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Biogenic laminar calcretes: evidence of calcified root-mat horizons in paleosols

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ABSTRACT

Laminar calcretes are described from the Lower Carboniferous of South Wales, the Upper Jurassic of southern England and the Upper Jurassic–Lower Cretaceous of northern Spain. They are interpreted as calcified root-mats (horizontal root systems) and are compared with other examples in the geological record and with possible modern analogues. All three occurrences consist of virtually identical, centimetre to decimetre-thick, locally organic carbon-rich, laminar micrites containing up to 50% by volume of millimetre-sized typically calcite-filled, tubular fenestrae set in an irregular but very finely laminated matrix. It is suggested that root-mat calcretes are probably very common in the geological record in peritidal, lacustrine margin and floodplain deposits, but owing to their crudely biogenic microstructure, they more closely resemble cryptalgal laminites than do other laminar calcretes. The recognition of such root-mat calcretes in sedimentary sequences not only provides evidence of subaerial exposure and vegetation cover but can also indicate positions of palaeo-water-tables in certain circumstances.

INTRODUCTION

Paleosols and other types of subaerial exposure features are now being widely recognized within ancient shallow water limestone sequences and continental facies. They can provide important information on base-level and sea-level changes, sedimentation rates and early diagenetic processes and porosity formation. Descriptions of subaerial surfaces and calcretes on Recent and Pleistocene limestones provide a suite of criteria useful for recognizing such surfaces in the rock record (Harrison & Steinen, 1978; Esteban & Klappa, 1983; Braithwaite, 1983). Some of the most commonly recognized features of this type are calcrete crusts which coat exposed limestone surfaces, or are associated with calcrete profiles. Such horizons resemble microbial stromatolites, and this has led to a debate on their differentiation (Read, 1976). The aim of this paper is to describe a type of laminar calcrete which has been found in three distinctly different geological settings, and are interpreted as calcified root mats. These calcretes more closely resemble microbial stromatolites than other laminar calcretes and they could be easily mistaken for such stromatolites.

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LAMINAR CRUSTS

Laminar calcretes ('croute zonaire' of the French usage, e.g. Freyet & Plaziat, 1982) are a characteristic feature associated with subaerially exposed limestones and with calcareous and calcrete-bearing soils. These laminar horizons are generally only a few centimetres or tens of centimetres thick and display a gently undulating form, especially when coating irregular topographies where they commonly thicken into hollows. They can occur even on very steep or near-vertical surfaces and can also completely coat objects to form coated-grains (ooids and pisoids). The laminar horizons generally have sharply-defined lower and upper boundaries and are commonly dark in colour, reflecting the presence of disseminated organic matter. The lamination is typically on a millimetre scale and is due to variations in microstructure or in the degree of organic staining. The microstructure is variable but commonly consists of dense micritic or microsparitic matrix with various forms of fenestrae and rootlet moulds. Sediment grains and soil fragments can be incorporated into such horizons. Some exhibit convoluted laminations and resemble microbial stromatolites, but differ from them in that they show an absence of the upwardly thickening, domed laminations so typical of stromatolites (Read, 1976). They may show evidence of phases of dissolution and typically contain micro-unconformities in the laminae. Some are associated with abundant evidence of micro-borings, related to the activities of lichens (Klappa, 1979). Detailed illustrations and descriptions of these laminar calcrete characteristics are to be found in numerous papers (for example, Multer & Hoffmeister, 1968; Read, 1974, 1976; Braithwaite, 1975; Harrison, 1977; Netterberg, 1980; Blumel, 1982; Esteben & Klappa, 1983).

A variety of different laminar calcrete types has been described but in broad terms three categories can be defined (Fig. 1); surficial, pedogenic and capillary-rise zone.

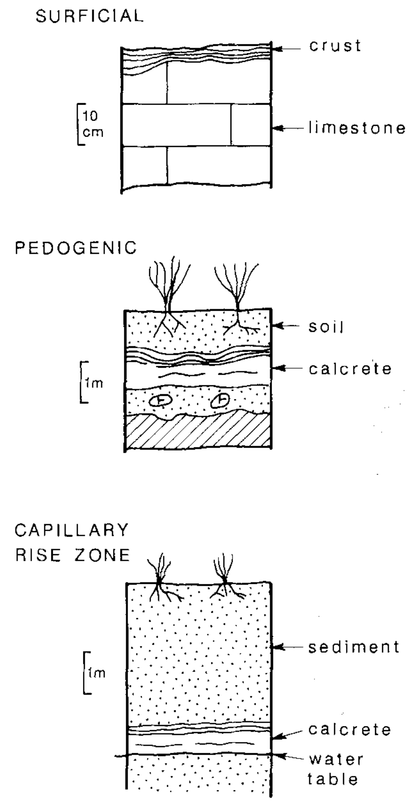


Fig. 1. Types of laminar calcrete (see text).

Surficial laminar calcretes

These form at the rock-atmosphere interface on lithified substrates. Many such laminar calcretes found exposed at the present time originally formed within soil profiles and have been exposed by erosion and differentiating them from true surficial forms can be difficult. Surficial laminar calcretes form in a similar manner to travertine in that calcium carbonate precipitates out from water flowing over the substrate or when it is ponded in depressions (Multer & Hoffmeister, 1968; Arakel, 1982; Lattman, 1973). However, other surficial forms are biogenic in origin and represent calcified microbial crusts (desert stromatolites of Krumbein & Giele, 1979). Klappa (1979) suggested that some laminar carbonate horizons are formed by lichens, which not only alter carbonate substrates but can also produce calcium carbonate and calcium oxalate to create 'lichen stromatolites'. These studies suggest that the differentiation of calcrete forms and stromatolites, which had been a focus of interest previously (Read, 1976) may be even more difficult because some subaerial (pedogenic) laminar horizons are biogenic in origin. Klappa (1979) did provide a number of criteria for recognizing lichen stromatolites and Coniglio & Harrison (1983) have used them to identify similar horizons in the Quaternary of Florida.

Pedogenic laminar calcretes

Laminar horizons can also form in association with soil profiles and usually cap either underlying impermeable horizons such as calcrete hardpans (Read, 1974; Netterberg, 1980; Arakel, 1982; Goudie, 1983) or underlying bed-rock, or cemented surficial sediments (Multer & Hoffmeister, 1968). The thickness of the overlying soil can vary from only a few centimetres, as in the case of rendzina-type soils, to a metre or more with some Aridsols and Xerosols. The generally held explanation for the formation of these soil-covered laminar horizons is that carbonate-rich water percolating through the soil profile is ponded above the impermeable layer and the calcium carbonate is precipitated to form an upwardly accreting horizon (Gile, Peterson & Grossman, 1966; Read, 1974; Arakel, 1982). As soils aggrade, new separate horizons can form, thus leading to the development of multiple laminar horizons (Arakel, 1982). An alternative explanation for the origin of laminar forms capping hardpan calcretes has been offered by Blumel (1982). He suggested that they are surficial forms formed by precipitation from run-off flowing over exhumed hardpans which could be later covered by more soil and so preserved within a profile.

Some of these soil-covered laminar calcretes contain a high percentage of tubiform pores, notably those from Florida described by Multer & Hoffmeister (1968) and Perkins (1977). We believe that these represent possible analogues for the examples described in this paper.

Capillary rise-zone laminar calcretes

A third type of laminar calcrete has been recognized forming just above the water-table in present day dunes in southwestern Australia (Semeniuk & Meagher, 1981; Semeniuk & Searle, 1985). Evaporation of water above the water-table, in the zone of capillary rise or updraw by deep-rooted plants leads to supersaturation of calcium carbonate and causes precipitation. The result can be the formation of an impermeable massive calcrete which acts as a substrate for the precipitation of a laminar horizon from ponded waters. The term non-pedogenic has been used by Semeniuk & Meagher (1981) to describe such horizons. However, we prefer the term capillary-rise zone laminar calcrete because surficial laminar calcretes could also be described as 'non-pedogenic'. Laminar calcretes forming at very shallow water-tables arguably can be pedogenic and some ancient examples are described in this paper. The distinction between pedogenic and capillary-rise zone types becomes meaningless in such cases.

DESCRIPTION OF LAMINAR CALCRETE

During our separate studies of paleosols we have found identical laminar calcretes of a type hitherto not described in detail from three distinctly different geological settings. They come from the Lower Carboniferous (Dinantian) of Miskin, South Wales, the Upper Jurassic (Portlandian) of Swindon, southern England and the Upper Jurassic–Lower Cretaceous of the Cameros Basin, northern Spain. We use the term calcrete in the sense of Goudie (1983) for all the carbonate accumulations described occur within paleosol profiles.

Lower Carboniferous laminar calcrete from Miskin

A distinctive laminar calcrete occurs in the Heatherslade Geosol, a complex polygenetic calcrete profile capping the Chadian Gully Oolite (syn. Caswell Bay Oolite) at Miskin, near Cardiff, South Wales (Fig. 2). Details of the locality and stratigraphy have been given by Riding & Wright (1981) and profile details were provided by Wright (1986, 1987). The laminar calcrete coats cobble to boulder-sized fragments of calcretized oolitic grainstones and reach a thickness of 35 mm; however, lateral extent was impossible to determine because the soil was modified by a later phase of Carboniferous pedogenesis (Wright, 1986) and because quarry blast-damage made lateral correlation difficult. It occurs within a calcrete conglomerate layer interpreted by Riding & Wright (1981) as a regolith overprinted by a massive calcrete (petrocalcic horizon). The regolith material contains a large suite of calcrete and vadose fabrics, including micritic grain coats, inter-granular fungal networks, needle-fibre calcite, tubiform rootlet moulds associated with alveolar-septal structure, probable calcified faecal pellets, meniscus cements, geopetal textures, and circumgranular cracks (Riding & Wright, 1981; Wright, 1986, 1987).

The laminar calcrete, which is almost black in colour, contains centimetre-sized angular fragments of the calcretized oolitic substrate set within a crudely laminar fabric, containing a few distinctive darker, denser laminae. The base of the horizon is sharply defined. Thin sections show that it has a highly irregular, contorted micro-fabric with smooth-walled calcite cement-filled cylinders, set in a matrix with a contorted micro-laminar fabric. (The term micro-laminar is here used to describe the very fine fibrous microstructure seen in thin sections, while we reserve the term 'laminated' for the coarser-scale layering seen in hand specimen). The cylindrical fenestrae which comprise 10–50% of the volume of the horizon are smooth-walled, and are oriented subparallel to sub-perpendicular to the underlying substrate (Fig.

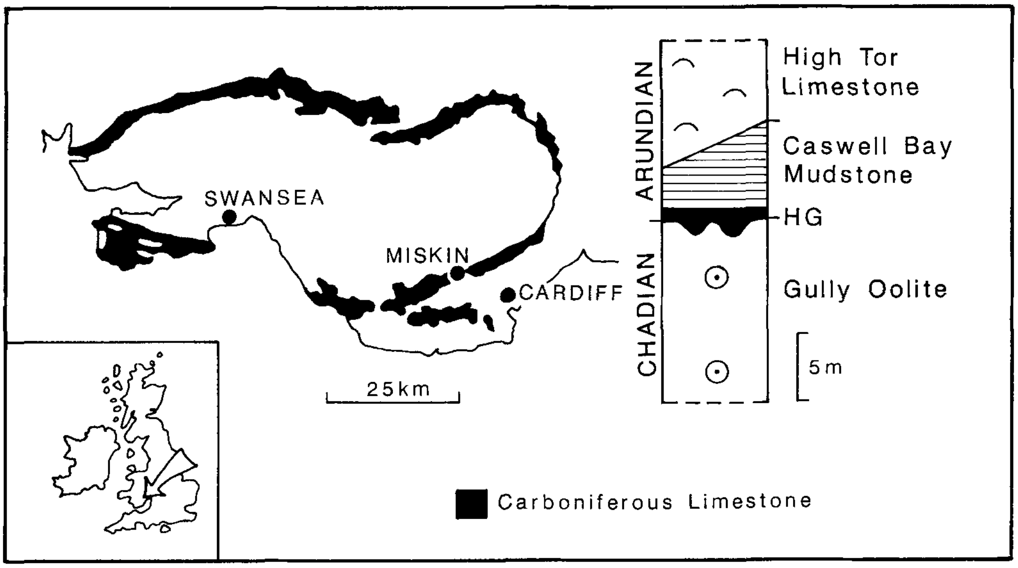


Fig. 2. Locality map of Miskin showing stratigraphic position. HG, Heatherslade Geosol. For further locality details see Riding and Wright (1981).

3a). the cylinders are filled with a drusy or equant medium to coarsely crystalline calcite cement, are up to 3 mm in diameter and up to 10 mm in length. They probably represent meandering, curved tubes which are cut by the plane of section. However, many show evidence of compression and have non-parallel margins (Fig. 3a), indicating that many, at least, were empty calcite-walled tubes before cementation by calcite cement.

The sparry calcite-filled cylinders have walls of dark micrite which are micro-laminar (Fig. 3b), that is, they are made up of several sheets of micrite up to 100 μm thick with individual layers traceable for up to a millimetre, separated by microspar layers which are up to 200 μm thick but are mostly in the range 50–100 μm. Rarely, some of the micro-laminae have poorly preserved partitions connecting the micrite layers giving rise to a crude cellular structure. A few tubes have crudely pelleted walls, the margins of which are defined by irregular micrite peloids up to 100 μm in diameter.

When the cylindrical structures are viewed in cross-section the micro-laminar structure is clearly seen to be concentric around them. Where the cylinders are densely packed, the inter-pore space only contains the micrite and microspar lamellae; where they are further apart, the micro-laminar zone passes into areas filled with a cloudy microspar exhibiting a much more crudely micro-laminated texture (Fig. 3c) which locally passes into poorly preserved alveolar-septal fabric. Well-preserved examples of this latter fabric do occur (Fig. 3c) and the curved septae are mainly 20–50 μm wide and less than 100 μm long.

The horizon also contains scattered ooids, presumably derived from the substrate, and small aggregations of rounded, sub-spherical, well-sorted peloids 40–50 μm in diameter (Fig. 3b) resembling the faecal pellets found in associated horizons (Wright, 1987). Amorphous organic-carbon is also visible in thin sections.

Upper Jurassic laminar calcrete from Swindon

The second example, occurs in the Great Quarry in Swindon, Wiltshire (British Grid Reference SU 153836) within the 2-m thick Town Gardens Member of the Portland Stone Formation (Portlandian) (Fig. 4) (Sylvester-Bradley, 1940; Wimbledon, 1976, 1981). The Town Gardens Member comprises a laterally highly variable sequence of fenestral lime mudstones, peloidal and quartz-rich bioclastic marine limestones and sandstones, some non-marine limestones and two prominent laminated calcretes. The two horizons each directly overlie a medium-bedded, marine limestone with large bio-moulds and 0·3 m below the lower unit is a distinctive sandy micritic limestone with mm-sized rhizocretions with alveolar-septal structures. Pebbles and boulders, including clasts of these marine

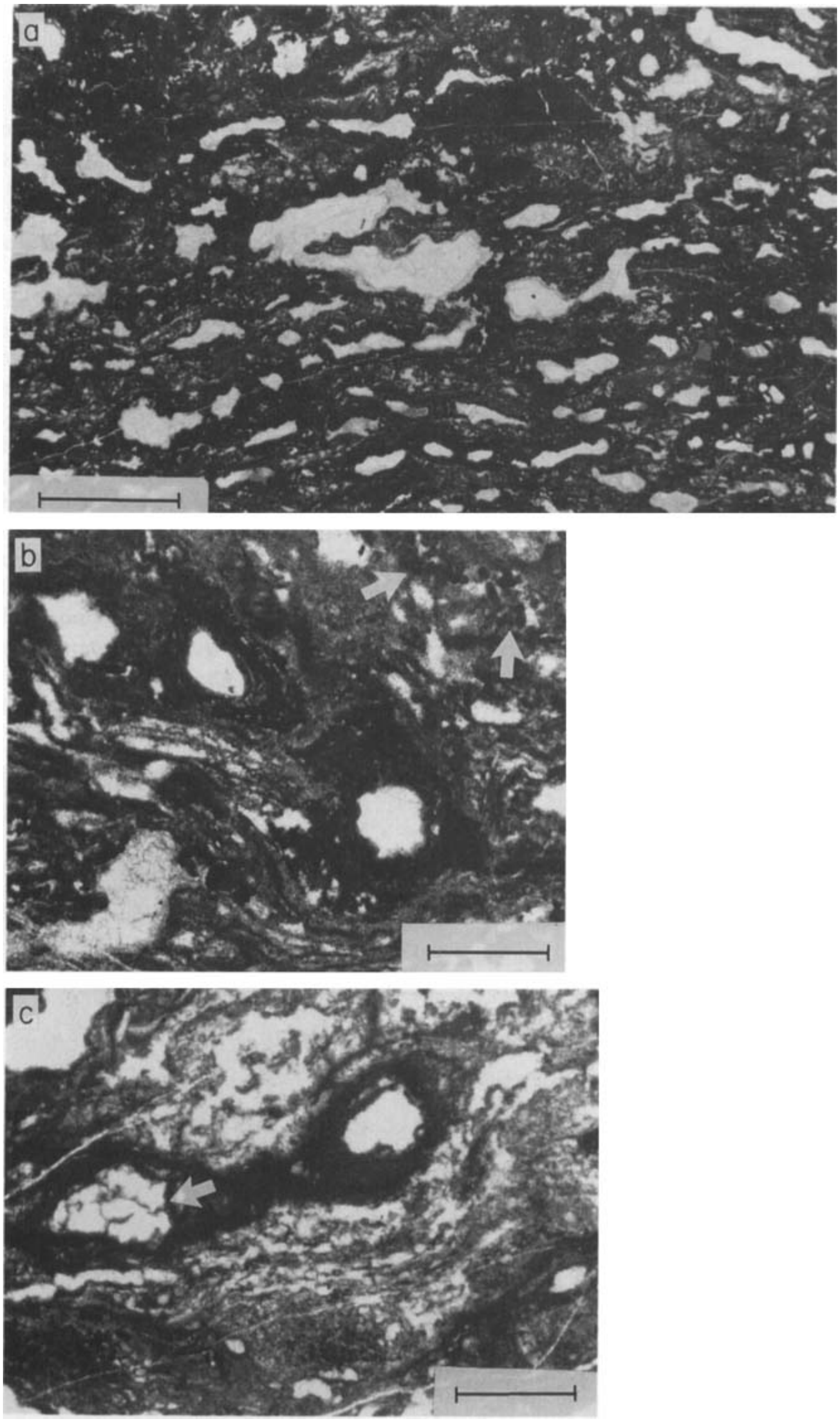


Fig. 3. Photomicrographs of the laminar calcrete from Miskin. (a) highly fenestral fabric. The long axes of the cylindrical fenestrae are subparallel to the base of the horizon. Note the larger irregular calcite-filled vugs. Scale bar represents 2·5 mm; (b) detail of microfabric, showing the dark micritic coating around the cylinders (transverse sections of tubes) and the crudely micro-laminar structure of the matrix. A small pellet concentration is arrowed. Scale bar represents 0·5 mm; (c) note dark micritic coatings around the spar-filled cylindrical fenestrae, passing into the crudely micro-laminar zone. Alveolar septal fabric (arrowed) occurs within a micrite-rimmed tubule, and the diffuse fabric resembling alveolar-septal structure above the two micrite-coated cylinders. Scale bar represents 0·5 mm.

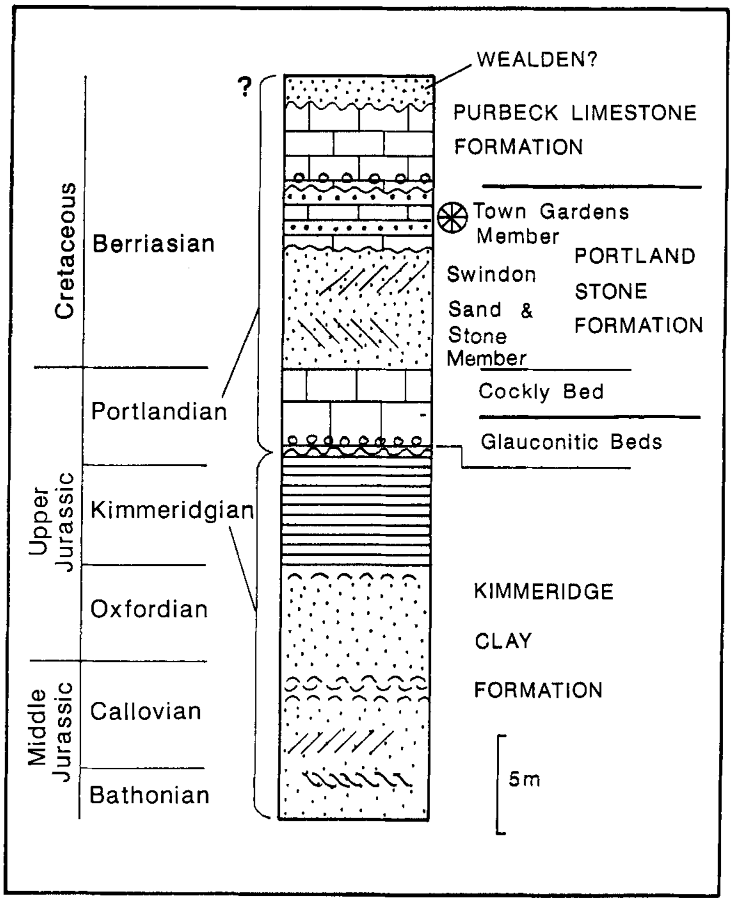


Fig. 4. Stratigraphy of the Swindon area showing the position (asterisk) of the laminar calcrete within the Town Gardens Member. (See text).

limestones, occur both between them and also beneath the lower one. The upper, thicker, porous marine limestone bed, with its laminated calcrete, is overlain by a fragmented white micritic limestone with freshwater gastropods. Both porous beds and their laminar calcretes are laterally discontinuous and the upper bed, in particular, is reduced to a mass of large cobble to boulder-sized, subrounded to rounded, spherical to oblate clasts for tens of metres along-strike. These relationships suggest phases of *in situ* reworking during deposition of the unit, reminiscent of regolith horizons. A similar series of deposits has been described by Perkins (1977) from the Pleistocene of Florida.

These clasts, and the parent rock from which they were derived, are calcite cemented, bioclastic, peloidal, medium to coarsely grained sandstones and limestones. The matrix around the clasts is a calcareous clay-rich sand.

This study concentrates on the lower much thicker laminar calcrete. Thin sections of the sandstone clasts show a variety of calcrete textures such as floating sediment grains set in a dense micritic matrix passing down into a grain-supported fabric in which the grains exhibit irregular, non-laminated micritic coatings up to a few hundred microns thick. Some small (average 1 mm diameter), subspherical nodules with sharply defined margins occur, containing several quartz-grains surrounded by micrite. Shell moulds are abundant and are only partially occluded by finely crystalline bladed calcite cement. The micrite matrix also exhibits sub-millimetre wide irregular cracks, including circumgranular cracks. Bifurcating tubular pores are also common, up to 500 μm in diameter, and locally showing alveolar-septal structure. This suite of fabrics shows that the unit underlying the laminar calcrete was modified by pedogenic processes.

The laminar calcrete itself is up to 50 mm thick (Fig. 5) but it thins over projections on the substrate to 15 mm. It is light buff-beige in colour and contains fragments of the underlying lithology up to 10 mm in diameter. The laminae, which have relief of one to two millimetres, are of two types: dark laminae, 1 mm or less in thickness which are traceable for several centimetres, separated by lighter coloured, highly contorted laminae. The waviness and contorted appearance is due to an abundance of small tubiform pores (under 1 mm diameter) occurring within the lighter coloured layers. The pores themselves are traceable laterally for only one or two millimetres.

The base of the horizon is sharp and shows no evidence of previous endolithic activity at the contact. However, from the base there are extensions passing downward into the substrate as sub-horizontal to sub-vertical, irregular (wavy) dark, micritic stringers. These are up to several centimetres in length and averaging 1 mm in width (Fig. 5). Internally these stringers have the same microstructure as the laminar calcrete.

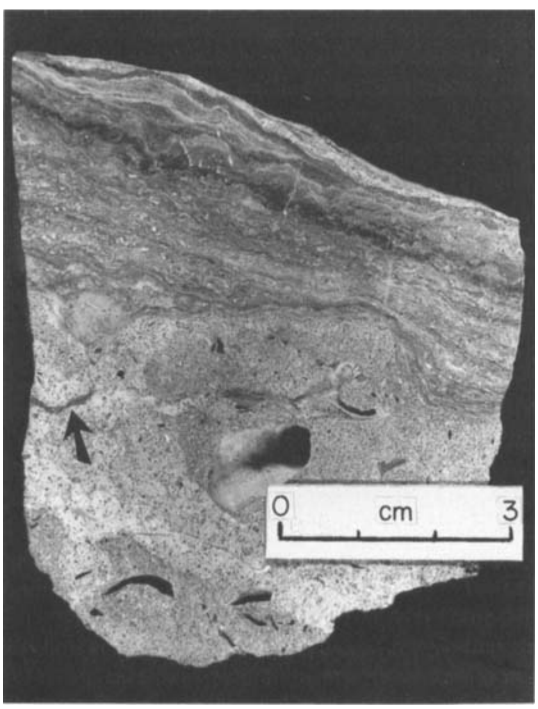


Fig. 5. Polished sample of the laminar calcrete from the Town Gardens Member. Note the biomoulds in the calcretized sandstone beneath the horizon. A small micrite stringer is arrowed. The mottled appearance of the sandstone is due to differential cementation by pedogenic micrite which occurs as grain coats.

Thin sections of the calcrete are strikingly like those at Miskin in exhibiting small tubiform cylinders (here as open pores) with micritic and microspar micro-laminar walls (Fig. 6a). The only differences with this horizon and that at Miskin are that alveolar-septal structures are more common, and that dense, micritic laminae occur. These latter occur both within the main part of the horizon, separating irregular cylindrical-micro-laminar layers, and near its top where they are more common and several millimetres thick (Fig. 6b). These thicker, dense zones have very few pores, exhibit a very fine wavy lamination and include layers of finely crystalline inclusion-rich, brown bladed calcite (Fig. 6b).

Laminar calcretes from the Upper Jurassic–Lower Cretaceous of the Cameros Basin, northern Spain

Similar calcretes (Fig. 9b) occur in the Upper Jurassic–Lower Cretaceous Tierra de Lara Group (Group I of Salomon, 1982) of the western Cameros Basin of northern Spain (Platt, 1986) (Fig. 7). They occur in both siliciclastic (Señora de Brezales Formation) and carbonate-dominated sequences (Rupelo Formation) (Fig. 7), and four different facies associations have been recognized (Fig. 8).

1 *Conglomerate/sandstone association (Fig. 8.1)*

Laminar calcretes occur in the alluvial Señora de Brezales Formation both within sandstones and capping channelized conglomerates. These clastic sediments have been interpreted as sandflat and streamflood deposits, respectively (Platt, 1986). The laminar calcretes which are 0·05–0·20 m thick, form laterally discontinuous, undulating horizons traceable for up to 5 m. They either cap the conglomerates, suggesting that their formation took place after the abandonment of the channels, or occur within the sandstone units where they are associated with cross-cutting, 1–2 mm diameter, carbonate stringers interpreted as fine-scale rhizocretions (Platt, 1986) (Fig. 8).

2 *Marl/paleosol association (Fig. 8.2)*

Laminar calcretes occur in both the upper part of the Señora de Brezales Formation and in the basal Rupelo

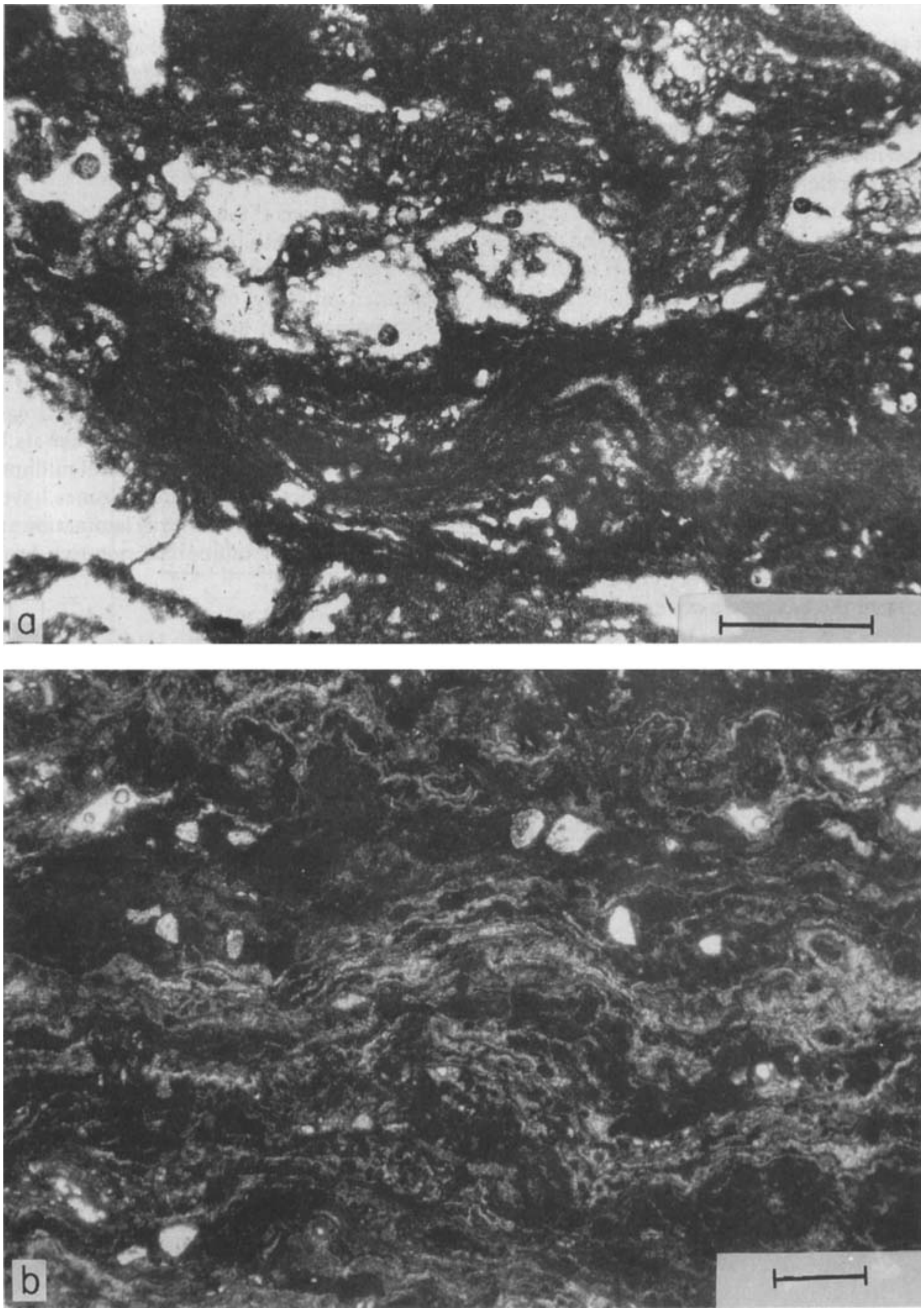


Fig. 6. Photomicrographs of the Town Gardens Member laminar calcrete. (a) porous, micro-laminar microfabric showing fine tubular and larger irregular pores (some with a crude septal structure resembling alveolar-septal structure) set in a micro-laminar matrix). Scale bar represents 0·5 mm. (b) dense micritic laminae forming layers several millimetres thick. Scale bar represents 0·5 mm.

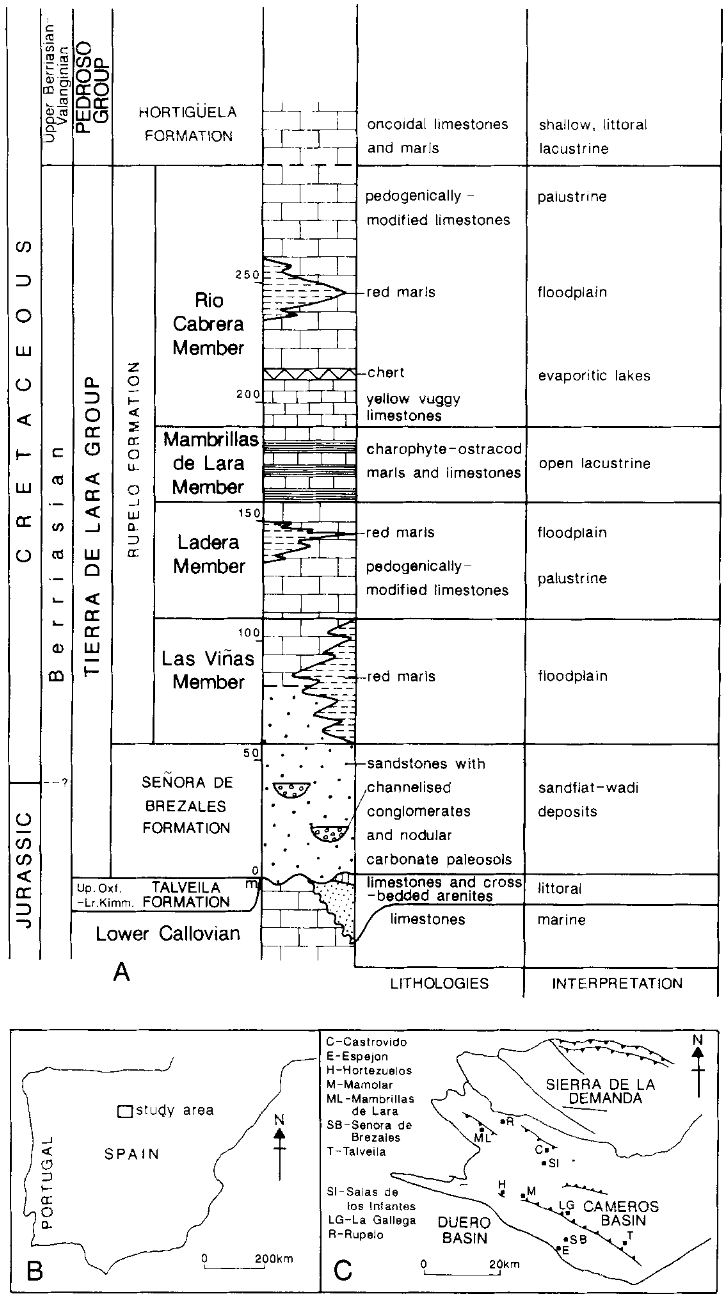


Fig. 7. Stratigraphy and locality of the Cameros Basin sequence. The study area is shown in B and localities (and outcrop area) shown in C (see Platt, 1986).

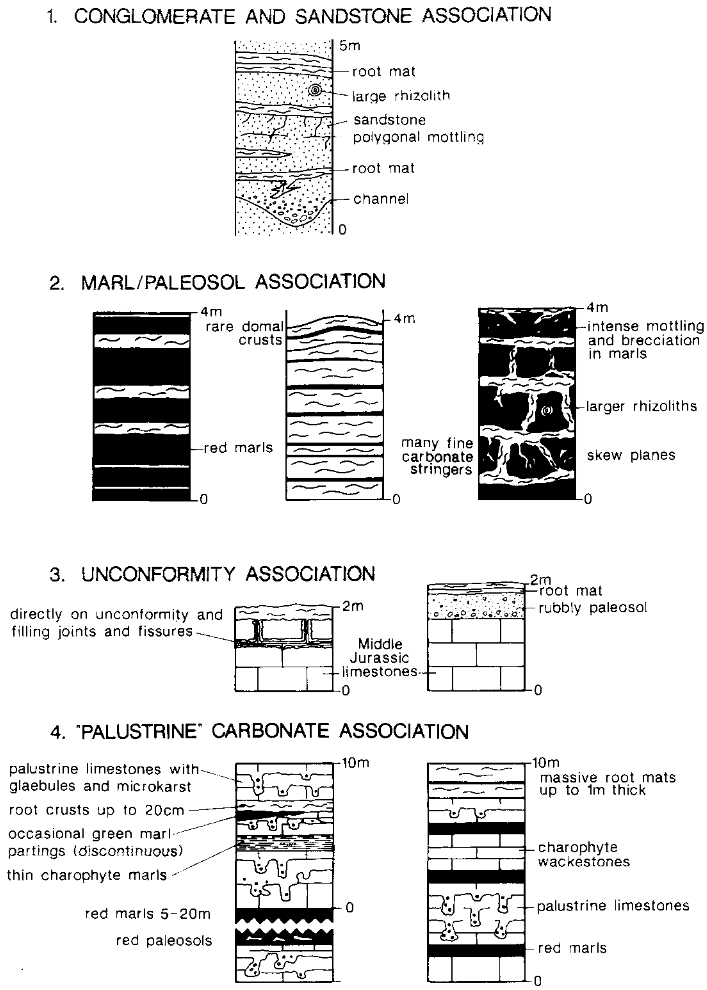


Fig. 8. Lithofacies associations of the laminar calcretes in the Cameros Basin sequence (see text).

Formation (lower part of the Ladera Member) associated with interbedded decimetre- to metre-scale red marls or variably brecciated grey and mottled limestones (Fig. 8). The marls are generally structureless and homogeneous, although where laminar calcretes are present they commonly show yellow-red-purple mottling. The marls contain a very sparse microfauna of ostracod and charophyte fragments, abundant disemminated clay, and scattered fine detrital grains up to 250 μm in size. The marls have been interpreted as the distal suspension deposits of a lake marginal alluvial plain (Platt, 1986). The absence of primary depositional features (such as lamination) is attributed to thorough bioturbation consequent upon relatively slow and discontinuous sedimentation. The limestones are micritic but are highly brecciated with abundant fine-scale anastamosing and circumgranular spar-filled cracks averaging 0·5 mm wide. Further evidence of subaerial exposure and pedogenic modification includes often intense yellow-orange-red-purple mottling, carbonate nodule (glaebule) development, occasional 1–5 mm 'black pebbles', and isolated 1 mm diameter concentrically-coated spar-filled tubular voids (interpreted as fine root tubules). Larger-scale 10–20 mm wide cracks also occur; these are filled either by grey, impure carbonate containing occasional floating clastic grains, or, more rarely, by densely-laminated micrite.

The marls commonly contain 20–30 mm diameter vertical tubular structures up to 0·3 m in length which have been interpreted as rhizocretions (Platt, 1986).

The marls alternate with the laminar horizons, which are generally 10–50 mm in thickness. The marls are commonly of similar thickness and the alternation may be regular and repeated many times in vertical sequence. Total thicknesses of regularly-bedded marl-laminar calcrete alternations are commonly 0·5–1·0 m (as at Espejon, La Gallêga and Talveila), but may locally reach 20 m (as at Señora de Brezales). However, the thicknesses of the laminar carbonate horizons and of the interbedded marls are locally variable. The calcretes may be only 10–20 mm thick, laterally impersistent over 0·2–0·5 m, and interbedded with marl units 0·5m or more in thickness; at other localities (e.g. Talveila), they are more laterally continuous (individual horizons may be traceable for up to 20 m or more) and separated by only thin (< 10 mm) red marl partings. Despite this variability, all of the scales of marl/calcrete alternation result in a gross centimetre-to-decimetre-scale laminar fabric which is strikingly apparent at outcrop. Locally, the combination of both vertical elements (rhizocretions, larger-scale desiccation cracks) and horizontal elements (laminar calcretes, desiccation sheet cracks) may create a crudely reticulate fabric (Fig. 8.2). At one locality (Señora de Brezales), sequences of stacked 20–50 mm bedded laminar carbonate units occur as gentle antiformal/domal structures 5 m across, up to 2–5 m across and with a surface relief of 0·5 m (Fig. 9a). Field evidence suggests these structures are original and not tectonic in origin.

3 *Unconformity association (Fig. 8.3)*

10–20 mm thick, gently undulating laminar horizons are also developed on Lower to Middle Callovian limestones at a prominent unconformity in the north of the study area (e.g. at Mambrillas de Lara and at Castrovido) (Fig. 8.3). The laminar horizons may locally occur beneath the main unconformity surface (at Mambrillas they are found down to 1 m below it), or may occur immediately beneath rubbly breccias which are developed on the unconformity surface. At Castrovido, the laminar calcretes and breccias occur only where the unconformity surface is not scoured by the conglomerate channels of the basal Señora de Brezales Formation. It is inferred, then, that the laminar horizons were developed in interchannel or upstanding areas, often at the exposure surface itself (beneath a soil), or along joints extending downwards from, the unconformity surface.

These laminar horizons associated with unconformity surfaces show a fabric similar to the other laminar forms, although micro-unconformities in the laminae seem to be more common. At Castrovido, the laminae are locally strongly blackened, a feature reminiscent of the crusts from the Carboniferous of Miskin, South Wales.

4 *Palustrine carbonate association (Fig. 8.4)*

Laminar horizons are also developed associated with thick (up to 80 m) sequences of marginal lacustrine–palustrine carbonate facies in the Ladera and Rio Cabrera Members of the Rupelo Formation. The limestones are pale grey in colour and are interbedded with rare, 0·5 m-thick, dark grey charophyte-rich marls. The limestones themselves are micritic mudstones and wackestones, and contain only rare charophyte stems and gyrogonites, ostracods and molluscan fragments. They show abundant evidence of pedogenic modification (Salomon, 1984; Platt, 1985) and are commonly brecciated on a millimetre-scale owing to the presence of many fine spar-filled circumgranular and anastomosing cracks. Rounded carbonate nodules 1 mm in diameter are also abundant. The limestones are locally strongly pink-purple mottled and contain centimetre-scale cavities with drusy sparry calcite and geopetal vadose cements with included peloids. These cavities are similar to the 'microkarst cavities' described from Cretaceous and early Tertiary palustrine carbonates of Languedoc by Freytet & Plaziat (1982) and Santander by Garcia-Mondejar *et al.* (1985).

These Cameros Basin limestones have been interpreted as lake margin deposits. Periodic prolonged exposure of shallow lake carbonate muds led to pedogenic modification and solution (Platt, 1986).

Laminar calcretes occur at many intervals within the Rupelo Formation but are usually very thin (5–20 mm) and laterally discontinuous on a decimetre to metre scale. At Mambrillas de Lara they occur interbedded with thin limestones (0·1–0·3 m thick) separated by 5–20 mm green marl partings. The thin limestones contain 1 mm diameter, concentrically micrite-coated tubules identical to rhizocretions described from Quaternary calcretes by Klappa (1980) (Platt, 1986).

Other laminar calcretes up to 1 m in thickness also occur at Mamolar and Rupelo (Platt, 1986). They are

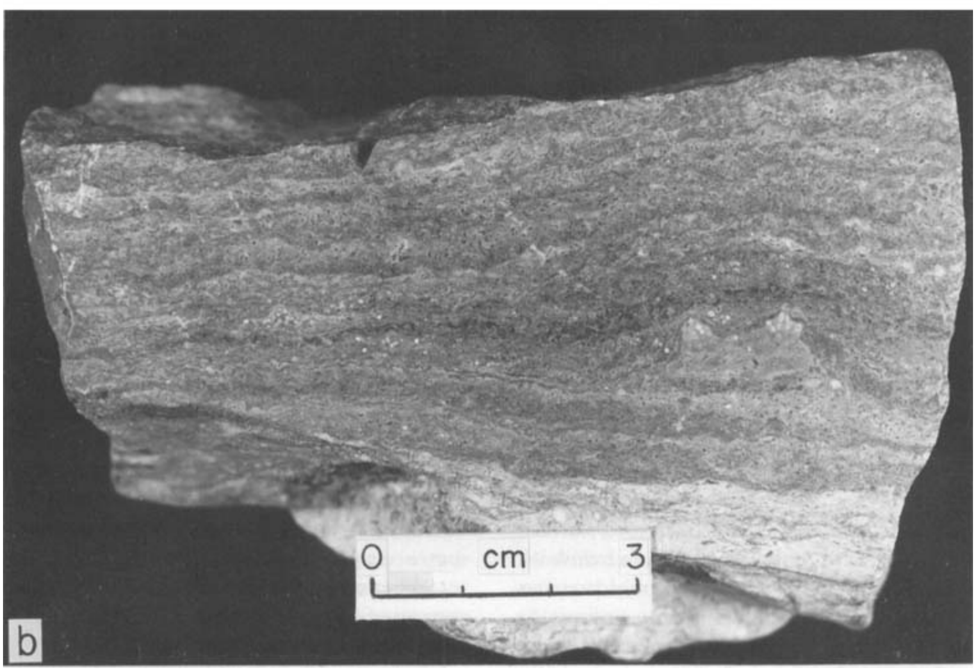


Fig. 9. (a) Thick multiple domal laminar calcrete from the Señora de Brezales Fm; east side of road from Espejon to La Gallèga, 3 km north of Espejon and 500 m north of the chapel of Nuestra Señora de Brezales. From the marl/paleosol association. (b) polished sample of laminar calcrete from the Rio Cabrera Member, 300 m west of Rupelo. Specimen taken from the top of a one metre thick horizon capping a palustrine sequence. From a palustrine carbonate association.

present near the top of the carbonate members (such as the Ladera and Rio Cabrera Members) or at major bedding planes which have been interpreted as depositional breaks (Platt, 1986). The latter are associated with micro-brecciated horizons indicating prolonged exposure and karstification. Thus, these thicker horizons seem to coincide with major depositional hiatuses in the sequence.

Petrography

Thin sections (Fig. 10) show that all these laminar calcretes in the Cameros Basin sequences are virtually identical to those from the Miskin and Swindon sections. The only differences are that small pellet concentrations (Fig. 10a) are more common and alveolar-septal structures (Fig. 10b) are more abundant but the characteristic, highly contorted cylindrical structures and micro-laminar micrite structure is essentially identical to that in the other two occurrences (Fig. 10c).

INTERPRETATION

The laminar calcretes are considered to be pedogenic in origin both because they are intimately associated with pedogenic profiles and because they internally contain pedogenic fabrics.

The striking similarities between the three types described indicate a common origin which we believe to be related to rootlet activity for the following reasons:

(1) The spar-filled cylindrical fenestrae and tubiform pores either represent burrows or rootlet structures. The former origin seems unlikely because of the absence of burrow features such as meniscate fills or pellet concentrations. Furthermore, the walls are not simply soil matrix pushed aside but have a distinctive concentric structure for which no obvious burrow analogue can be found.

(2) The laminar calcretes are underlain by cylindrical structures (stringers) which bifurcate downwards, a fabric suggestive of a rootlet origin. The stringers have the same internal structure as the calcrete.

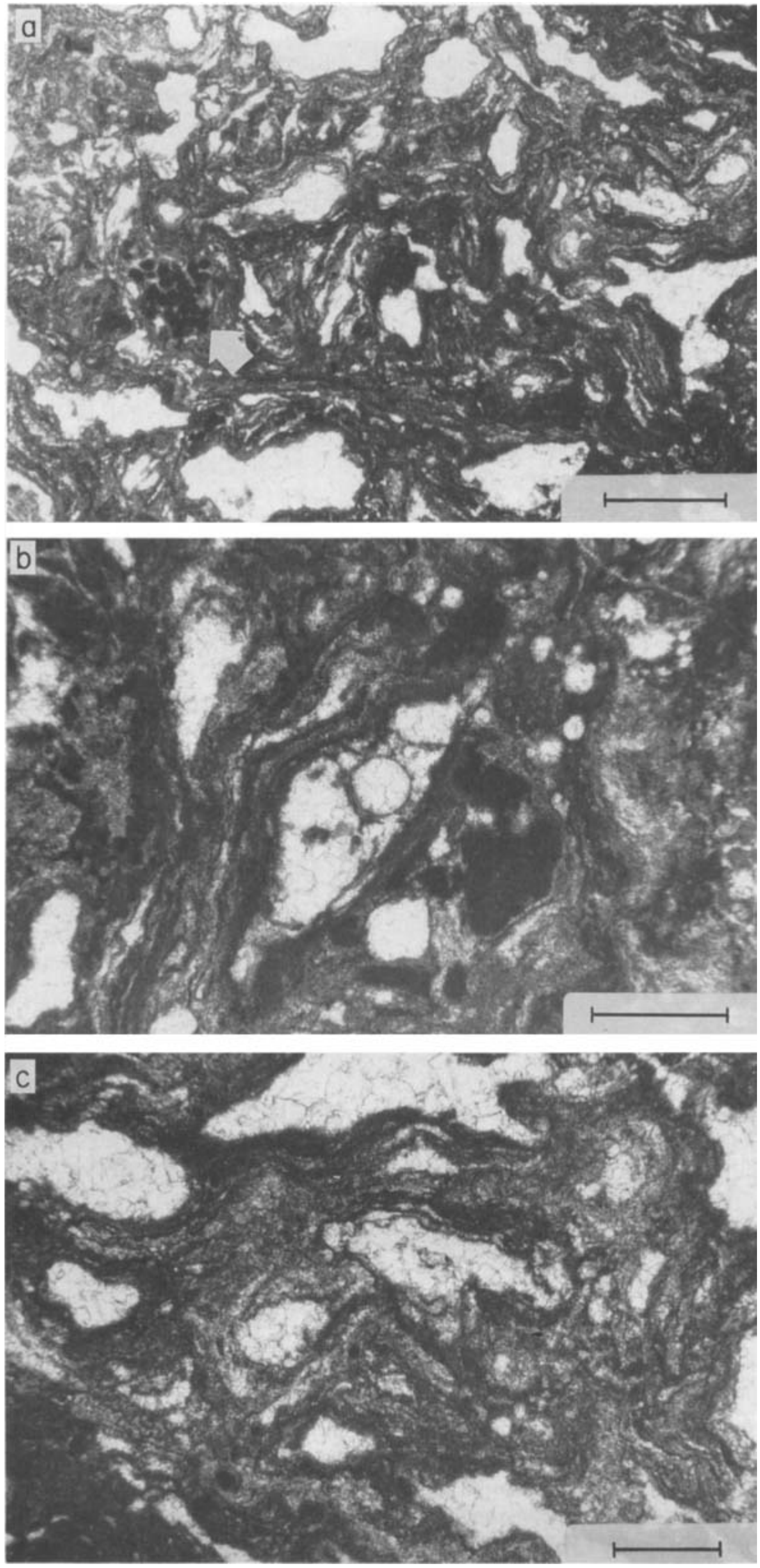
(3) The microstructure consists of concentric millimetre-diameter spar-filled cylindrical fenestrae or tubular pores with micritic and microsparitic coatings. Similar features have been described and illustrated from Quaternary rhizocretions (or rhizoliths), which are calcareous accumulations around living or dead roots (Calvet, Pomar & Esteban, 1975; Klappa, 1980, p. 621; Semeniuk & Meagher, 1981, p. 57; Arakel, 1982, p. 116; Wieder & Yaalon, 1982, p. 212; Mount & Cohen, 1984, p. 268).

(4) The tubular structures, whether calcite-cemented or open locally contain, or pass laterally into, areas displaying alveolar-septal structure. This is a fabric probably formed by calcified fungal hyphae associated with roots (Phillips & Self, 1987; Wright, 1986). Such structures are not diagnostic of root activity, but they are very commonly associated with rootlets and so provide circumstantial evidence for the laminar calcretes being rootlet related.

The calcretes are considered to represent densely interwoven rootlet horizons which were calcified, possibly while the rootlets were alive, by micritic and microsparitic calcite. Significantly Klappa (1980, p. 625) in his studies of Quaternary calcretes, noted that this type of concentric encrustation was especially characteristic of rhizocretions within sheet calcrete horizons, such as those described here.

Where the original rootlets were densely intertwined the whole rock has a micro-laminar microstructure, but where the rootlets were less closely spaced the pore-space was filled by alveolar-septal structure representing fungal activity around root hairs, rootlets or root voids. The denser micritic layers noted in the Swindon material, especially at the top of the horizon, probably represent simple precipitation without root calcification.

Calcified root mats have been described, although not in detail, by a number of authors. Cohen (1982) and Mount & Cohen (1984) have described horizontal, planar root mats up to 50 mm thick, covering hundreds of square metres, with tubes averaging 5 mm diameter, from the Koobi Fora Formation (Plio-Pleistocene) of Kenya. Perkins (1977), in a study of the Pleistocene of Florida, has briefly described dense masses of calicified rootlets which he referred to as 'root-rock'. Calvet & Julia (1983) have referred to 'root stromatolites' which overlie lithified substrates in recent calcrete profiles from Tarragona (Spain) (see also Julia & Calvet, 1983). Klappa (1980, p. 615) has offered the term *rhizolite* for a rock showing structural, textural and fabric details determined largely by the activity or former activity of plant roots. We favour this term and classify the laminar calcrete described in this paper as rhizolite laminar calcretes.


a
b
c

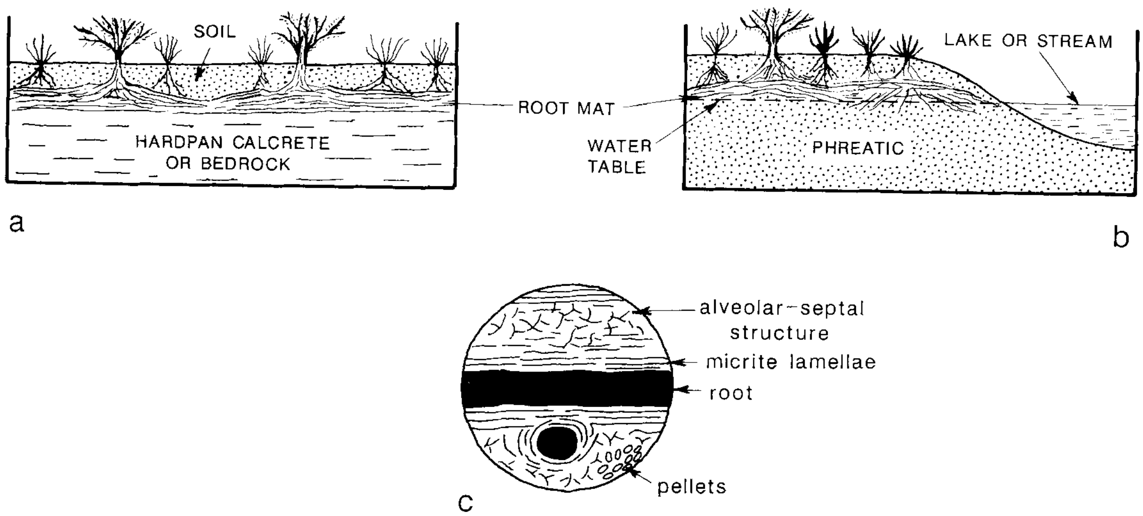


Fig. 11. Schematic diagrams to show the occurrences of dense root mats. (a) the mat has formed above on impenetrable hardpan calcrete or bedrock. (b) the mat forms at or just below the water-table. (c) typical microfabric of calcified root mats as described in this paper (see text and Figs 3, 6 and 10). The absence of large rhizocretions in the crusts described in this paper suggests that the vegetation cover consisted of relatively small plants.

DISCUSSION

The occurrence of rhizolite laminar calcretes in these three sequences requires comment. Root mats appear to form in two settings (Fig. 11): firstly, they occur above lithified zones, either bedrock or calcrete; secondly, they form in areas with very shallow phreatic waters where the roots extend to, or just below the water-table surface (Cohen, 1982; Mount & Cohen, 1984). The latter examples occur especially in shallow lacustrine or palustrine settings. The Miskin and Swindon examples occur on substrates which show evidence of extensive calcretization for example the development of grain coatings and calcrete matrix with floating sediment grains. The rhizolite horizons probably formed above a relatively impervious 'hardpan' layer. However, as noted earlier, some of the Cameros Basin horizons occur within a complex of floodplain–lake margin, palustrine settings and some may be found as discrete units within marl or lake margin carbonate sequences and *not* only in association with calcrete profiles of pedogenic or capillary-rise zone type. The marl and palustrine-associated forms probably represent the shallow phreatic type of root mat and may reflect the positions of former water tables. In this case their classification as pedogenic or capillary-rise type is ambiguous.

Mount & Cohen (1984), in work based on their studies of the Plio-Pleistocene of Kenya, offered criteria for distinguishing rhizocretions formed in well-drained settings from those formed in shallow phreatic settings. Those formed in horizontal root mats at or below the local water-table lacked obvious vadose features such as meniscus and pendant cements, but contained abundant clay and plant debris, as well as Mn concentrations as high as 4·5 cation percent. These features indicate formation in water-saturated conditions with reduced Eh conditions.

Few horizons described in this study contain obvious vadose cements (although such cements occur in associated horizons) and the clay and organic

Fig. 10. Photomicrographs of laminar calcrete showing typical microfabrics. Sections are from specimen shown in Fig. 9b. (a) irregular and cylindrical fenestrae surrounded by micro-laminar micrite. Note cluster of pellets (arrowed). Scale bar represents 1 mm. (b) irregular spar-filled fenestrae and micro-laminar micrite. Note micritic cylinder within one of the pores. This probably represents the light calcification of the outer margin of a rootlet or root hair. Scale bar represents 0·5 mm. (c) detail of microfabric. Scale bar represents 0·5 mm.

matter content of the Cameros material is no different to the other two types. Likewise the Mn content (as assessed from cathodoluminescence characteristics) is no different to the others. The pedogenic features and field associations of the Cameros calcretes seem to be more reliable palaeoenvironmental indicators than these other criteria.

The Cameros rhizolite calcrete examples are particularly significant. The wide range of facies associations and palaeoenvironmental settings inferred for their occurrences demonstrates conclusively that they are not unusual features developed only under particular and specialized conditions. They occur in a wide variety of settings including inter-channel, floodplain, marginal and ephemeral lake environments.

Calcified root-mat horizons are probably common in many ancient calcrete profiles and we have noted a number of descriptions and illustrations of very similar features in Carboniferous calcretes from the United States (Harrison & Steinen, 1978, fig. 6E; Goldhammer & Elmore, 1984, fig. 4C & D; Prather, 1985, p. 215). Strasser & Davaud (1982) have illustrated crudely similar horizons from the Purbeck facies of France. Similarly, possible Quaternary examples have been described briefly by Braithwaite (1975, p. 10 & 20) from the soils of Aldabra.

One problem in recognizing these root-mat horizons is their highly 'fenestral' and biogenic fabric. This means that they could be mistaken for true stromatolites or tufas even more easily than other laminar calcretes. However, in the three occurrences described here the presence of alveolar-septal structure has been ubiquitous and may provide a useful criteria for recognizing fossil laminar root-mat calcretes.

CONCLUSIONS

Distinctive laminar calcretes containing abundant millimetre-sized, calcite-cemented, cylindrical fenestrae or tubular pores, separated by concentrically or crudely laminated matrix with alveolar-septal structure, have been found in three different settings: (i) within a thick calcrete and regolith profile from the Lower Carboniferous of South Wales; (ii) as a laminar horizon in calcretized marginal marine sandstones and limestones from the Upper Jurassic of Swindon, southern England; and (iii) within fluvial channel, floodplain and palustrine deposits of Upper Jurassic–Lower Cretaceous age from northern Spain.

The laminar calcretes are interpreted as calcified root mats. The former two occurrences represent root mats developed on lithified calcretized horizons, while some from the latter area represent mats developed at shallow water-tables.

Such laminar calcretes are referred to as rhizolite laminar calcretes and are probably common in ancient paleosols from peritidal, palustrine and floodplain deposits. They are also probably important components of present day calcrete soils but have not been described in detail.

As a result of their plant origin they have a strong biogenic fabric and can be easily mistaken for microbial stromatolites or tufas. An awareness of rhizolite laminar calcretes may prove useful not only for the recognition of subaerial exposure zones but also in palaeohydrological studies enabling fossil water-tables to be indentified. They also provide evidence of rooted vegetation and surprisingly identical horizons have been found in Carboniferous to Cretaceous deposits despite probable differences in the plant originators.

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