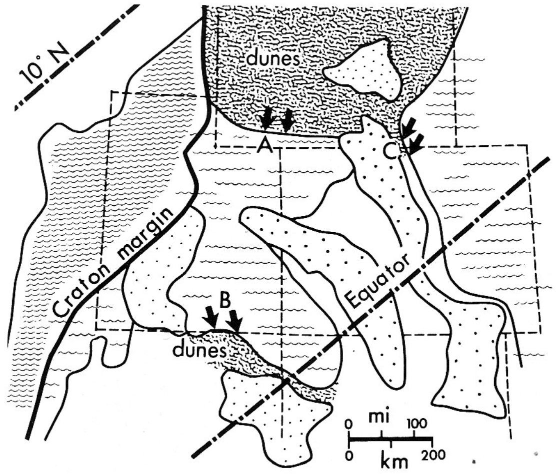

Fig. 12. Late Paleozoic paleogeographic setting for deposition of the Morgan Formation (A) (Driese and Dott, 1984), Hermosa (B), and Fountain (C) formations (this paper). Note offshore winds at A, onshore winds at B and C. Modified from Driese and Dott, 1984, fig. 22. See Heckel (1980, fig. 1) for alternative paleolatitudes.

Loope and Haverland (this volume) report evidence suggesting that, during Pennsylvanian regressive episodes, groundwater tables dropped as much as 5 m below the tops of previously deposited marine carbonate sediments. Carbonates above the groundwater table may have been broadly exposed and susceptible to deflation—a situation similar to that of the modern Qatar peninsula (Patterson and Kinsman, 1981, p. 1472).

The Morgan Formation, a sequence of interbedded eolian and shallow marine rocks of Desmoinesian age (Driese and Dott, 1984) and the overlying eolian Weber Sandstone (Fryberger, 1979) of northeastern Utah were deposited in coastal areas with winds directed offshore (Fig. 12). These units are apparently devoid of both windblown marine allochems and rhizoliths of the type described here.

Although carbonate allochems have not yet been described from eolian strata within the Casper Formation, the stratigraphic framework (Steidtmann, 1974, fig. 11) and paleocurrent data (Knight, 1929, fig. 30) suggest that it accumulated immediately downwind of a carbonate-producing

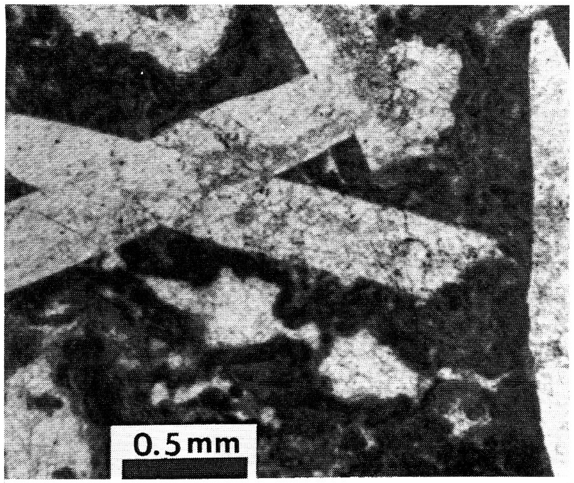

Fig. 13. Transverse section of rhizolith, showing gypsum pseudomorphs filled by calcite spar, upper Cedar Mesa Sandstone (Fig. 1, loc. 4; Needles Quad., 12SXT067215). Plane light.

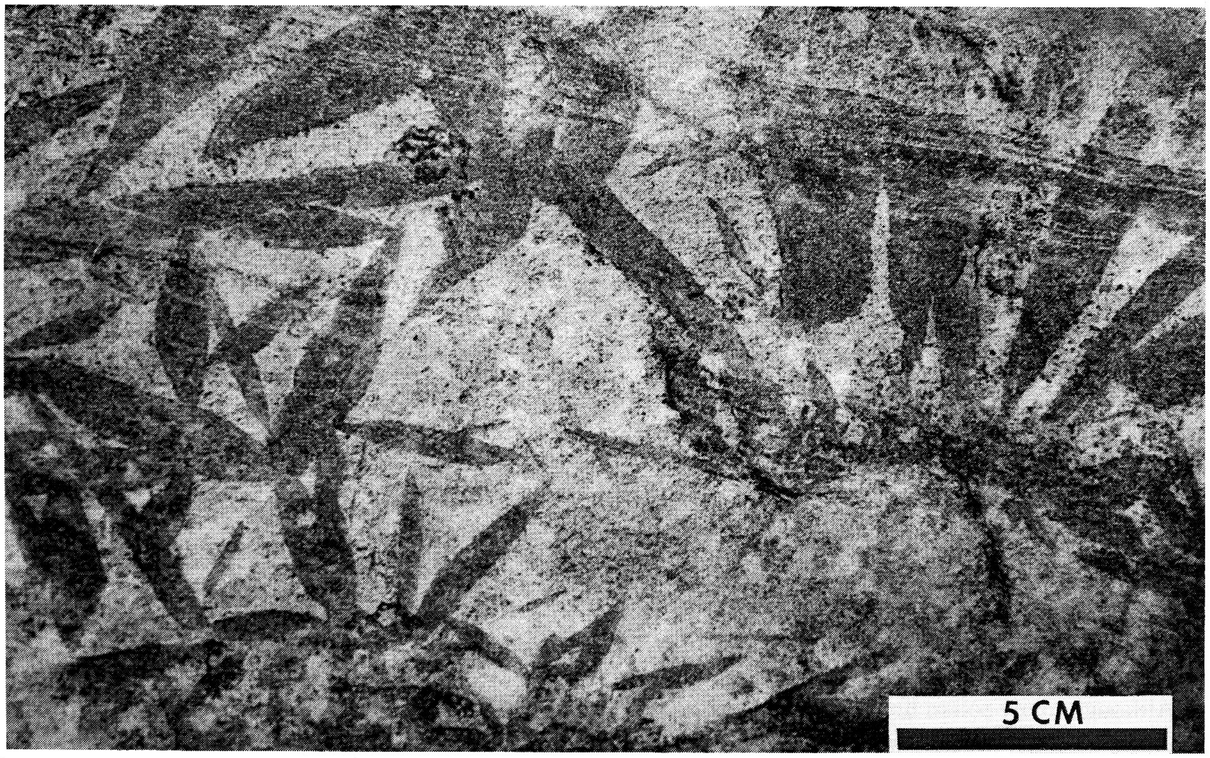

Fig. 14. "Ghosts" of former gypsum sand crystals ("desert roses"). Quartz grains within "ghosts" have hematite rims. Note cross-stratification passing through structures. Surface of outcrop is nearly vertical. Upper Cedar Mesa Sandstone (Fig. 1, loc. 4; Needles Quad., 12SXT116246).

epicontinental sea. Sand-sized carbonate grains may have been destroyed during diagenesis or calcium ions incorporated into rhizoliths may have been supplied by dust derived from exposed marine carbonates. There is no evidence, however, that the Navajo Sandstone of southeastern Utah was deposited in a coastal environment (Kocurek and Dott, 1983, fig. 3). As for many Tertiary and Quaternary calcretes of western U.S. (Gile et al., 1981), dust-fall is the most likely source of calcium ions for the rare calcareous rhizoliths within the Navajo Sandstone.

Paleoclimate

Were Paleozoic eolian dunes, like modern ones, mainly restricted to arid and semi-arid settings, or were they also active in humid environments because of the inability of Paleozoic plants to stabilize mobile sand? Semeniuk and Meagher (1981) and Semeniuk and Searle (1985) have studied the origin and distribution of rhizoliths and other forms of calcrete within Holocene coastal sands of Australia. Rhizoliths there are restricted to the vadose zone. They form in climatic regimes ranging from subtropical humid to semiarid, but decrease in abundance with increasing aridity. Rhizoliths are the only form of calcrete present at several of the semiarid sites; massive and laminar calcretes are restricted to areas with wetter climate (Semeniuk and Searle, 1985).

Rhizoliths are the dominant form of pedogenic carbonate in the Mesozoic and Paleozoic eolian rocks of southeastern Utah. Very little massive or laminar calcrete has been discovered, suggesting that the ancient settings may have resembled the semiarid sites described by Semeniuk and Searle (1985). The presence of gypsum pseudomorphs within rhizoliths (Fig. 13) as well as "ghosts" of former gypsum sand crystals (Fig. 14; McKnight, 1940; Loope, 1985) from the upper Cedar Mesa Sandstone support such an interpretation. Watson (1983) reports that gypsum sand crystals form near shallow ground water tables and are restricted to areas where rainfall is less than 200 mm yr^{-1} and there is a monthly excess of evaporation over precipitation throughout the year. For Desmoinesian rocks of the Paradox Basin, an arid or semi-arid setting for rhizolith development is indicated by the synchronous development of rhizoliths on the shelf and halite in the basin center (Fig. 1).

Plants and habitats

Modern calcareous rhizoliths appear to be best-developed in the vadose zone (Semeniuk and Searle, 1985, fig. 1). I have interpreted the planar, laterally extensive erosion surfaces that are directly above most of the ancient rhizoliths as products of deflation to the level of the groundwater table (Stokes, 1968; Loope, 1985). The proximity of gypsum sand crystals and lacustrine carbonates to these surfaces support this interpretation. The presence of rhizoliths as much as 3 m below the erosion surfaces, however, suggests that the level of the groundwater did not remain near the surface. Plants may have colonized deflation surfaces after these substrates were stabilized by evaporite crusts. Evapotranspiration by the plants themselves may have been responsible for the fall of the groundwater level and maintenance of a thick vadose zone.

On the basis of the work of Magdefrau (1956), Glennie and Evamy (1968) state that, "although some plants (e.g., *Walchia piniformis* and *Walchia filiciformis*) had already adapted themselves to arid conditions by the Early Permian, their root systems, if any, seem to have been only lateral and not to have penetrated deeply into the underlying sediment. The earliest dune (but not necessarily desert) plants with sediment-penetrating roots (*Nathorstiana, Weichselia, Hausmannia*) are known from Lower Cretaceous dune sands of possible coastal origin from Germany".

The plants represented by the rhizoliths described here were clearly capable of penetrating several meters of eolian sand (Fig. 8; Loope, 1985). The rhizoliths have not been studied by paleobotanists, and the taxonomic affinities of the plants remain unknown. The restriction of rhizoliths to horizontal surfaces, however, indicates that these were not "dune plants". They were apparently incapable of colonizing or stabilizing eolian bedforms. Undulatory bounding surfaces or disconformities underlain by rhizolith-bearing dune sand, similar to those described by Ward (1975, p. 527) and Talbot (1985) have not yet been documented from the pre-Quaternary rock record; such surfaces have good preservation potential and, if found, will bear additional evidence concerning the evolution of plant/sediment interactions.

Conclusions

(1) Calcitic rhizoliths are abundant and easily recognized structures within eolianites of at least three different stratigraphic packages of western U.S. Roots that grew in eolian sand but decayed before becoming mineralized may have been even more abundant, but are much more likely to be confused with burrows.

(2) The internal structure of large rhizoliths (modern and ancient) indicates that they are typically compound structures, formed by calcification of small rootlets that invaded the site of the large root after its death.

(3) Rhizolith formation required flat, geomorphically stable substrates for plant growth, highly permeable host sediments, and sources of calcium ions.

(4) Association of ancient rhizoliths with coeval evaporites suggests that many of them formed in an arid to semi-arid climatic setting.

(5) Carbonate-rich, rhizolith-bearing dune sands characterize low-latitude coasts with dominantly onshore winds. The abundance of these sediments in the Quaternary record and their discovery in upper Paleozoic rocks of western United States suggests that they are genetically related to glacio-eustatic sea-level changes.

(6) Future studies of ancient upland plants from a paleoecological/sedimentological point of view should be rewarding. Rhizoliths are worthy of attention because their distribution may provide clues to the evolution of plant/sediment interactions through Phanerozoic time.

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