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PEDOGENIC CALCRETES FROM COIMBATORE AREA, TAMIL NADU: MICROMORPHOLOGY, GEOCHEMISTRY AND PALAEOCLIMATE SIGNIFICANCE

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Abstract

In this paper we present geochemistry and micromorphology (petrography and SEM data) study of Quaternary calcretes formed in association with the vertisol and hardpan calcretes-dolocretes formed on bedrock occurring in Coimbatore area, Tamil Nadu. Coimbatore receives an annual average rainfall of 400-500 mm year^{-1}. Understanding the formation of calcretes is important as this region falls in the rain shadow region receiving both the south west as well as northeast monsoon.

In the study area the calcretes formed within the vertisols representing the Bk horizon occur as thick profiles (~3m) in the foothill zone while the laminar hardpan calcretes are found in the topographic lows on the bedrock (0.80-1m). Calcretes occurring in association with the vertisols are powdery calcrete, nodular calcrete and rhizoliths with 95.22% to 64.5% of $CaCO_3$.

Micromorphology study (thin section and SEM study) of the calcretes in vertisols show the occurrence of features such as alveolar septal structures, calcified filaments, coated grains, spherulites, calcified root cells and calcispheres that indicate the biogenic origin of the calcretes, mainly induced by plant root related microbial activity. They consist of quartzose sand grains cemented by fine crystalline, glaebular, grain-coating and pore-filling micrite. Micro fabrics of hardpan calcretes with detritus hosts show evidence of replacement, displacement and shrinkage, indicating that the calcretes formed under relatively arid conditions. These characteristics reflect that the calcretes formed in a relatively near-surface environment with relatively high rates of evaporation.

Development of the calcretes in the vertisol profiles took place in phases of soil formation, erosion and reworking. The relationships between these processes caused the formation of different accrete profiles in the foothill region.

Introduction

Calcretes, which are largely present in the arid and semi-arid lands, are good paleoclimate (Achyuthan and Rajaguru, 1997) and paleo-ecological indicators as the transformations and calcrete development takes place in the interfacing of lithosphere, hydrosphere, atmosphere and biosphere (pedological environment). Calcrete development is a characteristic feature in Quaternary hill slope deposits indicating very limited sedimentation and /or surface stabilization (Goudie, 1973). Calcrete formation on the hill slope surfaces also seems to be the genetic processes, in which plant roots and associated microorganisms play an important role (Montenat, 1981; Vogt, 1984; Verrecchaia, 1987; Wright, 1991; Sancho and Meledez, 1992; Alonsa-Zarza et al., 1998). Calcretes occurring in the northwestern part of the 'Thar desert' has been worked in great detail by number of workers (Dhir, 1995; Achyuthan, 2003) for understanding their palaeoclimate significance. Calcretes also occur in the southern peninsular region of India and their occurrence as to their process of formation have not been studied till date

The study area selected is Coimbatore, a plateau region, which commands the eastern approach to the Palghat Gap and the major pass through the Western Ghats (Fig.1). In the west, the Palghat gap is a wide depression in the Western Ghats range connecting the plains of Kerala and Tamil Nadu through a low pass. The plateau is bounded by the Nilgiri hills to the north and the Palani and Anaimalai hills to the south. Situated at an altitude of 409 m above sea level, to the east, the altitude decreases progressively. Three major rivers: Bhavani, Noyil, and Amaravati drain the study area. The geology of the study area consists of Precambrian crystalline rocks mainly represented by charnockite rocks, gneisses rich in minerals such as hornblende, chlorite and biotite and dolomite limestone.

This region receives showers of the Indian summer southwest monsoon (June-August) and also the north eastern rains during October to December. The average annual rainfall received is 400-500 mm year^{-1}. The mean annual summer temperatures vary between 39°C and 23°C while the winter temperatures fluctuate between 33°C to 20°C. Coimbatore has mild winters and moderate summers.

The general vegetational canopy around Coimbatore are represented by *Acacia farnesiana, Acacia nilotica, Acacia leucophloea, Adenanthera pavonina, Aegle* *marmelos, Ailanthus excelsa, Albizia lebbek [A. lebbeck], Azadirachta indica, Cassia fistula, Cassia javanica, Cassia siamea, Ceiba pentandra, Delonix regia, Delonix elata, Hardwickia binata, Holoptelia integrifolia [Holoptelea integrifolia], Leucaena leucocephala, Limonia acidissima, Parkia biglandulosa, Peltophorum pterocarpum, Polyalthia longifolia, Samanea saman [Albizia saman], Tamarindus indica, Terminalia arjuna and Wrightia tinctoria.* Most of these plants belong to the family of Artemisia, Acacia and Chenopodiacea.

The soils are have been classified as vertisols (vertic eutropepts) (Soil Survey Staff, 1975). Calcretes and their types cover nearly one third of the study area and their occurrence have bearing upon the proximity and the relief of the area. Calcretes are locally known as “Chunambu kal” and are often used as a raw material for painting houses and laying temporary rough roads. Understanding the formation of calcretes is important as this region falls in the rain shadow region receiving both the south west as well as north east monsoon rains. The formation of calcretes within the vertisols and as laminar massive hardpan calcrete in the area of rain shadow zone raises several questions as to their formation, source of calcium carbonate and as paleoclimate significance. Moreover, the study area is particularly interesting because of several morphological varieties of calcretes developed on different lithological and geomorphologic settings. The nature and development of calcretes in vertisol development on Precambrian shield under a monsoonal climatic regime has not yet been described. The purpose of this paper is to gather new data on calcrete formation.

Calcrete profiles

Several methods of classifying calcretes profiles have been developed (Gile et al., 1966, 81; Netterberg, 1971; Goudie, 1973). Most such classifications were based on the genetic factors, mineralogy and soil fabric changes. The classifications developed by Gile et al., (1966, 81) and Goudie (1973) were found to be most useful as they covered all the basic forms of calcretes in the study area. Seven soil profiles and palaeosols were classified following Soil Taxonomy (Soil Survey Staff, 1975) and these profiles were studied by macromorphological and micromorphological methods. Calcrete profiles were studied for their color, texture, structure and distribution of calcretes (Fig.2).

Lithosections of calcretes formed within vertisols

Vertisols are well exposed in the hill slope deposits along the rills of the hills at Marudanpatti, Nanjundapuram and Ramnathapuram. Vertisols on older colluviums are ~2.5 to 3 m thick. They exhibit a homogeneous yellowish brown (10YR 5/3 to 5/4) color but generally are lighter in colour down the profile due to the abundance distribution of calcrete. The profiles can be divided into six zones based on the sediment texture and calcium carbonate nodule distribution in the profile. The zones are: Zone I (0-50 cm thick) yellowish brown (10YR 5/3 to 5/4) moderately sorted, rich in angular quartz and feldspar grains, zone II (50-120 cms thick) with pea size calcrete nodule to vertically oriented rhizoliths of calcium carbonate. There is a prolific distribution of calcareous rhizoliths that occur at a depth of 60 cms to 120 cms and below (from the surface). Calcrete nodules are powdery to compact in nature with comparatively less content of quartz and feldspar grains, with a sharp increase in mica flakes. The area around the rhizolith is bleached in color generally brownish yellow (10YR 5/8) in color. The sediments are moderately sorted and fine grained. Zone III (120-160 cms) is with high content of calcium carbonate nodules varying in size from 2-3 cms across, varying in shape from well rounded to spheroidal in nature. Calcium carbonate generally masks the original sediment colour. The proportion and hardness of the carbonate nodules increase with depth. This layer is also rich in manganese oxides in form of small concretions and dendrites along the slickenside and around the tubular porosity. The sediments are fine grained and moderately sorted with fewer amounts of quartz and feldspar grains and an increase in mafic minerals and biotite flakes. Zone IV (160-215 cms) consist of calcretes nodules varying in size 3-5 cm across, distributed in poorly sorted, subangular-angular fine silt. Zone V (215-260 cms thick) consist of small well rounded calcrete nodules (1-2 cms across) in the lower horizon of this unit (i.e. between 240-260 cms). The soil sediment has slightly higher contents of clay and silt (6–7% clay and 8–9% silt). Zone VI (260-305 cms) is devoid of any calcrete nodules and the sediments are yellowish brown, moderately sorted, subangular to angular in shape.

On the other hand vertisols formed over the alluvium exposed in the river cuttings at Uchanayur, Vellikinyur and Madattur are generally 1.5 to 2.0 m thick, dark grey to dark olive brown color (5Y 5/2 to 5/3). The morphological properties are largely represented by vertical-subvertical cracks that are clearly visible at the soil surface. At the depth of 0.10 - 0.25 m, a coarse prismatic structure and below 0.80 – 0.85 cm depth sphenoid structure is poorly visible. At about 1.60-1.69 m depth (9 cm thick) grayish black horizon predominantly occurs. The layer between 0.80 m to 2.50 m is speckled with calcium carbonate nodules of varying size (0.50 mm to 2 cm across) and shape (well rounded to amboidal) with rhizocretion. Calcified roots or rhizoliths are preserved as vertical and horizontal tubes of about 3-5 mm width and 5-7 cm in length. They are usually formed of white calcite and dolomite that consist of micrite and micro-pseudospar with some clay infillings. Veins are mostly horizontal but show different patterns from relatively regular and straight to highly sinuous. They were originally desiccation cracks probably later enlarged by root penetration.

Laminar massive hardpan calcretes (Fig. 3a and 3b).

Laminar massive hardpan calcretes are exposed in the plains and low lying areas over the bedrock of Precambrian charnockites, dolomite limestone, gneiss and schistose rock (~80 cm thick) at Maillampatti, Chinna Tagadam. 4 short profiles of hardpan calcrete-dolocrete profiles (Fig. 4) occur in the study area, mostly concentrated in the basin. The individual calcrete-dolocrete profiles average 0.80 m in thickness and can be divided in to three zone I (10-30 cms- quartz and feldspar rich), zone II (30-60 cms with increase in carbonate content and zone III (60-80 cms with high content of calcite and dolomite percentage). They are developed on dolomite limestone and Precambrian basement rocks. The complete profile consists from bottom to top, of three horizons: The prismatic horizon, 0.10 to 0.80 m thick sharply overlies the weathered bedrock and the contact is gradual. This unit is formed only after the nodular calcretes of the upper part of a calcified soil horizon becomes more heavily cemented. The hardpan generally consists of cemented honey comb calcretes, cemented calcareous powder and coalesced nodules giving rise to petroclastic horizons. These calcretes are often underlain by nodular of calcareous powdery loam with their boundaries being gradational. Locally, both dolomite and calcite are present within the same profile. This unit is represented by well developed sacharoidal crystals of calcite and dolomite. This horizon is sharply overlain by fine silty clay with root traces.

Materials and methods:

Samples of laminar massive hardpan calcretes and nodular calcrete from the vertisol profiles were collected for geochemical analyses to determine the major oxide content following Shapiro and Brannock (1962). The results are presented in table 1.

Undisturbed soil and calcrete samples were collected for micromorphological studies. 28 thin sections were made on air-dried samples following Guillore, (1985). Soil micromorphological features were described according to Bullock et al., (1995), and Federoff and Courty, (1994).

The mineralogy of carbonate nodules and the fine fractions were determined by X-ray Diffraction method using Cu Kα radiation at The Indian institute of Technology, Chennai. Nodules and hardpan calcretes were studied using scanning electron microscope (SEM): Model Leica Stereoscan No 430 I, equipped with Oxford Link Pentafet, Leica Cambridge Ltd. for semi quantitative element analyses.

Results

Morphology and distribution of calcretes associated with vertisols

Calcrete in the vertisols of the hill slope deposit commonly occur as nodules of irregular morphology with varying size and shape than the calcretes in the distal end of the hill slope and the laminar hardpan calcretes occurring in the plains.

Fine grain mineralogy

Mineralogical analyses of the non-clay fine fraction (>2 mm fraction) of the hardpan calcretes show low-magnesium calcite and lesser amounts of quartz which are the two dominant minerals present within the calcrete with trace amounts of non-ferroan dolomite (Ca $Mg(CO_3)_2$) with graphite crystals, feldspar, chlorite, titanite, chlorite, hornblende, garnet, hematite and altered biotite.

X-ray diffraction analysis of the powdered samples of the calcretes and clay (fine fraction) indicates dominance of calcite, dolomite over quartz, phyllosilicates and feldspar, montmorillonite, smectite, and traces of kaolinite, dehydrated illite-vermicullite.

Micromorphology of calcretes associated with vertisols

Groundmass

The groundmass / matrix of all calcrete types (calcrete nodules, rhizoliths and laminar hardpan calcretes0 consists of calcite which is the cementing medium. The size of the calcite crystals ranged from less than 2 µm to 15 µm in size. Three types of calcite cement occur in the matrix. They are broadly divided into:

- Micrite (2 to 4 µm) occurs as a cementing material between the skeletal grains and as a clear rim around the grains within the groundmass (Fig. 4a). The rim is 2 to 3µm in size, which at places may or may not join the particles lying in the close proximity. Micrite also occurs as micritic rims around the micritic nodules. Micrite also occurs as needles (Fig. 4b). Easily weatherable minerals such as plagioclase, hornblende and biotite grains are replaced by micrite/ microspar calcite (Fig. 4c-d).
- Microsparite and Sparite (4 to 10 µm) are subhedral crystals. Microsparite and sparite occur as drusy mosaic filling between the micritic rimmed grains and rock fragments. They were also observed in the following cases: a) The microsparite essentially occurs as hypocoatings around the voids and cavities (Fig. 5a). b) The calcite crystal size increases away from the walls of the grain / channels or cavities (Fig. 5b). c) Microsparite and sparite are generally elongated the direction of elongation is perpendicular to the wall of the cavity/ channel or grain boundary (Fig. 5c). The boundary between the micrite, microsparite, and sparite contact is serrate. Sparite (10 µm and above) generally occurs as infilling crystals within channels and voids (Fig. 5d).

Groundwater features

Groundwater features include recrystallised mottles consisting of ferruginous impregnations, cracks related to desiccation and fractures, clay mineral replacement such as dehydrated illite, smectite, concretionary laminations and etched non-carbonate grains. Biotic features observed in the field and within the thin sections are roots and rootlet filaments coated with powdery calcite (micrite). The groundmass is microcrystalline to crystalline and strongly cemented with clear calcite. Coarse quartz grains are coated by clear microspar (Fig. 6a). Channels and voids within the nodules are filled with microsparite and sparite.

Biological features

Biological features are generally represented by root pores, voids, channels and fractures. Voids are generally root pores that are infilled with micrite or clear microsparite. Staining by Alizarin Red shows that the calcite within the voids is ferroan calcite. Larger voids are cavities filled at places with sparite. These are generally observed in the nodular calcretes. In thin sections the channels either have loose collapsing walls, or are lined with calcitic clay coatings. The channels are loosely filled by grains or partially to completely filled by microsparite / sparite). The shapes of the channels vary from tubular with rounded or tapering ends, to being bent at various angles and being cylindrical. It has been observed that biological remains such as root filaments or remains of animal excrement loosely fill the channels. Fractures and shrinkage cracks are present in the hardpan calcretes of Marudanpatti, Nanjundapuram, Ramnathapuram, Madattur and Uchayanur. In most of the cases the fractures are filled by micrite or micro sparite, or remain unfilled. Thin sections of the rhizoliths reveal no occurrence of root cell pseudomorphs, which implies that calcitization of rhizomorphs has occurred only outside of root cells supporting the view of Callot et al., (1985). They suggested that fungi and bacteria feed on the decaying root organic matter.

Calcitic features

Calcitic features are represented in the calcretes only in the form of calcitic coatings, hypo coatings, and calcitic nodules.

Nodules (N)

In thin section that was studied nodules occurring in the vertisols and hardpan calcretes have been subdivided into the following types:

- Diffuse nodules (**N_1**) which are microporous has a gradual boundary with the soil matrix. In the field these nodules are whitish, soft, and small as observed in Zone I. They are always associated with hypo coatings.
- Rather dense nodules (**N_2**) (Zone II and III), which are grey or grayish and dense with a clear boundary with the adjacent soil matrix (Fig. 6b). Partially dissolved calcitic nodules have been observed in Uchayanur, Madattur, Ramanathapuram, Sanganoor Pallam. They show effects of biological activity in the form of fractures, root channels or pores. The soil matrix immediately adjacent to the nodules appears clearly depleted of calcium carbonate in sandy silt horizons.
- Very dense nodules (**N_3**) (Zone III, IV and V) are grayish white in color and their groundmass is microcrystalline, but larger crystals are also present as infillings of channels and voids. Irregular sesquioxidic impregnation is present (Fig. 6c). Calcitic particles also occur as coatings around the fine silt grains. In the field these nodules are greyish, large and hard, irregular in shape and have been observed in deep horizon of buried sediments which show signs of water logging. These can be best seen in Marudanpatti and Nanjundapuram area. Calcitic features are present in the form of compound nodules within the sandy matrix. Microsparitic calcites cement sub angular to angular grains.

Features of dissolution and reprecipitation of microsparite are observed between the grains and the matrix (fig. 6d). A gradual increase in size of calcite from micrite to sparite within the nodules is observed. As the calcium carbonate concentration increases with the depth, the microstructure evolves to pellicular grain and to intergrain micro aggregate microstructure. The porosity is high and consists of loosely packed voids and a few channels that are sometimes lined by fine micritic calcite or fine clay fillings as passage features. Micromorphological studies of the nodules exhibit a variation in the process of calcification, calcite mineral size and also in fine calcitic particle content.

Micromorphology of calcrete features occurring within the vertisols indicates three types of calcrete formation.

Type-1calcrete:

The type –I calcretes are small (0.5 mm to 2 cm across), well rounded to oval shape, and occurs in strongly developed soils of older members of soil chronoassociation i.e. The soils occur in the middle to upland interfluves of Sanganoor Pallam with very gentle slopes and deep groundwater table. The fabric of the calcrete is defined by thick continuous to discontinuous micrite and diffused calcite needles mixed with soil matrix. It also occurs as coatings (4-5 µm) around the coarse detrital grains of quartz and feldspar. Intense weathering of feldspar and biotite has occurred in these calcretes (Fig. 4c).

Type II calcretes exhibit features such as alveolar septal structures, calcified filaments, micrite coated grains, micritic spherulites indicating pedogenic processes.

Type III calcretes are calcified root cells and calcispheres that indicate the biogenic origin of the calcretes, mainly induced by plant root related microbial activity. They consist of grains of quartzose sand cemented by fine crystalline, often glaebular, grain-coating and pore-filling micrite. The calcretes were formed initially in the soil and represent the Bk horizon.

Hardpan calcretes and dolocretes in the basin:

Chemical composition of the hardpan calcretes reveals that they are predominantly composed of comparatively low-magnesium calcite. The ratio of CaO to MgO is almost 2 to 1. The low MgO content in the calcretes reflects the original carbonate and Mg phase. The second most important constituent of the calcretes is silica. The ratio of $SiO_2/CaCO_3$ is not equal as a result of calcite accumulation and void filling. Reeves (1976) made similar observations. Minor constituents include Al_2O_3 and Fe_2O_3, which are also low in content (Table 1). Low iron content in calcite is consistent with removal of available Fe^{2+} by Hydrogen sulphide. The slight ferroan composition of matrix calcite in individual calcrete nodules within the hardpan calcretes could have resulted from earlier and shallower precipitation during microbial reduction of Fe^{3+}. Low proportion of insoluble residue in the hardpan calcretes indicate that they formed by more than a simple process of dissolution, filling, reprecipitation, recementation and recrystallisation. $CaCO_3$ values vary from 80-90%. The oxide concentration indicates the upper limit of the fluctuation of an old water table.

Micromorphology of laminar Hardpan calcretes

The horizon is formed by a relatively dense mosaic of microspar in which some floating and etched detrital grains and some clay aggregates occur in the voids. Micromorphological analyses of the laminar hardpan calcrete exhibit polycyclic and polyphase development of calcitic nodules.Calcite also cements detrital grains of quartz, dolomite feldspar, and rock fragments of dolomitic limestone and charnockites. Micromorphology shows a variety of features such as meniscus cement, clay coating around the quartz and feldspar grains within the individual calcic nodules, alteration of mica, and iron oxide impregnation that can be interpreted as the result of groundwater action and pedogenesis. Therefore, these hardpan calcretes are not singularly “alpha-type or beta type” calcretes but are a combination of the two (Wright, 1990). Individual nodules consists of carbonate rims (0.3–0.5 µm thick) (1-2 in number) around the detrital grains and nodules of calcium carbonate (Fig. 7a). The alternate light and dark brown rims (10–15 µm thick) of microcrystalline calcite (Fig. 7b) were clearly visible on staining microcrystalline calcite with Alizarin red `S´. The dark laminae can be correlated to the Fe/Mg oxides and micrite and the lighter laminae to the pale pink microsparite. Darker laminations occur by the breakdown of primary iron-bearing minerals from the Precambriam gneissic and charnockite rocks. There is a direct relationship between the thickness of the laminae and the host grain size: coarser the grain size - thicker the laminae (Fig.7c). Alonso-Zarza (1999) also corroborates the same view. Wavy layers of dark coloured micrite occur as a rim all along the microsparitic and the sparitic nodules/ iron oxide nodules (Fig. 7b.). These types of nodules at places are also dissolved at their edges. With the increase in depth the distribution of nodules becomes high. This is an evidence of groundwater action, which is supported by features like loosely packed, single grain type of microstructures. Between the interface cement (micrite/microsparite) and the pore space; meniscus cement has formed at localised grain contacts. The individual nodules within the calcretes (0.1–0.5 mm across) are spherical or ellipsoidal with one concentric rim (10–15 mm thick) of grey micrite (Fig. 7b). At the point contact, the cement consists of fine clear microspar or micrite, formed by the process by which freshwater films around the grains dissolve carbonate to allow original point contacts between the grains to become flatter (Knox, 1977). This cement is evidence of fluctuating ground water activity (Achyuthan, 2003).

Floating texture was also observed. Exfoliation of biotite grains (Fig. 7d) many a time forming iron oxide halo around it is common within the individual nodules. Some of the intergranular fractures within the laminations are cemented with either micrite or sparite. These crystals are from 0.1 to 1 μm across and their morphology varies from sub-anhedral to sub-euhedral.

Hardpan calcretes display calcified rootlets and filaments, which is indicative of some rooted vegetation overlying the hardpans during the formation. In a few voids acicular crystals of calcite were observed forming a mat on the nodule surface (Fig. 7e). The pores are spherical and 1-5 μm in diameter and are lined by micrite crystals. SEM images (Fig. 7f) of calcified organic structure probably represent the cell walls of vascular tissues of roots (?).

Discussion

No dates have been obtained on these paleosols. However, occurrence of Mesolithic-Upper Palaeolithic artifacts on the vertisol surface, and over the laminar calcrete and also the thickness of the soil profiles dates the landscape to a minimum age of Terminal Pleistocene or last glacial maximum.

The type of plants that presently grow on the hill slope surface since the late Pleistocene period corresponds to a sparse cover of xeroesclerofile bushes and shrubs of Chenopodiacea, Acacia and Artemisia. These plants are characterized by the development of extensive root systems. The roots systems expand over broad zones also favor extensive carbonate precipitation, dissolution, restructuring and reworking. The present vegetation of plant species indicate similar occurrence of semi arid-dry conditions probably that were operating during calcrete development. The geochemical analysis and the micromorphological studies of the soil sediments and the various types of calcretes reveal that $CaCO_3$ is the predominant oxide and the calcrete nodules have been formed by the complex process of pedogenesis and groundwater action.

The Terminal Pleistocene hill slope surfaces studied here, show features of calcrete development within the vertisols such as calcified filaments, coated grains, rhizoliths, alveolar septal structures and peloids that are commonly recognized as biogenic or β-calcretes (Wright, 1991). The recognition of different horizons and the occurrence of rhizoliths are indicative that most carbonate accumulation occurs in the soil (Gile et al., 1966; Esteban and Klappa, 1983; Machette, 1985; Mack and James, 1992), but it is mainly induced or accelerated by the activity of root plants. However, some of the structures reported here, such as spherulites, have developed at the soil atmosphere surface (Verrecchia et al., 1995).

The occurrence of fine calcitic crystals as hypo coatings, and impregnate calcitic features could be the initial stages of pedogenic calcitic accumulation to form nodules. The source for the fine calcitic crystals could be the weathering of calc rich minerals and also the dissolution of calcic grains from the upper layers getting accumulated and reprecipitated in lower horizons. The dissolution and reprecipitation of calcite also takes place in the form of needles within the intergrain voids and spaces. The process of dissolution and fast reprecipitation can explain the presence of distinct dull grey micritic envelopes occurring around the sparitic and microsparitic nodules. The process of the dissolution of calcite crystals forms fractures within the nodules.

The entire paleosol sequence is rich in both calcite and dolomite of different sizes and morphologies. Whereas carbonate in zones III varies from 64.5 to 95.22%, that of zones II, reaches up to ~80-85% forming carbonate nodules with chlorite, garnet, hornblende and titanite as accessory minerals. In general, dolomite is medium to coarse grained and more dominant in the lower part (i.e., zones III), whereas calcite is fine grained and more abundant in the lower part of the sequence (i.e., zones II). In zone IV dolomite is uniformly fine-grained with specks of graphite and is also mixed with calcite.

The mass fraction of carbonate gradually decreases downward and ceases ~1.60m below zone I. Carbonates in zone I (quartz-rich) primarily appear as cements of quartz-grain boundaries, suggesting they precipitated under an evaporitic condition.

Carbonates in zones II and III are characteristically euhedral, and fine (50 to 60 μm) calcite-rich grain and Fe-poor (<3.5 % Fe_2O_3; - Table 1). Zoning texture is observed in coarse dolomite grains from the top part of zone III, suggesting the dolomites precipitated from repeatedly percolating fluids (either soil water or groundwater) with various Mg/Ca ratios. Some calcites in zone III have small dolomite cores, indicating that calcite formed later than dolomite in this zone. The carbonates in the vertisol calcretes are pedogenic; they formed by utilizing Ca that leached from the upper soil section by downward flowing soil water (rainwater), CO_2 from the atmosphere (rainwater), and additional CO_2 generated by the oxidation of plant roots and soil organisms. Most of the carbonate minerals in the silicate-rich zones (I, II and III) of the Sanganoor Pallam, Madattur, Ramnathapuram paleosols are pedogenic.

Traces of hematite are indicative of an oxygenated environment (Jaynes and Chafetz, 1997). The quartz, feldspar, and biotite are interpreted as being lithogenic and/or detrital in origin. Quartz and feldspars are common to the dust, vertisols, and limestone residues within the region, and are considered to be locally derived.

Mg and Fe in the carbonates (Fe-rich dolomite and Mg-rich calcite) of the paleosol sequence could have been supplied by alteration of the pyroxene and amphiboles which contains high amounts of Mg and Fe. Studies of modern massive pedogenic carbonate horizons show that the primary source of Ca is generally eolian carbonate dust from regional sources rather than weathering of the parent material (Capo and Chadwick, 1999; Van der Hoven and Quade, 2002; Achyuthan, 2003).

The main processes occurring at any precise stage are clearly seen at the macroscale in the hill slopes (Fig. 7a). The main stages are

Stage 1

Formation of transitional horizon begins with the Bt horizon of the previous soil that is overlain by detrital sediments varying from clays to medium gravels. The vegetation grew over the sediments and roots reached the Bt horizons. The soil fauna creates channels and voids through which the solutions flow preferentially. Calcium carbonate that is dissolved and removed from the upper horizons of the soil accumulates lower in the soil matrix void and channel porosity. The solutions evaporate and the calcium carbonate precipitates as small micro calcite crystals or needles. This recrystallization particularly affects the walls of the channels and the voids, giving rise to hypo coatings and impregnative infillings. As in the colluvium area, it may suggested that hypo coatings and impregnative infillings represent the first stages if calcite accumulation whereas evapotranspiration culminates in the precipitation of calcite crystals in a diffuse form. Hypocoatings and impregnative infilling are gradually coalesce and nodules become denser as simple packing voids and grain pores are in filled with secondary calcite crystals.

Stage 2

Increased carbonate precipitation around roots results in the formation of carbonate nodules of variable size and morphology. The transition between the stage 1 and nodular horizon is progressive. Subsequent growth of nodules is characterized by partial coalescence of nodules giving rise to a hardened but still friable, nodular horizon.

Stage 3

Deposition is greater than erosion. Carbonate precipitation is very intense and does not follow the root structures, but also occurs throughout the uppermost part of the K horizon. At this stage, the K horizon is progressively indurated and porosity is drastically reduced, leading to the occurrence of perched / episodic micro-water table above it (Alonso-Zarza et al., 1998). At this stage plant roots, looking for water have extended laterally promoting the development of sub-horizontal root networks. The laminar horizon forms in the still unconsolidated uppermost zone. The degree of development, thickness of this horizon depends on the time that the root systems are able to be supported either in the upper soil horizon or by the new detrital deposits. As the accumulation of calcium carbonate increases the porosity and permeability of the soil sediment decreases. The original constituents of the host material are progressively replaced with increasing amounts of calcite. At this stage the $CaCO_3$ nodules may be counteracted by soil fauna or by local colluvial transport causing local reworking. But in deeper horizon due to a rise in the level of ground waters the nodules are dissolved disrupted and are eventually recemented. Thin carbonate laminae with detritus sediments indicates relatively short periods of stabilization probably followed by rapid sedimentation (Alonso-Zarza, 1999). Longer quiescent periods probably account for the formation of thicker carbonate laminar calcretes (Machette, 1985, Sanz and Wright

1994). Sesquioxidic features are characteristic of very dense nodules or nodules at deeper horizons. Their occurrence can be explained as the consequence of water logging in deep horizons generating reducing conditions that favor the mobility of ferrous iron. As accumulation of calcium carbonate increases, a point is reached when the soil fauna/organisms can no longer maintain viability. The intensity of soil forming processes diminishes and eventually ceases to be important.

Stage 4

Plant roots induce mechanical weathering, degradation and reworking of the topmost laminar horizon, which results in the development of calcrete rubble progressively leading to the development of calcrete breccia. The size of the calcite crystals in the ground mass indicates that the first stage of calcium carbonate precipitation is not due to vertical leaching from top to bottom but is the result of a vadose crystallization of calcium carbonate transported by groundwater. This is amply supported by features like meniscus cement, laminar features, etc. the nodules were then modified due to vertical leaching or reworking during erosional phases. Erosion or high sedimentation rates will inhibit both lamina formation and preservation. Repeated succession and combination of these various processes have thus given rise to complex features.

Stage 5

Erosion rate is higher than sedimentation rate. The upper part of the calcrete profile (B horizon or sediments) is removed and the laminar horizon is directly exposed to the atmosphere. Laminar brecciated horizons at surface indicate episodic runoff erosion that would have removed earlier overlying weathered materials (Alonso-Zarza et al., 1998). Diagenitic processes, mainly recementation, and replacement leads to the fossilization and indurations of calcretes into palaeocalciorthids. The indurated calcrete profiles if they remain at the land surface are subjected to further processes, which disrupt and alter the calcitic nodules. Further pedoturbation carbonate dissolution and reprecipitation leads to the formation of reworked calcitic clasts and /or recemented calcrete breccia. This process of calcrete formation is commonly observed in the depression and calcrete nodules formed within aeolian and fluvio-aeolian sediments (Raghavan, 1987).

Stages 4 and 5 can be developed in the same profile at different times and even be repeated several times resulting in a complex arrangement of horizons and micro fabrics in the soil profiles.

On the other hand laminar massive hardpan calcretes reveal a complex process of development. Micromorphology characters such as the admixture of non-cemented coarse fragments in the calcium carbonate nodules suggest that some of the nodules could have been transported or reworked. More over uncoated sand size and well-rounded nodules also suggest reworking.

Laminar massive hardpan calcrete formation:

The sequence of events in the hard pan calcretes can be reconstructed (Fig. 7b) as follows:

- In the study area- a landscape devoid of a hydrographic system an increase in the rainfall induces the waters to infiltrate through the sand, thus raising the ground water levels almost up to the surface of the soil in the depressions and above the surface in the deepest parts. Due to evapotranspiration during the dry seasons, calcium carbonates precipitate. Accretion processes form nodules.
- During erosional phases, probably once again due to heavy rains in arid conditions nodules behave as coarse elements and are transported by water. These nodules act as nuclei and are recemented by calcium carbonate. Rock fragments also get cemented along with the transported calcium carbonate nodules. Structures reported here, such as spherulites, have developed at the soil atmosphere surface. Calcitic spherulites that are relatively common in thick laminar calcrete profiles (Wright et al., 1996) have been interpreted to have been formed in desiccating surficial ponded waters (Verrecchia et al., 1995). In this study the spherulites in the laminar massive carbonate zones (I and II) are interpreted to have precipitated under air and/or water bodies (shallow pond) by locally discharged groundwater, rather than within soil (pedogenic) by downward-flowing soil water for the following reasons:

    (a) The desiccation-like cracks and sparry calcite at the top of zones II and III (Fig. 6i) suggest the carbonates precipitated either under air or in a shallow water body before the accumulation of silicate-rich rocks in zones III and I. If the carbonates mostly formed under air, they would have been dissolved by the low-pH (high pCO_2). Therefore, the massive carbonates probably precipitated in a high-pH water body (shallow pond) by local discharged groundwater.

(b) The abundance of carbonate minerals changes abruptly from ~50% in the massive carbonate zones (III and II) to ~10% in the overlying silica-rich zones (I). This also suggests that the silicate-rich zones were not present during the formation of the massive carbonate zones.During more stabilized phases, the landscape is affected by pedological processes due to the growth of vegetation or increased density of vegetation thus altering the original fabric. Micronodules within the hardpan calcretes have been interpreted as being formed by either cyanobacteria or bacteria (Verrecchia et al.,1995; Wright et al., 1996).

- Frequent repetition of this cycle and the succession of micro phases within it have given rise to laminar massive hardpan calcretes in low-lying areas. Fluvial action of streams having their catchments in nearby Western Ghats was responsible for the disruption of hardpan calcretes into fragments or boulders, cobbles and gravels. As the succession of the phase can vary the hardpan calcretes have been formed by groundwater and pedological processes forming compound profiles formed on hard substrates.

Paleoclimate inference

Lack of intense leaching by rainfall often leads to the formation of laterally extensive pedogenic carbonate in layers (Capo and Chadwick, 1999). In our study presence of clays such as smectite, montmorillonite, hematite and illite vermiculite and absence of sepiolite-palygorskite associated with low magnesium calcite indicate that the calcretes formed under semiarid climate (mean annual rainfall between 300-500 mm) similar to the present climate of the area. Formation of hematite requires very high temperatures or environments wherein the activity of water is considerably reduced. More over sepiolite and palygorskite are generally present in soils of drier climates (arid, mean annual rainfall 50-100mm) (Verrecchia and Verrecchia, 1994; Jimenez-Espinosa and Jimenez-Millan, 2003).The clay mineralogy of the vertisols in hill slope deposits do not indicate important changes in the climatic regime before and after the calcrete formation. Calcretization appears to have been controlled by stability of the slope. Plant colonization of the colluvial surface deposit leading to the formation of calcrete has taken place under relatively stable conditions in a semi arid environment.

Conclusions

No dates have been obtained on these paleosols. Occurrence of Mesolithic-Upper Palaeolithic artifacts on the vertisol surface, and over the laminar calcrete and also the thickness of the soil profiles date the landscape to a minimum age of Terminal Pleistocene or last glacial maximum.

Micromoprhology studies inidicate that calcrete development was initially nucleated along the prismatic structures of the previous red alluvial soil (Bt horizons),supported by root decomposing activity which controlled the morphology of the carbonate accumulation within the soil during the earlier stages of development.

The occurrence of micro-spar calcrete crystals, adhesion of clays and silt-sized detritus grains in the micrite, spherulites either in thin laminae or within the calcrete and brecciated laminar horizons, indicate that these calcretes do not represent a unique and continuous stage of soil formation, but that degradation, reworking and exposure of some previously formed horizons (mainly the laminar horizon) occurred throughout calcrete development, especially in distal areas of the hill slope. The formation of the thick calcrete profiles took place in different more or less well differentiated stages that were repeated over time. Pedogenic calcretes formed within vertisols and laminar massive hardpan is mostly compound paleosols.

Laminar massive hardpan calcretes can be used as indicators of depositional environments with periods of relative stability with a thin soil cover that allowed the growth of vegetation followed by events of sedimentation thus giving rise to composite profiles in a semi arid environment.

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Table 1: Major oxide concentration of calcrete nodules.

Site: Marudanpatti

Sample No.	Depth (cms)	SiO_2 (%)	Al_2O_3 (%)	Fe_2O_3 (%)	$CaCO_3$ (%)
1	20	18.08	1.3	1.5	77.12
2	50	13.88	0.6	1.3	82.22
3	80	16.24	0.6	2.1	80.06
4	110	19.78	0.9	1.2	77.12
5	140	18.76	1.1	1.6	76.54
6	170	15.36	1.2	1.4	80.04

Site: Nanjundapuram

1	15	2.32	1.32	1.8	92.56
2	25	10.32	1.44	2.4	83.84
3	65	8.35	1.27	3.0	85.38
4	75	5.4	2.2	2.7	87.7
5	150	1.1	1.08	0.6	95.22

Site: Ramanathapuram

1	20	17.64	1.7	3.3	75.36
2	45	8.74	0.6	2.7	85.96
3	60	13.37	0.9	2.1	81.63
4	80	5.3	0.8	1.1	90.8
5	100	2.8	1.65	0.8	93.75
6	150	13.41	2.6	3.0	78.99

Site: Madattur

1	15	21.24	1.8	2.4	72.56
2	40	25.7	2.2	3.3	66.8
3	65	25.2	2.4	2.1	68.3
4	120	26.7	2.9	3.9	64.5

Site: Uchayanur

1	20	17.93	2.6	3.3	74.17
2	50	7.32	0.8	3.0	86.88
3	65	8.74	1.1	2.4	85.76
4	80	20.08	1.0	2.7	74.22
5	90	25.89	1.7	3.6	66.81
6	110	28.6	1.6	3.3	64.5
7	150	25.76	1.2	1.8	69.24

Table 2. Micromorphology of calcretes formed in the vertisols and in the hardpan calcretes.

Site and depth	Calcrete type	Course fraction mineralogy	Texture	Features
Sanganoor Pallam (10 cms – 30 cms, 40-60 cms, and 80-85 cms) Uchayanur (20 cms - 40 cms) Madattur (70 cms - 90 cms)	N_1	Quartz, Chlorite, hornblende, garnet, hematite Calcite.	Angular to sub angular grains of the minerals.	Voids and mineral grains surrounded by calcite coating, clay pellets with micritic calcite, Oolitic features.
Sanganoor Pallam (110-140 cms, 160-170 cms), Vellikinur canal cutting, (230 cms - 250 cms and 300 cms - 320 cms) Nanjundapuram (60 cms - 80 cms) Ramnathapuram (90 cms-110 cms)	N_2	Quartz, Biotite, Calcite, Chlorite, garnet, hematite, limonite Plagioclase.	Sub rounded. Angular to sub angular grains.	Calcite coating, brown clay coatings around certain quartz grains. Unfilled voids are present.
Sanganoor Pallam (180 cms -195 cms and below) Vellikinur canal cutting. (270 cms – 280 cms) Ramnathapuram (115cms -120 cms)	N_3	Quartz, Biotite, hematite, Magnetite, Chlorite, Calcite.	Sub angular grains of quartz, sub rounded calcite, Flakes of biotite, prismatic and elongated Chlorites	Calc coatings around the voids and certain mineral grains. Fracture filled with micrite.
Maillampatti (1 cms-10 cms, 40 cms to 50 cms , 80 cms to 85 cms)	Hardpan calcretes	Quartz, biotite, garnet, titanite, calcite, dolomite with graphite crystals, hematite and magnetite.	Grains are small to medium and are angular to subangular.	Some grains coated with two layers of calcltic coatings. These grains are first surrounded by grey micrite and then by clear calcite coating. Voids are filled with micrite and microspar. Channels are lined by micaceous clay and in filled with grey micrite and clear microspar calcite. Micrite spherulites within the laminae.

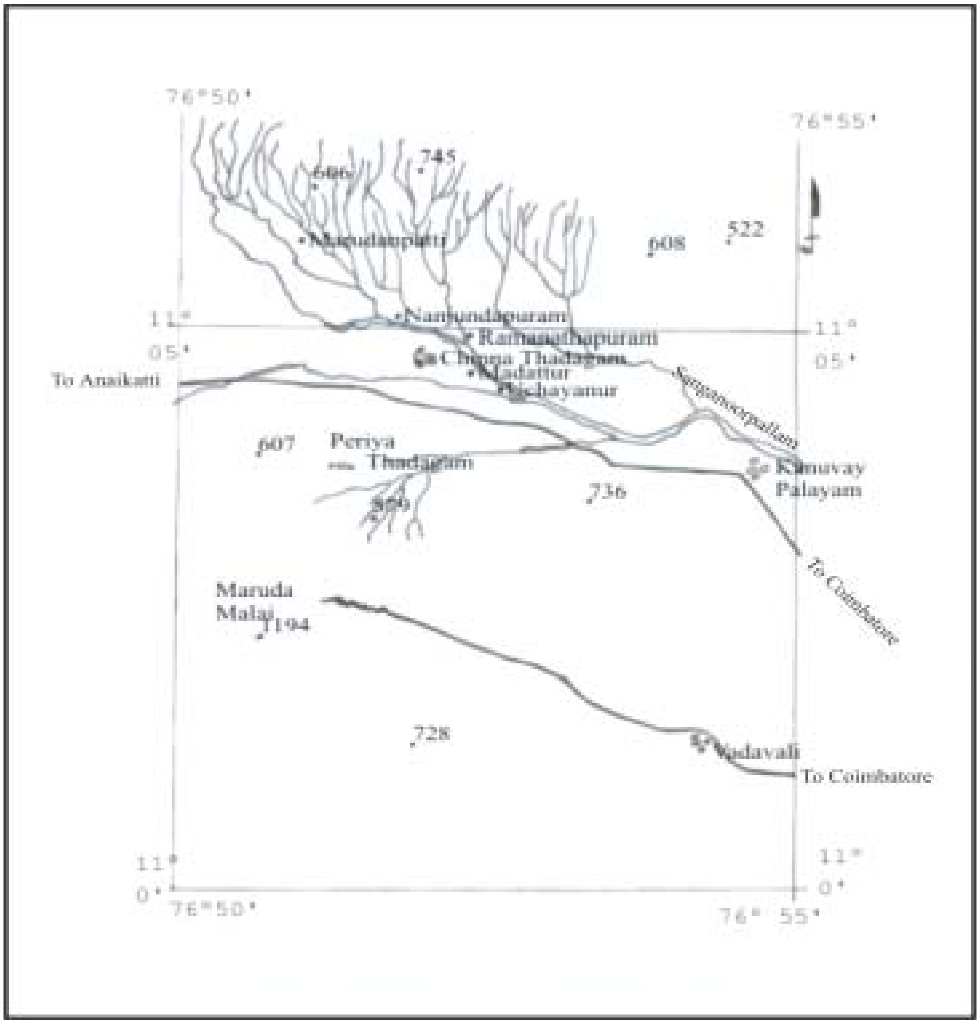

Fig. 1. Location map of the study site. Circles indicate the location of different sites of the Coimbatore region.

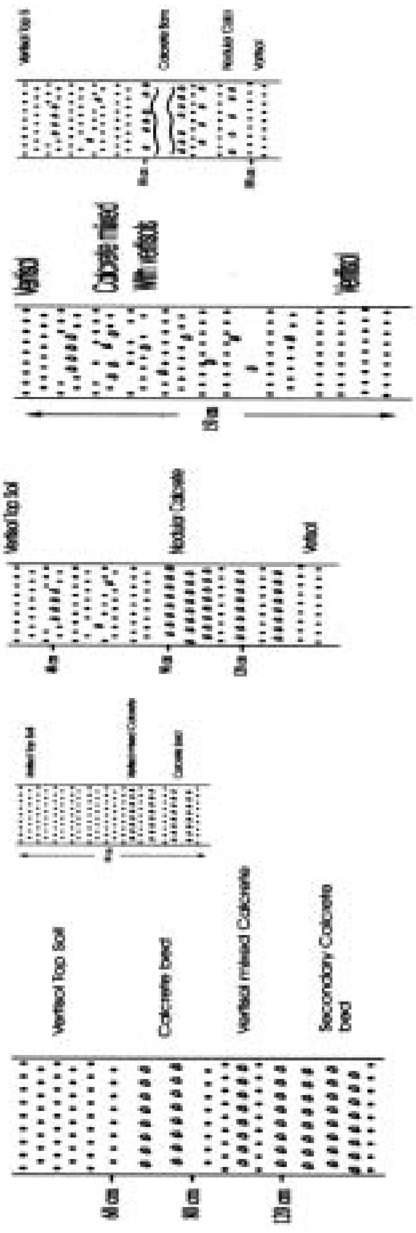

Fig.2. Lithosections observed at: a) Marudanpatti, b) Nanjundapuram, c) Uchayanur I, d) Uchayanur II, e) Madattur.

Fig.3a. Laminar Hardpan Calcrete profile exposed at Maillampatti

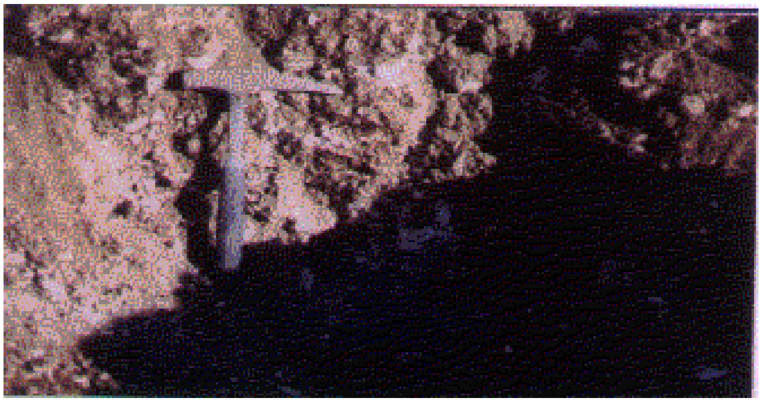

Fig.3b. Close-up View of the exposed laminar hardpan profile at Maillampatti.

Fig. 4a. Stereo photomicrograph showing micrite occurring as cementing material between the fine grains and as a clear rim around coarse grain. X50.

Fig.4b. SEM image of micrite needles.

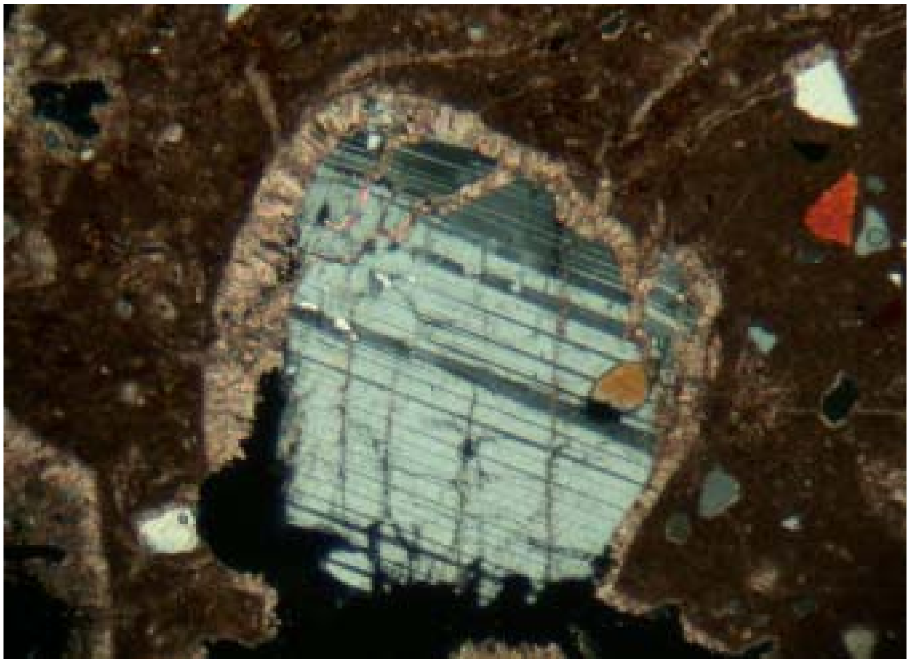

Fig. 4c. Photomicrograph showing plagioclase grain getting altered and getting replaced by micrite. BXN. Magnification X50.

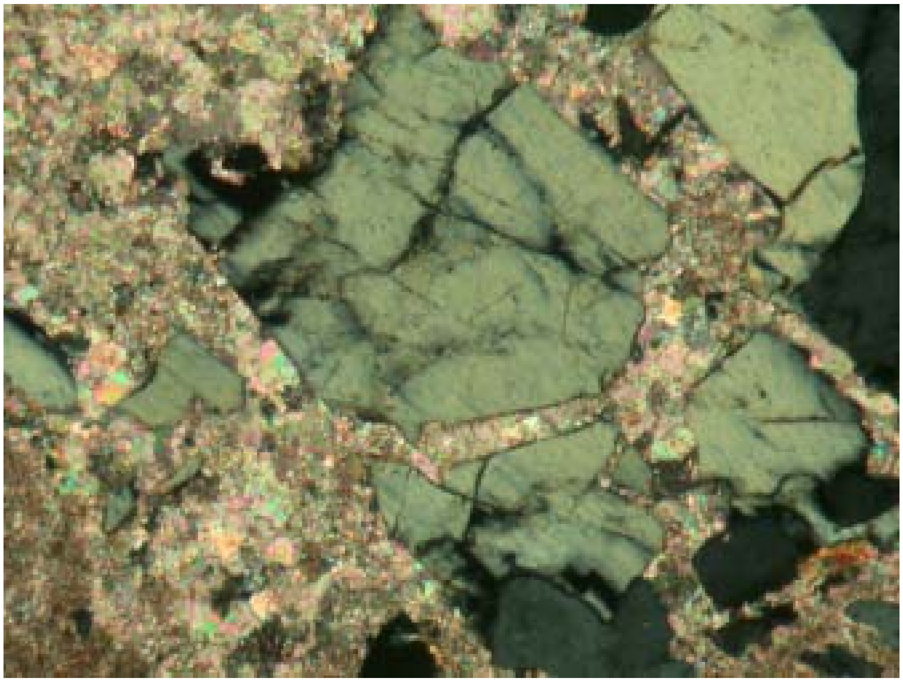

Fig 4d. Photomicrograph showing hornblende grain getting altered and getting replaced by micrite. BXN. Magnification X50.

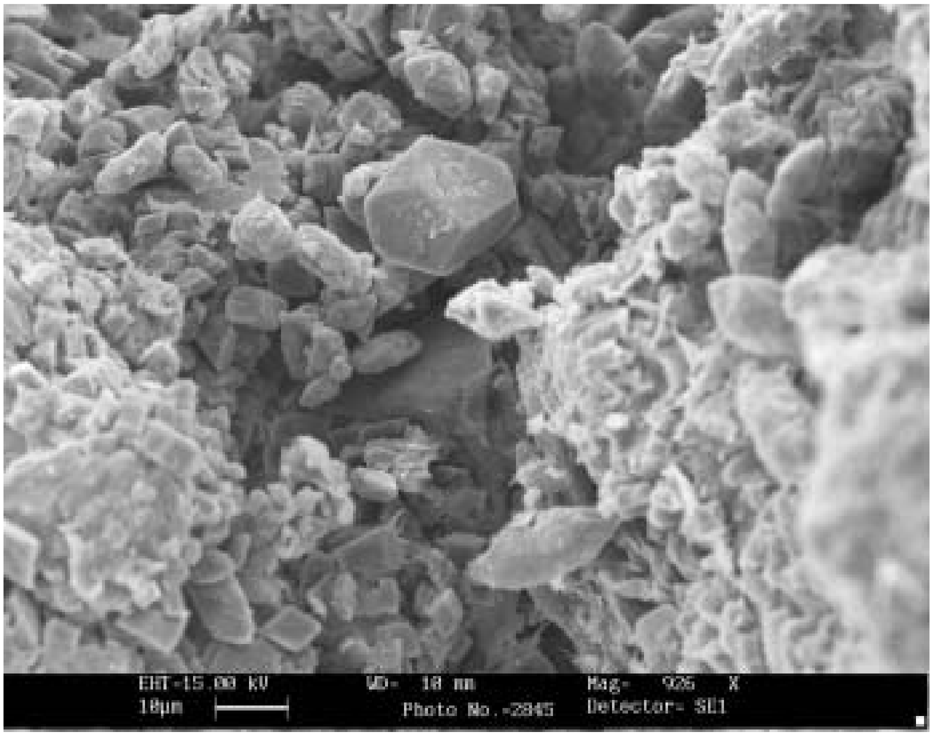

Fig. 5a. SEM image of microsparite occurring as hypocoatings around voids.

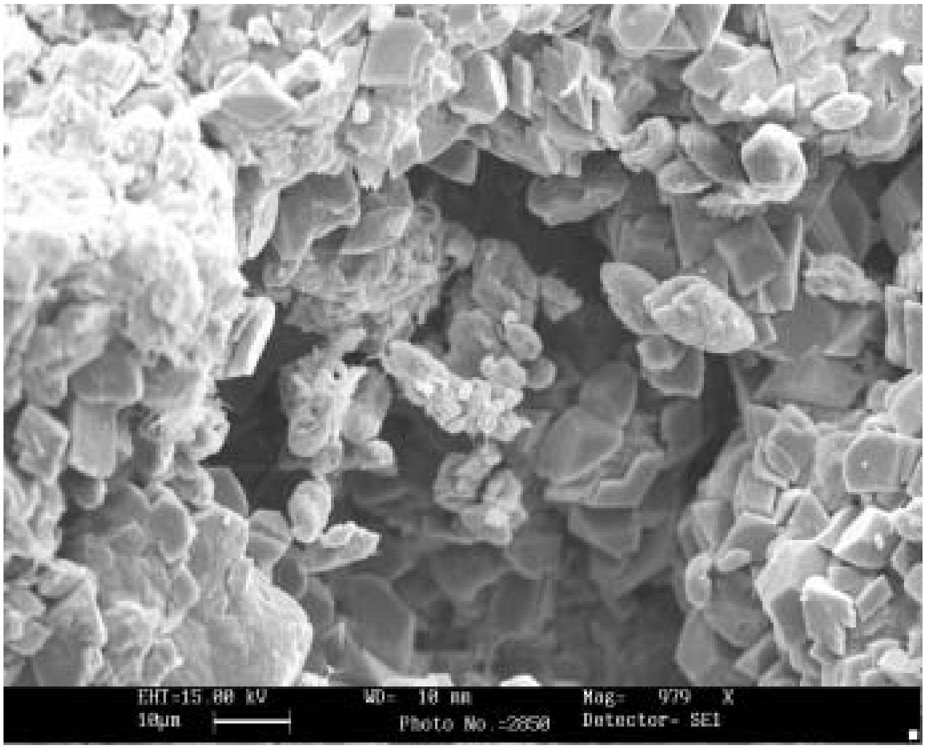

Fig. 5b. SEM photograph of calcite crystal size increases away from the walls of the cavity/ pore space.

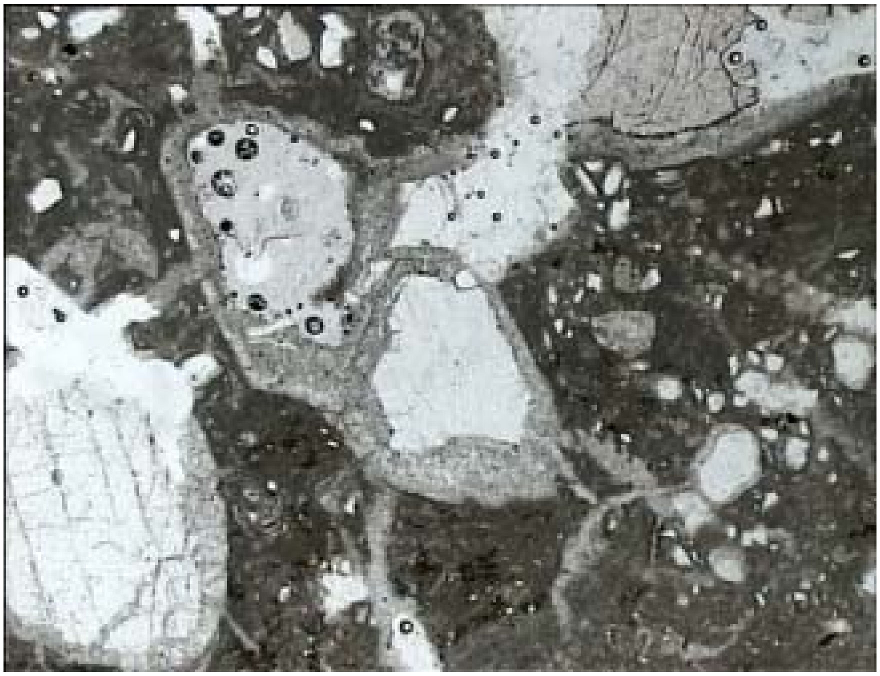

Fig. 5c. Syereophotomicrograph of calcrete rhizolith showing elongated of micrite calcite to the grain boundary. Note the arrow mark. Magnification X50.

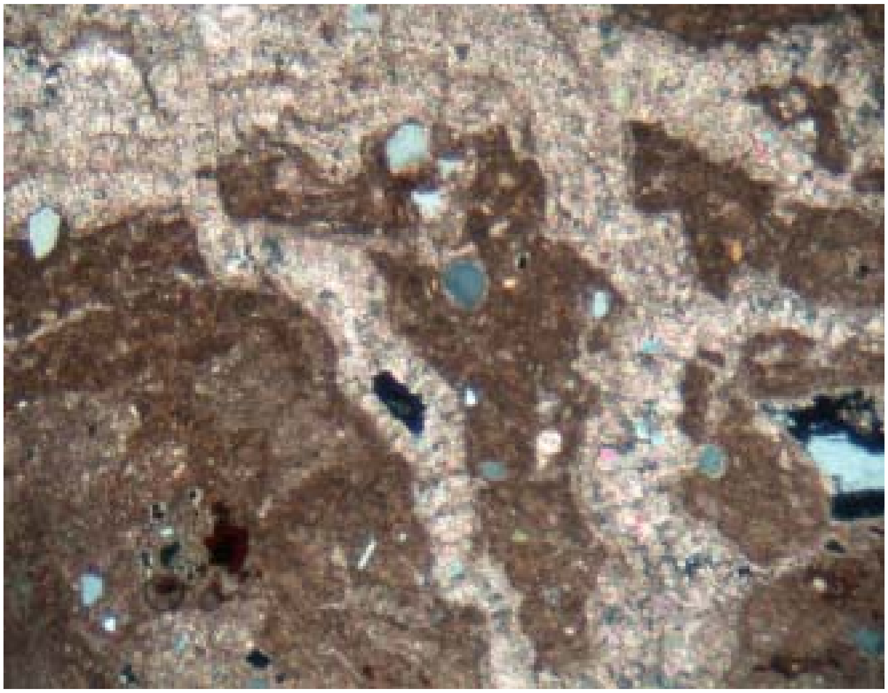

Fig. 5d. Photomicrograph showing channels getting filled by clear micrite and microspar. BXN. Magnification X50.

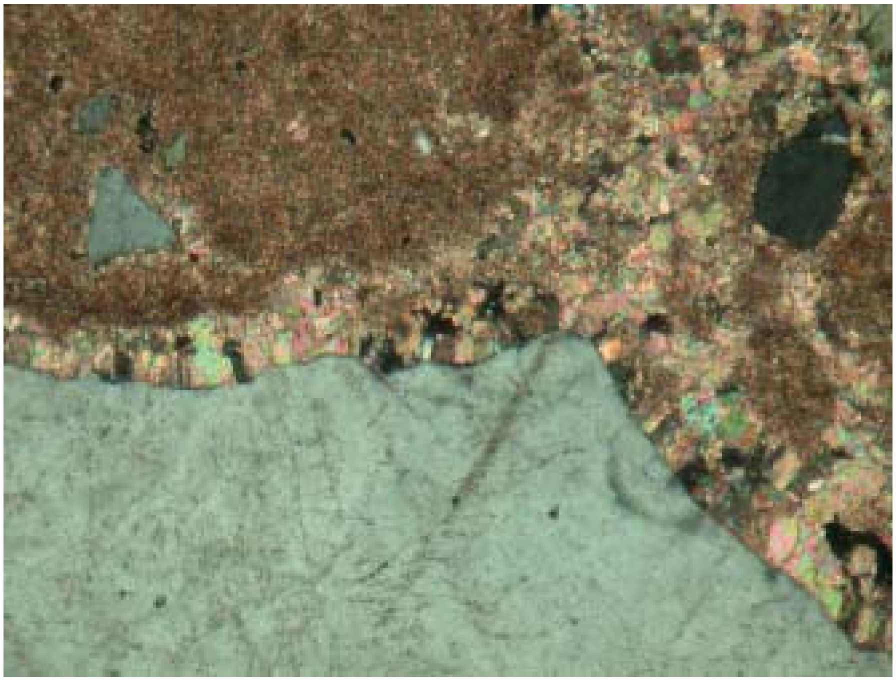

Fig. 6a. Photomicrograph of a part of quartz grain lined around by microspar and micrite. BXN. X50.

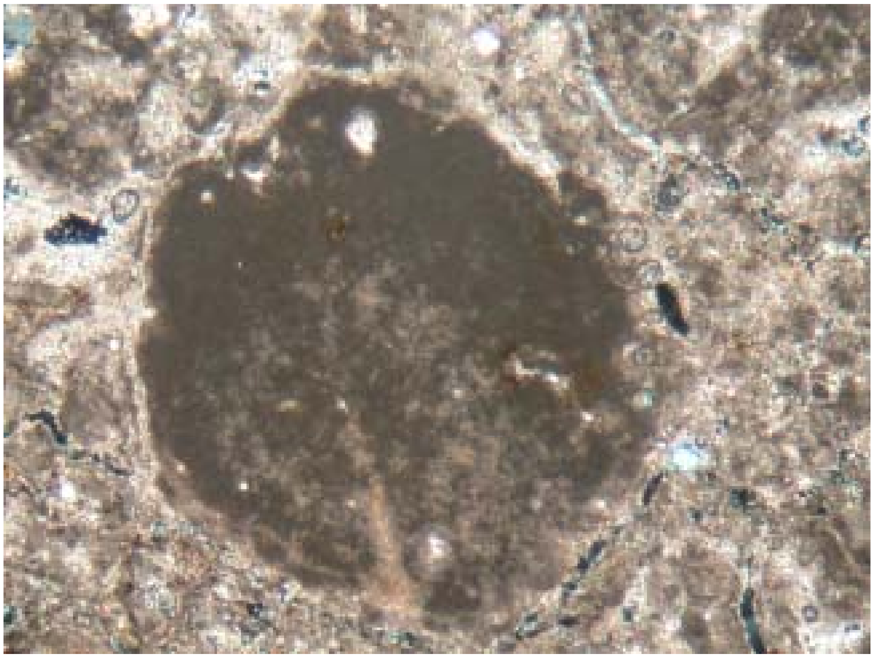

Fig. 6b. Photomicrograph showing dense grey micrite nodule in a micrite cement. P.P.L. X60.

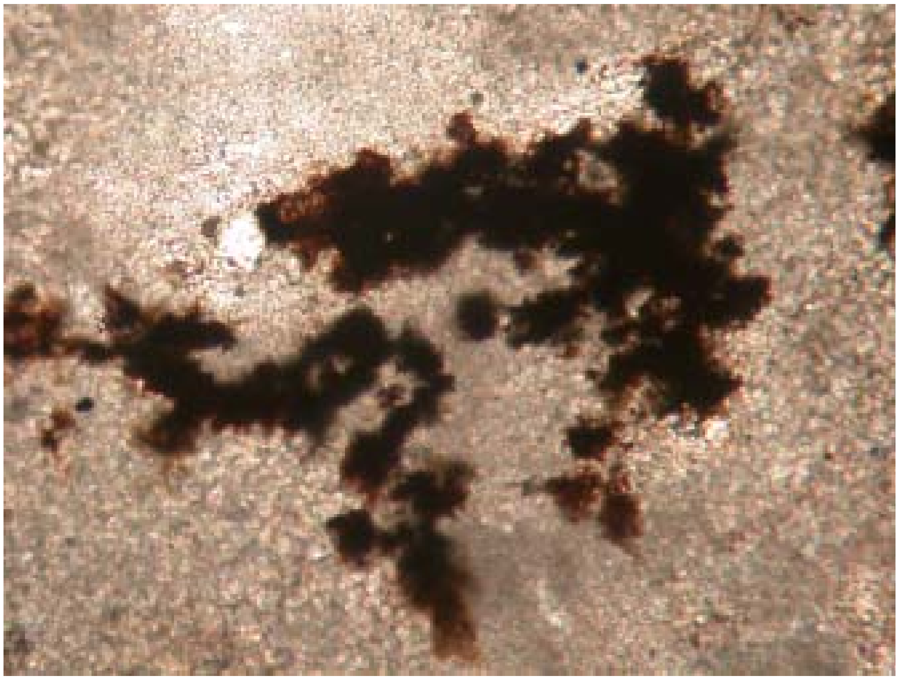

Fig. 6c. Photomicrograph of dendrtiic impregnation of sesquioxides in a micrite groundmass. BXN. X50.

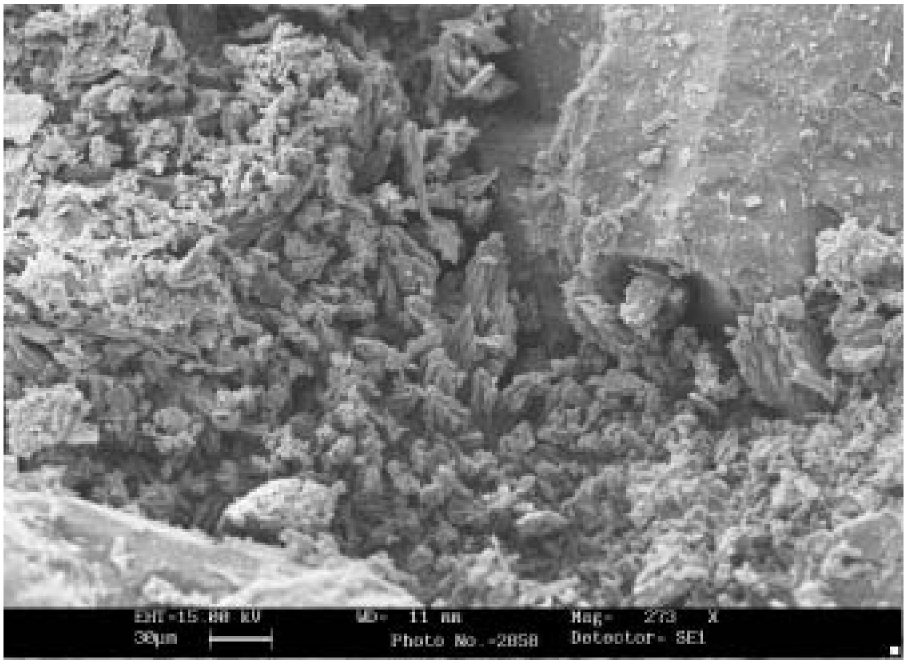

Fig. 6d. SEM image of microspar in a hardpan calcrete. Their faces show dissolution features.

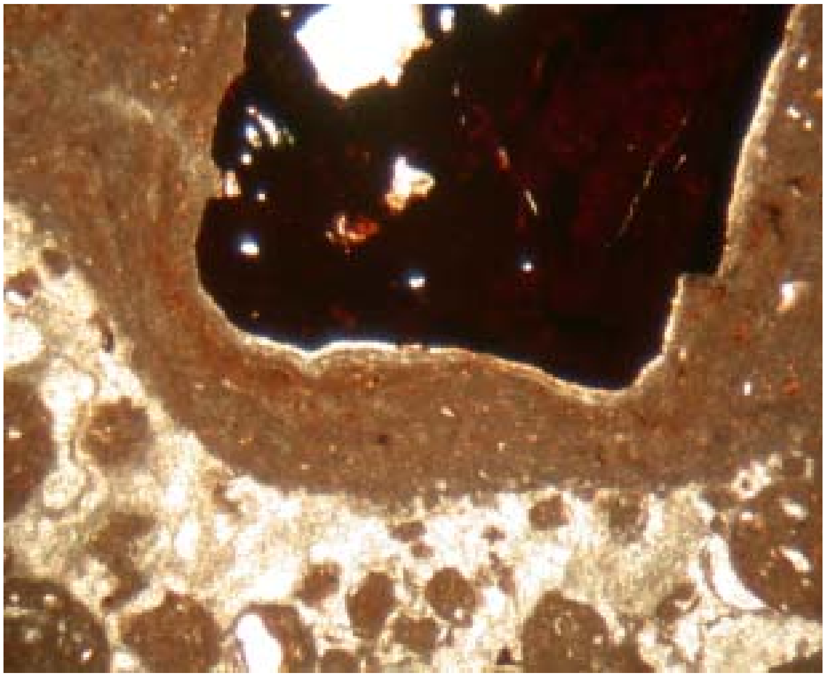

Fig. 7a. Photomicrograph of calcrete showing a thick wavy micrite rim around the iron oxide nodule. Note spehrulites of micrite in the channel. P.P.L. X60.

Fig. 7b. Stereophotomicrograph of a laminar hardpan calcrete showing micronodules with micrite rim cemented with detrital grains. Magnification X50.

Fig. 7c. Stereophotomicrograph showing the details of micrite laminae around the micronodules. Magnification X50.

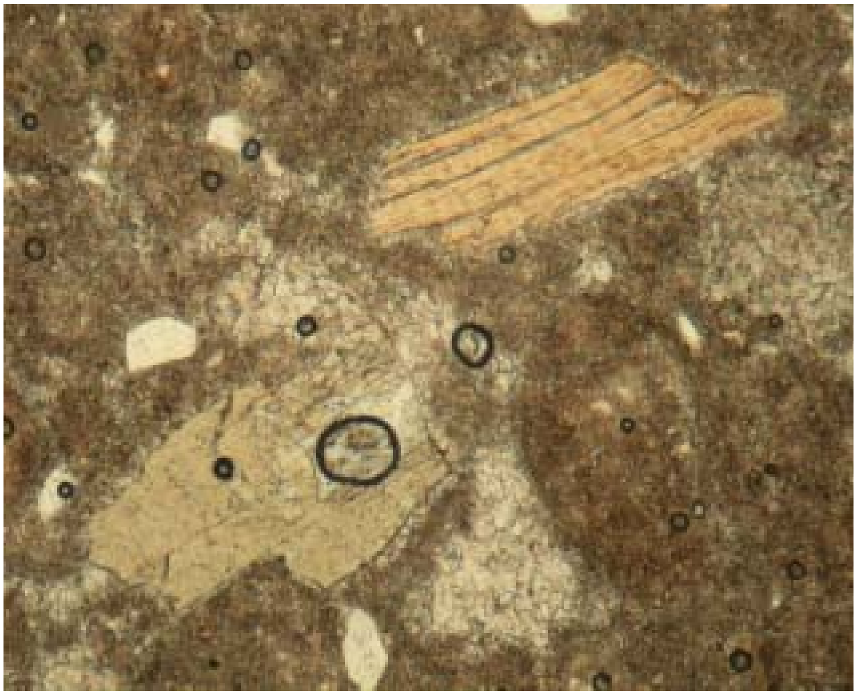

Fig. 7d. Photomicrograph of a hardpan calcrete showing exfoliation of biotite grains. Note the occurrence of micrite peloid in the micrite cement.P.P.L. Magnification X50.

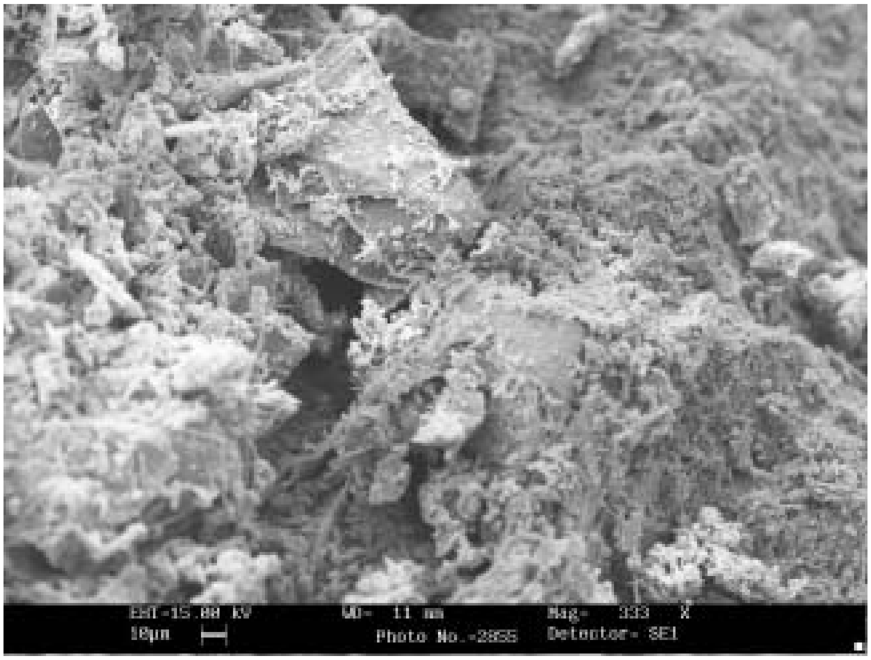

Fig. 7e. SEM image of micrite fibers enveloping the grains. The coatings are formed by calicifed filaments that are interconnected. Note the arrow mark.

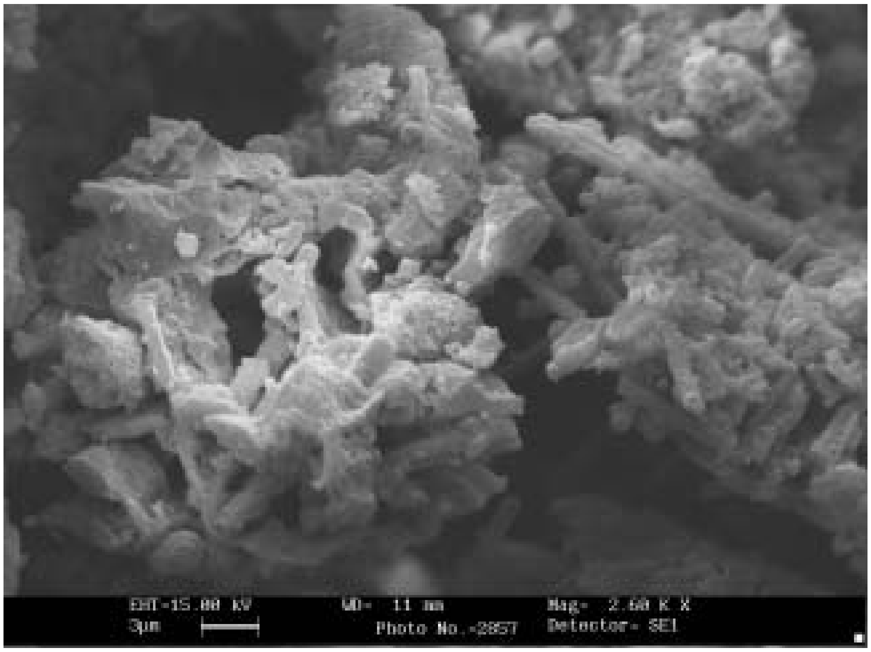

Fig. 7f. SEM image of the calcified organic structure representing the cell walls of vascular tissues of roots (?).

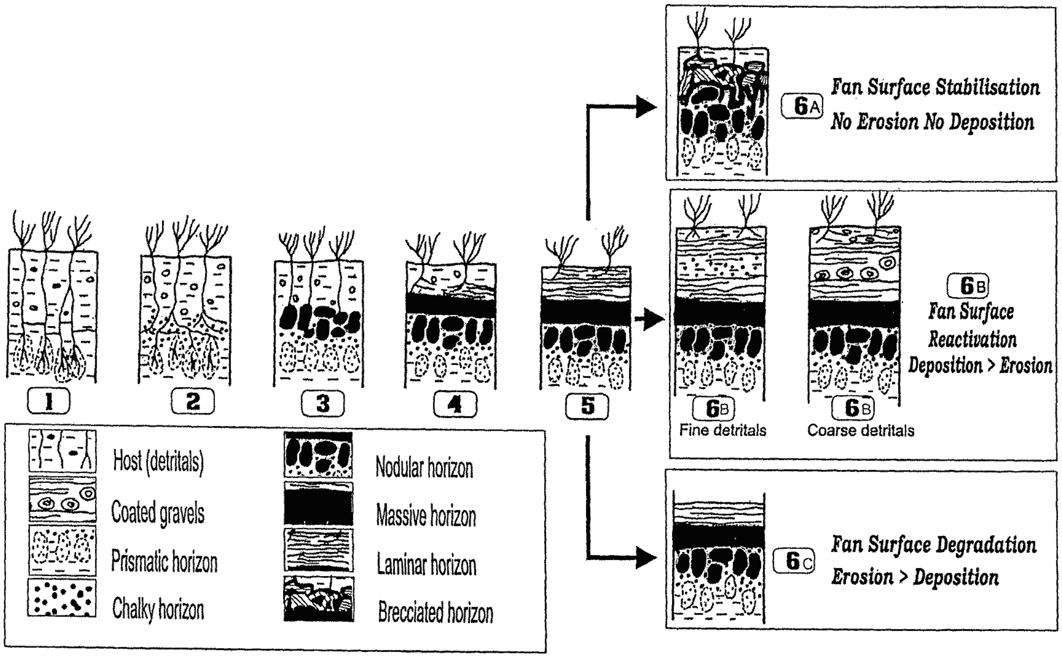

Fig. 8. Model for the formation of different calcrete profiles in the study area. For Stage 6, different erosion/sedimentation relations are envisaged as well as different host sediments. See text for detailed explanation. (After Alonso-Zarza et al., 1998)