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Dune Associated Calcretes, Rhizoliths and Paleosols from the Western Continental Shelf of India

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Abstract: The calcareous deposits on the western continental shelf of India, off Bhatkal (water depths 50 to 58 m) occur as crusts, sheets, cylinders and reddish brown mudstones. The outer layers of the crusts are micrite-dominated and beneath this layer detrital/carbonate sands with thin heavy mineral laminations are found. Textural studies indicate that the detrital sands are derived from dunes. Drusy calcite and neomorphic calcite cements are associated with the sands. Sheet deposits contain coarse calcareous component-dominated layer within micrite layers and abundant micrite cements. These are similar to dune associated calcretes.

Cylinders are rhizoliths and show different stages of root calcification. Circular bodies, about 0.15 mm to 0.70 mm diameter, interpreted as vascular cylinders of the root tissues are typical. Radial fibrous calcite and spar calcite with inclusions indicate neomorphic cements. Reddish brown mudstones contain calcified root-hair sheaths, micrite glaebules and reworked pollen suggesting that these are indurated soils. X-ray diffraction studies indicate the presence of ferroan calcite, quartz, pyrite and dolomite in rhizoliths and ferroan calcite, goethite and quartz in mudstones. Mudstones and some rhizoliths are Fe-rich and some other rhizoliths are Fe-poor but enriched with Mg and Mn.

The particulate matter in the calcareous deposits were initially at the proximity of the coast and cemented by metastable calcites during the ultimate Pleistocene interglacial sea-level stands on the shelf. Pedogenic cementation processes overprinted and developed them into eolianites and paleosols during the subsequent Late Pleistocene sea-level regression. The compositional differences of these deposits were apparently controlled by type of sediments and associated sedimentary environments.

Keywords: Sedimentology, Calcretes, Rhizoliths, Paleosols, Continental shelf.

INTRODUCTION

Eolianites and paleosols are important indicators of exposure surfaces and develop mostly in warmer climates. Alternating sequences of calcareous eolianites and soil zones have been reported in coastal regions of Bermuda, India and Yucatan Peninsula. These developed due to changes in sea-level during the Pleistocene (*see* McKee and Ward; 1983). Similar calcretes in Quaternary calcareous dunes and soils have been documented (*see* Wright, 1994 for review). Present day continental shelves were exposed during the Late Pleistocene sea-level regression and again submerged during the Holocene. So eolianites and/or paleosols should be expected to have formed during regressive phases. Provided that there was very little subsequent erosion during the transgression, and these horizons were not buried by subsequent sediments, they should still occur at or near surface positions submerged on the continental shelf. Logan *et al.* (1970) reported submerged Pleistocene dune rocks at Shark Bay.

Several dredge/grab samples were collected on the western continental shelf of India. The samples collected at the transition zone (between inner shelf clastic zone and outer shelf relict carbonate zone) revealed that the lime deposits corresponding to subaerial exposure surfaces occur all along the coast from Ratnagiri to Cochin (Fig.1). Caliche pisolites were recovered at 50-60 m depths (stations 10 and 63 Fig.1) in the northern part (*see* Rao, 1990; Rao and Nair, 1992) and rhizoliths (at 30 m depth) in the southern part (stations 30,

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Gj-1 Fig.1). A variety of calcareous deposits characteristic of subaerial exposure surfaces were recovered also at 52 and 58 m water depths off Bhatkal. Here, we investigate these lime deposits and report them as submerged calcretes and paleosols.

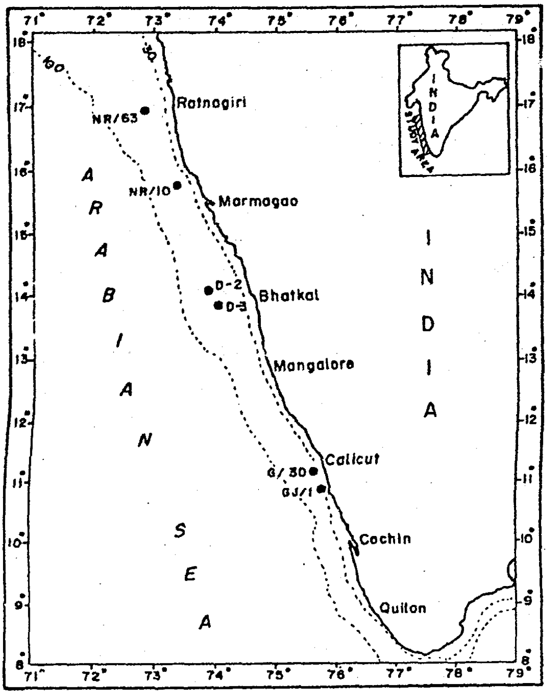

Fig.1. Location of the dredge/grab samples on the western continental shelf of India. The lime deposits from these stations show typical features of subaerial exposure surfaces. Stations D-2 and D-3 are discussed in this paper.

MATERIAL AND METHODS

During the 18th cruise of *R.V. Gaveshani*, a pipe dredge was operated off Bhatkal at about 52 and 58 m water depth (Fig.1). The calcareous deposits recovered occur in the form of crusts, sheets, cylinders and reddish brown semi-indurated to indurated mudstones. Sheet deposits were abundant at both stations. Crusts, cylinders and a few mudstones were recovered at station D-3 and only mudstones at station D-2 (Fig. 1). Most of them were extensively bored and encrusted with serpulids or coralline algae. Polished thin sections of these calcareous deposits were made and thin sections were stained following the method of Dickson (1965). Mineralogy of the samples was studied by X-ray diffraction and selected elements were analysed by ICP-AES (Table I). Based on chemical composition and polished and thin section studies, grey cylinders were selected and radiocarbon dated at two different laboratories.

Table.I. Mineralogy, geochemistry of the acid (10% HCl) soluble aliquot and weight percentage of the acid insoluble residue in different limestone samples.

Type of calcareous deposits	Minerals present in order of abundance	Geochemistry					Wt % of acid insoluble residue
		Ca	Mg	Fe	Mn	Na	
Crust calcretes	LMC, QT, FELD,	22.0	0.7	1.4	0.4	0.5	45.75
Brown sheet calcretes	LMC, QT, FELD.	24.3	1.0	2.1	0.1	0.5	43.35
Dark-grey bored sheet calcretes	LMC, QT, FELD.	26.0	1.2	2.7	0.4	0.4	30.38
Brown calc cylinders •	Fe.LMC, QT, PY, GOE,DO.	17.0	1.8	10.0	0.6	1.1	21.50
Grey calc. cylinders	Fe.LMC, QT, PY, DO	15.0	3.0	3.7	1.8	0.6	—
Reddish brown semi-indurated mudstones	Fe.LMC, QT, GOE,	8.6	1.9	14.0	2.3	1.5	40.65

LMC - low magnesium calcite; QT-quartz; FELD-feldspar; PY-pyrite; GOE-goethite; Fe.LMC- ferroan calcite (Ferroan low-magnesium calcite); DO-dolomite.

RESULTS

A. Dune Associated Calcretes

Crust and Sheet deposits

Crust deposits occur as 4 cm thick brown lumps. They show a 0.5-1.0 cm thick dark brown micrite-dominated layer at the periphery and light brown sandy layer inside (Fig.2A). The sandy layer further consists of dark brown patches and 1 to 2 mm thin parallel heavy mineral laminations. Low-magnesium calcite, quartz, feldspar and heavy minerals (dominated by ilmeno-magnetite) are present. The textural studies on acid insoluble residue of the crusts indicate that the mean size, standard deviation and skewness values of the sands are 3.45ϕ, 0.5ϕ, 0.02ϕ, respectively. The plot of these values on Friedman (1961) curves indicate that they fall within the dune environment.

Thin sections show that the sandy layer is a grainstone and consists of quartz, heavy minerals, calcareous pellets and several benthic foraminifers. Drusy calcite occurs as pore filling cement and as thin veins between grains (Fig. 2B). Sparry calcite is abundant and its size ranges from microspar (about 15 μm) to coarser spar calcite (about 120 μm) (Fig. 2C). Neighbouring areas of the coarser calcites show microspar with linear inclusions. Needle-like inclusions are preserved in the sparry calcite mosaic.

Sheet deposits are 1.5 to 4.0 cm thick, flat calcified bodies. They may be brown or dark grey. Faint laminations are seen on polished sections of the brown sheets. The dark grey sheets show peripheral cracks filled with pyrite and/or goethite. Calcite and quartz are the major minerals.

Thin sections of the brown sheets show sand dominated layers sandwiched between micrite layers. Individual sand layers contain largely skeletal particles (Fig. 2D) comprising

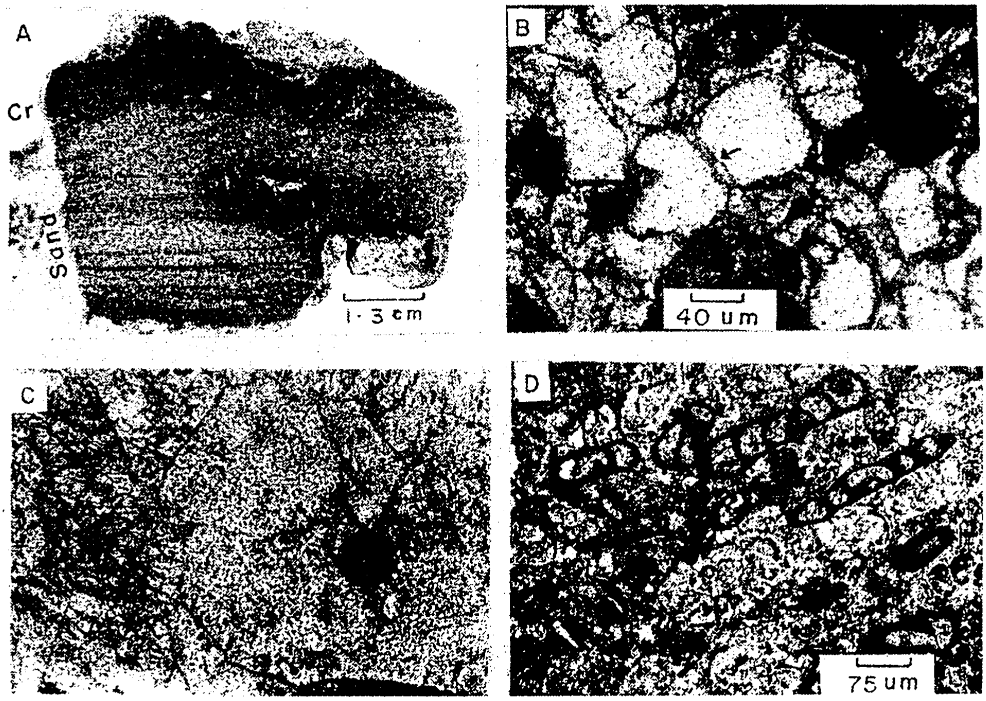

Fig.2. (A) Polished section of calcareous crust showing dark brown crust (cr) layer at the periphery and light brown sandy layer with thin (1-2 mm) heavy mineral laminae inside; (B) grains bound by drusy calcite walls similar to the partition structures; (C) coarser spar calcite with inclusions, adjacent areas show inclusion rich microspar(M); (D) Skeletal fragments (miliolites and other skeletal fragments) in sheet calcretes which are aligned parallel to the lamination.

benthic forams such as miliolids, ammonids, quinqueloquina and rotalids, ostracods, shell fragments and a few quartz grains. Micrite is the dominant cement and the grains show dissolution at the boundaries. Microspar occurs at the grain contacts. The thin sections of the dark grey sheets contain endolithic filaments, large mouldic pores and pyrite associated micrite matrix.

Interpretation of crust and sheet deposits

Quartz, heavy minerals and shallow water skeletal grains in sandy layers of the crust deposits suggest that the sediments were probably derived from beaches and/or nearshore marine environments. Thin (1-2 mm) parallel laminations (Fig. 2A) with lower heavy mineral content are characteristic of dune environments (*see* Stapor, 1973). Textural studies indicate that the sediments are dune-derived. The lighter carbonate grains are probably wind blown and may have accumulated as calcareous grain-dominated layers of sheet lime deposits. We, therefore, conclude that the particulate matter in crust and sheet deposits are derived from dunes.

Abundant micrites and microspar at grain contacts are typical in vadose zone calcification. The grain partition drusy calcite cements (Fig. 2B) are similar to bridge cements described by Knox (1977) and originate from the influence of capillary and gravitationally held waters in the vadose zone. Fibrous inclusions in the coarser spar (Fig.2C) and needle-like inclusions in the spar may indicate that the spar crystals were recrystallised probably from aragonite precursor cements. Folk and Assereto (1976) reported similar inclusion-rich calcite and suggested that the needle-like inclusions were acicular aragonite preserved in neomorphic calcite.

The presence of neomorphic fabrics suggest that these sediments were intially proximal to the coast and stabilized by metastable marine cements which subsequently altered to low-magnesium calcites during exposure to meteoric water associated with sea-level regression. Micrite and microspar developed as overprints via subsequent pedogenic processes. Crusts showing thin micrite coatings represent stage 1 formation of calcretes. Some sediment apparently accumulated above the unconformity surface and was cemented into abundant sheet and some crust calcretes.

The peripheral cracks in dark grey sheets may be due to desiccation fracturing. Black to dark grey lithoclasts with high organic carbon and due to endolithic algae were reported to occur in shallow subtidal, intertidal and supratidal zones and they aid in locating the ancient coastal rocks (*see* Strasser, 1984). Blackening can also be due to carbonisation from scrub and bush fires. The presence of pyrite indicate that the calcretes were either buried under anoxic marine sediments or located within the reach of sea water at the time of their formation. Pyrite associated micrite matrix, endolithic algae in dark grey sheets indicate that they were located closer to the paleoshoreline during the ultimate Pleistocene interglacial sea-level stands on the shelf and subsequently developed into sheet calcretes during the regressive phase. This inference is also supported by the presence of neomorphic cements (marine cement superposed by meteoric cement fabrics) in crust calcretes.

B. Rhizoliths

Cylinders

Cylinders are about 1.5 to 3.0 cm diameter and up to 15 cm long and may be brown to reddish brown or grey. Their transverse sections show voids (Fig.3A) or calcite filled voids in the centre; voids cannot be differentiated in some others (Fig. 3B). Calcite, quartz and minor dolomite are present in the bulk samples and quartz, pyrite and minor goethite in the acid-insoluble residue. The calcite reflections on X-ray diffractograms occur between 30 and 30.3° 2θ indicating a shift in calcite reflection due to the incorporation of

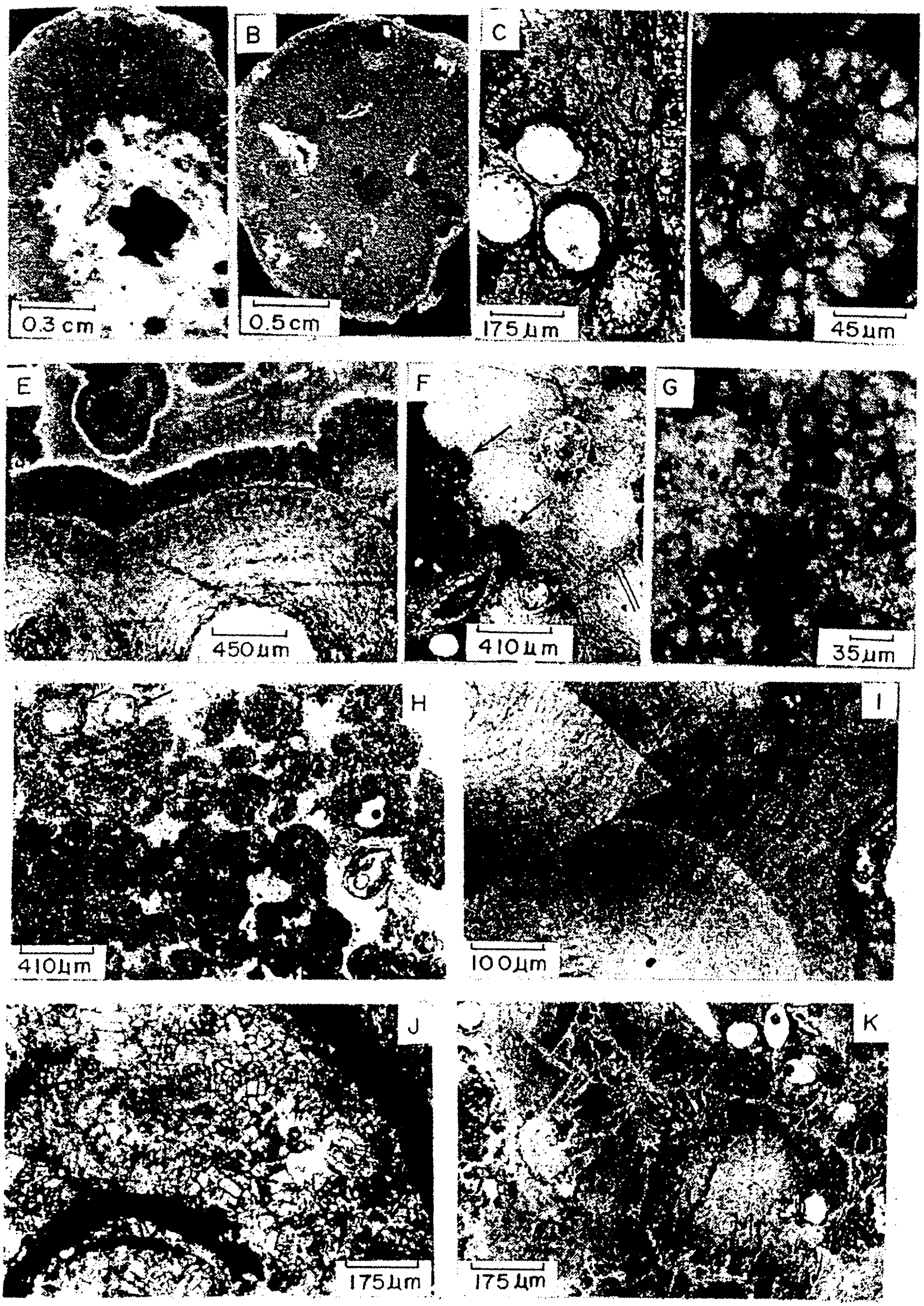

Fig.3. (A-B) Transverse sections of cylinders showing different stages of root calcification; (C-K) photomicrographs from cylinders. (C) ovoid to circular bodies; (D) enlarged view of calcified circular bodies showing the cell structure inside and micrite coating around; (E) microbotryoidal structure around circular bodies showing light and dark bands; (F) the transition zone showing calcified root (lighter part) and pedogenic micrite (darker part on the left), arrows point pyrite at the contact, coarser calcite crystals (double arrows) show several inclusions and turbid boundaries; (G) rounded to ovoid dolomite crystals; (H) peloidal structures, arrows at the left top point to hollow peloids; (I) radial fibrous calcite at botryoid margins, adjacent botryoids show coarser crystals; (J)-neomorphic spar within the skeletal structure; (K) dendritic calcite around grains and following planes.

either magnesium, iron or manganese in the calcite structure. Thin sections were stained with Alizarin Red S and Potassium ferricyanide (Dickson, 1965) indicating abundant occurrence of ferroan calcite (ferroan low-magnesium calcite) and some dolomite. The geochemistry of the acid-soluble aliquot (Table I) shows iron content is variable with higher Fe in brown and reddish brown cylinders and relatively low Fe, more Mg and Mn in the grey cylinders. The ^{14}C ages of grey cylinders (Fig.3B) are 10,480±65 years and 10,080±150 years B.P.

i) *Microstructure:* Circular to ovoid bodies (Fig. 3C) ranging from 150 to 680 μm diameter (the most common are about 300 μm) are typical in all transverse sections. Internally they contain cell-like structures (Fig. 3D) which are pseudomorphically replaced by calcite. Some circular bodies are hollow (Fig. 3C) and others are micritised. The light brown carbonate at the center of some cylinders (Fig. 3A) is homogenous and it exhibit laterally linked microbotryoidal banded structures separated by bright and dark laminae of variable thickness (Fig. 3E). Some botryoids attain a spherical shape. Pyrite occurs as shrub-like growths (Fig. 3F), as minute granules between peloids and disseminated all through the section, especially around the circular bodies. Microdolomites (6-15 μm diameter) occur as ovoid to rounded bodies (Fig. 3G) and are linked one to the other in a chain or form aggregates around circular bodies. Peloidal structures are common at the peripheral parts (Fig. 3H). The longitudinal thin sections of the cylinders show miliolids and several other calcareous fragments and quartz grains.

ii) *Cements*: Micrite is abundant and altered to microcrystalline spar calcite around root voids. Botryoid margins show radial fibrous calcite, which extends into the pore spaces; adjacent botryoids show coarser calcites (Fig. 3I). Neomorphic spar occludes the inter- and intra-particle porosity (Fig.3J). Neomorphic spar crystals sometimes fill the root moulds. Calcite needles organised in the form of dendrites also occur in calcite-filled portions of some transverse sections (Fig. 3I). The dendrites are light coloured and consist of primary and secondary needles expanding from a point source. These dendrites curve around some surfaces and apparently followed some planes and/or fractures. They extend into vein-like structures and also surround smaller peloids.

iii) *Interpretations of Cylinders*: The cylinders are rhizoliths i.e., root casts of higher plants. The voids and calcite filled voids in the center correspond to the root moulds and calcite filled root mouldic pores. The clear calcite in the centre, surrounded by well-cemented micrite (Fig. 3A) is a typical feature in many rhizoliths (*see* Mount and Cochen, 1984). The transverse sections (Fig. 3A-B) thus reflect different stages of root decay, preservation and calcification. The circular bodies (Fig. 3C-D) may represent root hairs. Circular hollow bodies represent root moulds. Similar size root moulds were reported in rhizoliths by Klappa (1980) and Goldstein (1988). The abundant occurrence of these circular bodies in transverse sections may actually be related to vascular cylinders in the cortex portions of the root. The botryoidal banded growth (Fig. 3E) seems to reflect calcification around a root tissue and the dark and light bands are probably different stages of growth reflecting the composition of solutions around roots during calcification. Some peloids present here (Fig. 3H) are internally hollow and some others apparently formed by the micritisation of the root tissues with a subsequent addition of micrite that modified them into large rounded to ellipsoidal forms. Both organic and inorganic processes have been reported in the formation of peloids (*see* Wright, 1994). Jones and Squair (1989) reported peloids produced by mites in softer cores of roots.

It is evident that in places microspar is a recrystallisation of micrite (Fig.3J). Radial fibrous calcite (Fig. 3I) and adjacent calcite crystals are the replacement products of pre-existing cements. The lime mud filled pore spaces adjacent to the radial fibrous calcites and coarse calcite crystals suggest that they developed from micritic textured precursor cements. Coarser calcites also contain some inclusions and turbid boundaries. (Fig. 3F). Kendall and Tucker (1973) interpreted similar inclusions, bands and associated subcrystals as growth stages of radiaxial fibrous mosaics that replaced acicular cements. They also suggested that larger calcites can form from the replacement of acicular crystals.

Dendrites following the planes (Fig. 3K) and extending in the form of veins around grains imply they are secondary calcite fillings and may record varying types of interstitial solutions. The dendrites are considered as abnormal crystal growths (Buckley, 1951) that form rapidly in supersaturated or highly supersaturated solutions. It has been suggested that higher temperatures or super cooling and also the role of algal filaments (Jones and Kahle, 1986) favour the formation of dendrites.

C. Paleosols

Reddish brown semi-indurated to indurated mudstones

Reddish brown indurated mudstones, about 2-4 cm thick form lens shaped bodies. They contain abundant ferruginised fine-grained material with grey micrite bodies (< 2 mm size) referred as glaebules (after Brewer, 1976) (Fig.4A). Ferroan calcite, quartz and goethite are major minerals with minor illite, kaolinite and chlorite in acid-insoluble residues. The organic carbon content is 1.22%. Tubular bodies (about 40 µm diameter) (Fig. 4B), similar to the calcified root-hair sheaths reported by McKee and Ward (1983), are present as micrite enveloped glaebules (Fig. 4C), circum-granular cracks filled with microspar, carbonised wood fragments of 30 µm and

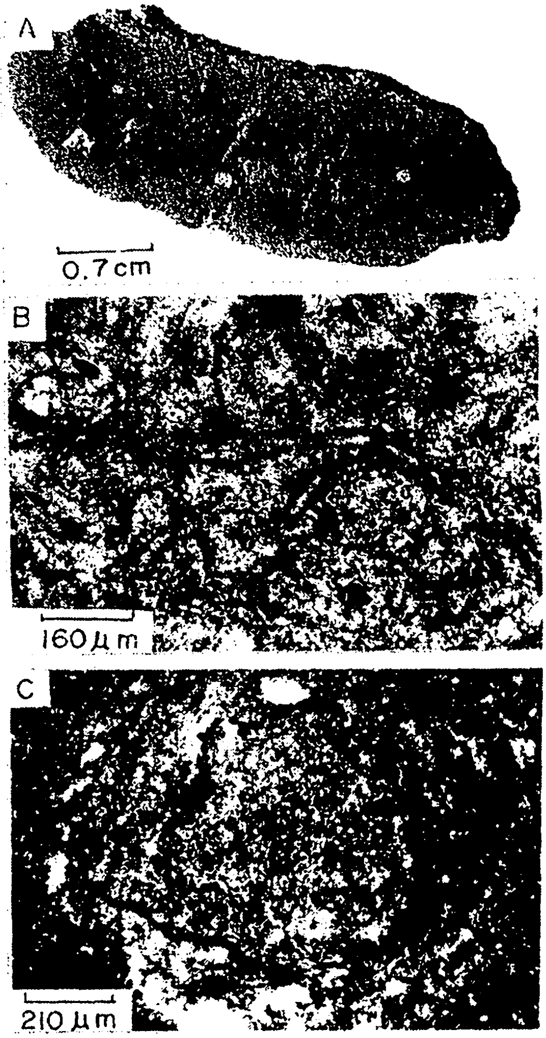

Fig.4. Reddish brown indurated mudstones: (A) polished section showing micrite glaebules in the centre, (B) calcified root hair sheaths in the matrix; (C) a glaebule showing micritic coating at the boundary and microspar in the centre.

vegetal debris such as cuticles. Pollen grains are rare and badly preserved. The identifiable ones belong to Poaceae i.e. herbaceous plants. (C. Caratini, *personal communication*).

Interpretation of mudstones

The presence of root hair sheaths (Fig. 4B), micrite glaebules (Fig. 4A, 4C), pollen of herbaceous plants, wood material and high clay content (Table I) in the mudstones implies that these are semi-indurated to indurated soils. Circumgranular cracks indicate that the soils were hardened close to the exposure surface (*see* Esteban and Klappa, 1983). A soil is a concentration of residuals of various weathering processes (from both continental and eolian sources) and iron often builds up as a weathering and leaching product of various minerals (*see* Goebel *et al.* 1989 and references therein). Red colour and fine-grain size of the soils indicate that eolian processes might have dominated. Grasses are generally associate with dunes. As finer and lighter materials like pollen of grasses are accumulated in the soils, it is likely that the soils formed as soon as active dune aggradation ceased and dunes provided some material to the soils. Modern reddish fine-grained soils, derived from eolian dust, have accumulated on coastal limestones in the Bahamas, Bermuda and in the Mediterranean region (cf. Joeckel, 1989) and as small pockets within the sequences of eolianites (*see* Mckee and Ward, 1983). Nettleton and Peterson (1983) suggested that the glaebule-rich horizons in soils form at or near the common depth of wetting. Since mudstones occur as lenses, it may be that these soils formed as small pockets adjacent to the dunes and flat paleotopography plus permeability of the unconformity surface and type of sediments controlled their formation.

DISCUSSION

A. The Relationship Between Ferroan Calcite, Pyrite and Dolomite

Ferroan calcite in rhizoliths is a neomorphic product after metastable cements. At near surface conditions, meteoric pore waters are considered to be responsible for the formation of ferroan calcite (*see* Bathurst, 1983). Pyrite in soils is a characteristic product of marine hydromorphic influences (*see* Wright, 1994). The occurrence of pyrite at the contact between root periphery and the outer pedogenic micrite envelope (Fig. 3F), around root tissues and as replaced material in the tissues suggest that pyrite formed during the early stages of root decay, in contact with marine waters and prior to the formation of ferroan calcite. The microdolomite present here is a non-ferroan variety, similar to the Coorong dolomites which formed by evaporation (Warren, 1990). As there are no present day dolomites, the environmental conditions during dolomite formation were different from the present day. These points imply that pyrite and microdolomite may have co-precipitated with metastable cements within the micro-environments in varying sulfate reducing conditions. Subsequently, meteoric water percolated into or passing through the rhizosphere altered the metastable calcites into ferroan calcite.

B. Possible Ages of Calcretes, Rhizoliths and Mudstones

The dunes of Holocene or Recent are mostly unconsolidated, while those of the Pleistocene occur as dune rocks (*see* Mckee and Ward, 1983). Dune associated calcretes reported here are therefore older than Holocene. The dune sediments accumulated above an unconformity surface apparently developed into crust and sheet calcretes during the last glacial phase.

The ^{14}C ages of the grey rhizoliths are about 10,000 years B.P. As they contain some altered cements, the radiocarbon ages of rhizoliths may be representing younger ages than the actual. As calcretes and rhizoliths contain similar particulate matter and neomorphic cement fabrics, we suggest that plant growth and dune formation on the shelf was contemporary.

The thin lenses of mudstones without fossils suggest that the plant growth on the exposed shelf probably started prior to soil development and roots may have penetrated into the substrates that contained marine fauna. Alternatively, the marine fossils may have been winnowed away, leached and dissolved within the soil profiles. Similarly, pollen of grasses in mudstones suggest that soils were formed slightly later than dune associated calcretes. It, therefore, appears that calcretes and soils represent sequence of eolianites and soils formed more or less contemporaneously.

C. Compositional Differences of Calcretes, Rhizoliths and Paleosols

Although calcretes and mudstones formed at near surface conditions, they differ in their composition (Table I). The former are enriched with Ca and depleted in Fe and consist of calcite. The latter are enriched with Fe and depleted in Ca and contain ferroan calcite. These differences could be due to the sediment type and their porosity. Calcretes for example form in net moisture deficient conditions with intense evaporation. The porous and coarse grained sediment types associated with calcretes probably favoured rapid evaporation of rising capillary water before the ground/ponded meteoric waters are enriched with iron. On the other hand, mudstones are fine-grained, less porous and originally enriched with Fe that derived from different weathering products. Permeability of the unconformity surface and finer sediment types probably favoured for retaining Fe within the ground waters of the soils which in turn precipitated into ferroan calcite.

Calcitisation of pre-existing cements in the roots may be relatively slow as it is a subsurface process. So the iron and other elements that leached from surface layers accumulated in pore waters of the rhizosphere and were gradually incorporated in calcite structure during neomorphism. High Fe content in some rhizoliths and high Mg and Mn and less Fe in others probably reflects the characteristics of pore water solutions. Therefore the differences in composition of calcretes, rhizoliths and mudstones may reflect different sedimentary environments. Type of sediments, and their porosity and permeability and type of unconformity surfaces played a major role in their formation.

CONCLUSIONS

1. The lime deposits in the study area occur as crusts, sheets, cylinders and reddish brown mudstones.
2. The reworked particulates in crusts and sheet calcretes are derived from dunes. These were initially located at the proximity of the coast and cemented by metastable cements. This stage may corresponds to ultimate Pleistocene interglacial sea level stands on the shelf. Pedogenic cementation processes overprinted on them during the Late Pleistocene sea-level regression.
3. The dune rocks and mudstones probably represent sequences of eolianites and soils formed more of less simultaneously. Their compositional differences may be due to the inherited constituents and porosity and permeability of sediments and bedrocks.
4. Cylinders are rhizoliths. The plant growth and dune formation on the shelf was contemporaneous.
5. The rhizoliths on the sea bed surface indicates that the soil in the upper horizon was probably eroded during the Holocene marine transgression or due to present day submarine erosion.

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