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Lacustrine carbonates and pedogenesis: sedimentology and origin of palustrine deposits from the Early Cretaceous Rupelo Formation, W Cameros Basin, N Spain

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ABSTRACT

The Berriasian Rupelo Formation of the W Cameros Basin consists of a 2–200 m thickness of marginal and open lacustrine carbonate and associated deposits. Open lacustrine facies contain a non-marine biota with abundant charophytes (both stems and gyrogonites), ostracods, gastropods and rare vertebrates. Carbonate production was mainly biogenic. The associated marginal lacustrine ('palustrine') facies show strong indications of subaerial exposure and exhibit a wide variety of pedogenic fabrics. Silicified evaporites found near to the top of the sequence reflect a short hypersaline phase in the lake history. The succession was laid down in a low gradient, shallow lake complex characterized by wide fluctuations of the shoreline.

Carbon and oxygen stable isotope analyses from the carbonates show non-marine values with ranges of $\delta^{13}C$ from −7 to −11‰ and $\delta^{18}O$ from −3 to −7·5‰. Differences in the isotopic composition of open lacustrine carbonates are consistent with sedimentary evidence of variation in organic productivity within the lake. Analyses from the entire sample suite plot on a linear trend; isotopic compositions become lighter with increasing evidence of pedogenic modification. This suggests progressive vadose zone diagenesis and influence of meteoric waters rich in soil-derived CO_2. The stable isotope data thus support evidence from petrography and facies relations that 'palustrine' limestones form through pedogenic modification of lake carbonates.

INTRODUCTION

Studies of modern and ancient lacustrine carbonates have emphasized sedimentation in relatively deep, stratified lakes, commonly those with high-gradient, temporally stable, 'marl-bench' type margins (e.g. Murphy & Wilkinson, 1980; Brown & Wilkinson, 1981), or those with low-gradient, wave-influenced margins, as represented in parts of the Green River Formation of the W USA (Williams & Picard, 1974). In contrast, carbonate sedimentation in low-gradient, low-energy, unstratified lakes has received relatively little attention outside Southern Europe, where spectacular sequences of shallow lake carbonates developed under warm, arid to semi-arid climatic conditions during the Mesozoic and Tertiary. Freytet & Plaziat (1982) and other authors (e.g. Cabrera, Colombo & Robles, 1985) have described ephemeral carbonate lake margin facies as 'palustrine'. This term is broadly equivalent to 'paludal' (=swampy, marshy; e.g. Treese & Wilkinson, 1982) and is the approximate lacustrine analogue for 'peritidal' or 'paralic'.

This paper summarizes the results of a detailed investigation of an extensive lacustrine/palustrine carbonate sequence from the Berriasian (earliest Cretaceous) Rupelo Formation of the W Cameros Basin in Northern Spain (Platt, 1986). Many documented 'palustrine' sequences (e.g. Glass & Wilkinson, 1980; Freytet & Plaziat, 1982; Wells, 1983; Cabrera *et al.*, 1985) are from foreland basin-type tectonic environments. In contrast, the Rupelo Formation is an example from an extensional rift setting. Deposition post-dated Late Jurassic fault reactivation but preceded a sharp acceleration of subsidence at around the Valanginian. The Rupelo Formation may thus provide a useful model for shallow, ephemeral lake carbonate deposition in the isolated sectors of developing rift systems. Modern analogues with comparable tectonic settings may include lakes developed in isolated intermontane basins within the modern extensional province of the semi-arid Basin and Range in the United States (Fouch & Dean, 1982; Dean & Fouch, 1983).

The ephemeral nature of the palustrine environment is evident from the abundant indications of subaerial exposure present in palustrine limestones. Esteban & Klappa (1983) noted that palustrine limestones commonly show similar fabrics to those of calcisols. On the basis of petrographic evidence and facies relationships, Freytet (1973) suggested that palustrine limestones formed through pedogenic modification of lacustrine carbonate muds, although geochemical evidence to support this hypothesis has not been presented to date. Sedimentological analysis of the Rupelo Formation presented here is complemented by a stable isotope study designed to investigate the origin of palustrine limestones.

GEOLOGICAL SETTING

The Cameros Basin lies in the Northern Spanish provinces of Burgos, Soria and La Rioja, 200 km to the NNE of Madrid (Fig. 1). The Late Jurassic–Early Cretaceous was a time of rapid sedimentation over much of the Iberian Peninsula. Rifting associated with the opening of the Bay of Biscay and the North Atlantic caused subsidence rates to increase dramatically in several major Mesozoic rift basins, for example in the Cameros (Salomon, 1982, 1983) and S Vasco–Cantabrian Basins (Sbeta, 1985) of N Spain and in the Lusitanian Basin of W Portugal (Leinfelder, 1987). Upper Jurassic–Lower Cretaceous continental sequences up to 5 km thick were deposited above Late Jurassic unconformities in each of these basins.

In the W Cameros Basin this succession is over 2 km in thickness (Platt, 1986). The lower part of the sequence, the Tierra de Lara Group, consists of two formations (Fig. 2): the predominantly siliciclastic Señora de Brezales Formation, which is up to 75 m thick, of ?Kimmeridgian to Berriasian age, and lies unconformably upon a 500 m thick sequence of marine Jurassic carbonates; and the overlying Rupelo Formation, which comprises a series of lacustrine facies carbonates traceable over more than 2500 km^2, and up to 200 m in thickness. Presence of the charophyte *Globator incrassatus* indicates a Berriasian age (P. O. Mojon, pers. commun., 1985). The remaining 2 km of Lower Cretaceous sedimentary rocks consist of fluvial conglomerates, sandstones and mudstones, with only thin oncoidal carbonates near the base.

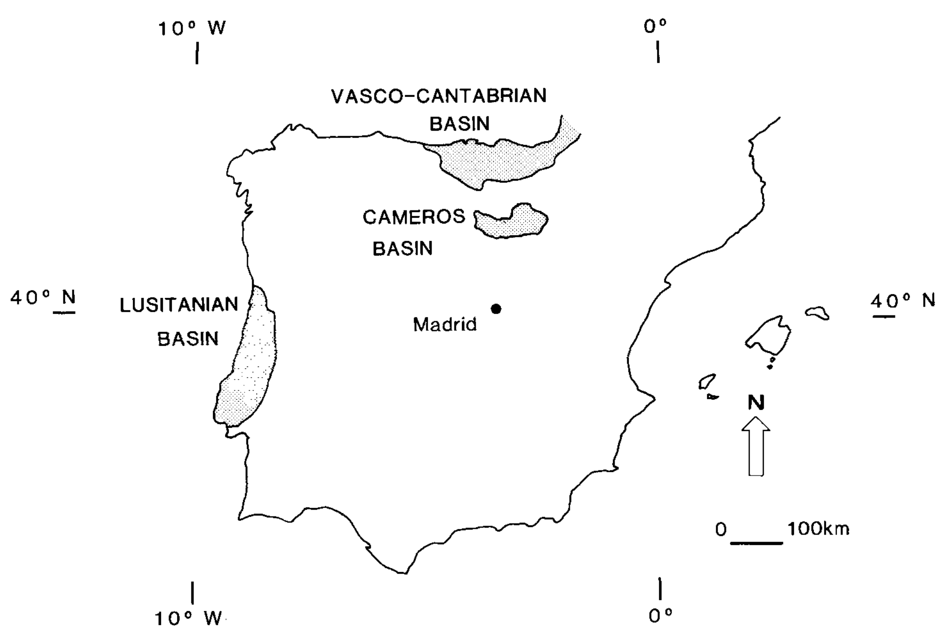

Fig. 1. Map of Iberia showing location of the Cameros Basin and of other basins mentioned in text.

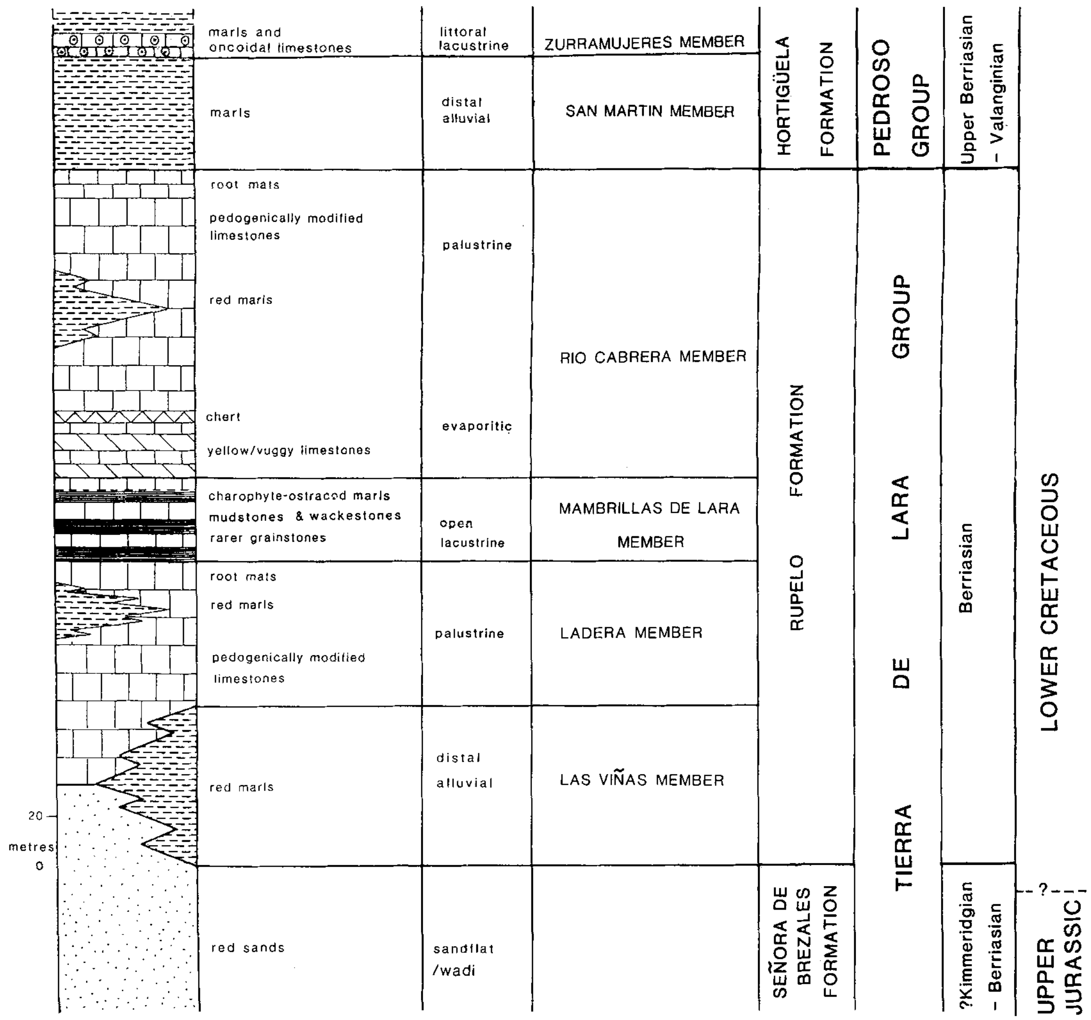

Fig. 2. Stratigraphy of part of the Upper Jurassic–Lower Cretaceous continental sequence.

THE BERRIASIAN RUPELO FORMATION

The Rupelo Formation may be lithostratigraphically and biostratigraphically correlated with other latest Jurassic–earliest Cretaceous ('Purbeckian') marginal marine carbonate sequences of NW Europe, for example in S England (West, 1975; Francis, 1986) and in the Jura Mountains of France (Strasser & Davaud, 1982) and Switzerland (Strasser, 1987, 1988). However, the Rupelo Formation is apparently unique among Purbeckian successions because it shows no indications of marine influence. Sedimentological and faunal evidence indicates deposition in a very shallow lacustrine complex. The Rupelo Formation is dominated by shallow water limestones rich in charophytes (including calcified stems) and displaying abundant evidence of subaerial exposure and pedogenesis. Distal alluvial sediments and minor evaporites are also intercalated. Depositional facies represented in the Rupelo Formation can be subdivided into five main associations:

(1) open lacustrine carbonates
(2) reworked lacustrine carbonates
(3) marginal lacustrine–'palustrine' carbonates
(4) distal alluvial
(5) evaporitic

Facies association 1: open lacustrine carbonates

This association comprises well-bedded 30–100 cm mid- to dark-grey mudstones and wackestones interbedded with grey marls. The limestones (Fig. 3A) contain gastropods 1–3 cm in size, some with partial geopetal fillings of internal sediment, 0·5–2 mm Cyprideae ostracods, and many charophyte stems and gyrogonites. The marls are especially rich in charophytes. Vertebrate bones and bone fragments up to 30 cm in size occur in the marls and mudstones. Vertebrate footprints 30–50 cm across were also observed. Polygonal desiccation cracks occur on the top surface of some beds, and fenestral cavities 1–2 cm across showing geopetal fills of crystal silt are also locally present.

Lamination is virtually absent; only in the darkest of the limestone beds does a diffuse and disturbed lamination occur (Fig. 3B). Rarely, however, some of the interbedded grey marls display mm-scale fine graded silt laminae rich in 10–20 μm subangular quartz grains. These occur only in the NW of the basin, where rare 10–50 cm beds of limestone conglomerate and cross-bedded sandstone with erosive bases were also found. Elsewhere, siliciclastic material is virtually absent.

Interpretation

The biota of these facies consists entirely of 'freshwater' elements typical of lacustrine environments with salinities of less than 5‰ (Sbeta, 1976); Cyprideae ostracods, charophytes, and gastropods. The predominance of mudstone textures suggests low-energy sedimentation. Carbonate production was mostly biogenic; carbonate mud was probably derived chiefly from degraded calcified charophyte débris. Modern charophytes commonly live in warm, shallow, alkaline waters, in depths of less than 10 m, or down to a maximum of 15–20 m (Cohen & Thouin, 1987). Charophyte stems are delicate structures, and the preservation of some intact stems provides further evidence for periods of low-energy deposition without significant transport. Spherical reproductive gyrogonites are more easily transported, even by relatively gentle currents. This may explain their paucity in beds where stems are abundant and their concentration in a few darker carbonate mudstone beds where stems are absent.

The footprints and polygonal cracks indicate shallow depths and occasional emergence, but their preservation rules out pedogenic reworking. Indeed, the limestones show little evidence of pedogenic modification, although the fenestral cavities may be solution vugs, also suggesting occasional emergence.

The general absence of lamination in these carbonates implies bioturbation of the sediments and low salinity, oxygenated bottom waters, and indicates that stratification of lake waters was not permanent. The scarce diffuse lamination noted was commonly disturbed. The fine clastic laminae are similar to laminae

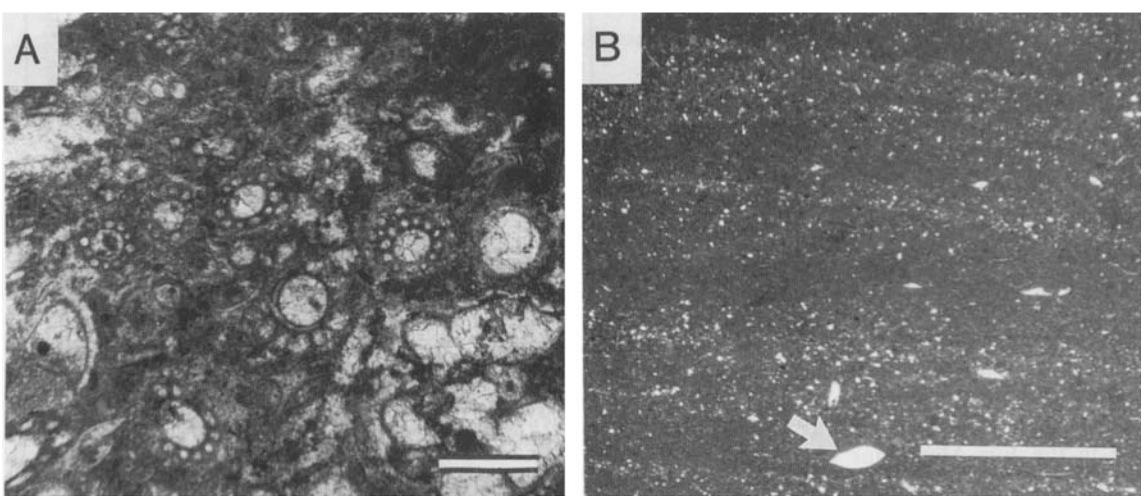

Fig. 3. Open lacustrine carbonates. (A) Wackestone with abundant charophyte stems in transverse section; gastropods associated. Scale bar = 1 mm. Interpretation: open lacustrine biogenic carbonates. (B) Fine, mm-scale graded silt laminae defined by terrigenous material. Ostracod test (arrowed) probably reworked. Scale bar = 1 mm. Interpretation: deposition from gentle, perhaps river-generated, density currents.

reported from modern West African lakes by Talbot (1984) and interpreted as the deposits of small-scale lacustrine density currents. Density currents may have been river-generated; the occurrence of clastic laminae associated with the thin clastic units exclusively in the NW of the basin points to terrigenous input into the lake from that direction. The preservation of lamination indicates periods of reduced bioturbation, either as a result of increased salinity or O_2 deficiency at the lake floor during times of increased organic productivity.

Facies association 2: reworked lacustrine carbonates

Associated with, or laterally equivalent to, the 'open lacustrine' carbonates, are an association of wackestones, grainstones, and intraformational conglomerates.

Wackestones contain angular intraclasts. Grading is locally developed above sharp, erosive bases. The intraclasts are from 0·5–2 mm in size and most are of pale beige micrite. Many intraclasts contain mm-sized peloidal structures, which are commonly associated with fine, curving sparry cracks. Dark 0·5–3 mm intraclasts are also locally abundant. These are angular and their colour ranges from black to mid-grey, commonly within a single pebble.

Grainstones are present in 1 m beds and consist of angular mm-sized charophyte mudstone clasts cemented with coarse spar (Fig. 4A). The clasts show no evidence of pedogenic modification. Cathodoluminescence reveals the presence of two principal non-ferroan calcite cement generations: a first, non-luminescent phase, and, rarely, a later brightly luminescent and locally zoned cement generation (Fig. 4B).

Intraformational limestone conglomerates are commonly developed at prominent bedding planes. They are difficult to recognize in the field because there is little lithological contrast between the irregular, weakly-rounded, grey micrite clasts 0·5–2 cm across and the mid-grey marly matrix. Rare dark clasts also occur in these conglomerates, but here they are generally larger, up to 3 cm across. The conglomerates drape sharp, erosive bases which are locally scoured to form shallow channels 2–3 m wide and up to 30 cm deep.

Interpretation

Each of these carbonate types contains reworked clasts.

The intraclasts present in the wackestones show evidence of pedogenic modification such as the mm-sized peloids (these spheroidal structures resemble pedogenic nodules or 'glaebules'; Brewer, 1964), and the associated curving sparry cracks are similar to 'circumgranular cracks' described from pedogenic carbonates (e.g. by Swineford, Leonard & Frye, 1958, and Ward, 1975). The intraclasts were presumably derived either from brecciated marginal lake deposits or from immediately underlying beds. Their concentration above sharp erosive surfaces suggests that they were washed in during storms.

The dark intraclasts can be compared to 'black pebbles' ('cailloux noirs' of the French usage; Cayeux, 1935), common in carbonates from aeolian (Ward, Folk & Wilson, 1970), lacustrine (Freytet, 1973), and pedogenic (Esteban & Klappa, 1983) settings. They probably document input of stabilized organic matter from a vegetated hinterland (Strasser & Davaud, 1983; Strasser, 1984). Shinn & Lidz (1987) related formation of black pebbles at modern subaerial exposure surfaces to burning of organic matter in forest fires. Shinn & Lidz warned against possible confusion with subtidally-blackened clasts, but the gradation of blackening and angular nature of the larger pebbles observed here are features cited by Shinn & Lidz (1987) as characteristic of subaerial fire blackening. The presence of smaller (0·5–1 mm) dark intraclasts in the wackestones suggests abrasion during transport.

The intraclasts present in the grainstones are of open lacustrine facies. They contain charophyte stems and show no evidence of pedogenic modification. However, the erosion of lithoclasts suggests early lithification. Winnowing may have been performed subaqueously within the lake, for example by traction currents or by small storm-generated waves on exposed shorelines or offshore bars.

The dominance of early non-ferroan, non-luminescent blocky calcite cement (probable low Mn, low Fe compositions) points to predominantly oxidising conditions during cementation (Scoffin, 1987). The rare later development of zoned, luminescent cement suggests increased incorporation of Mn, possibly associated with the onset of reducing conditions. This evolution is consistent with cementation in the meteoric phreatic environment during lake regression and subsequent transgression (cf. Scoffin, 1987).

The intraformational conglomerates also indicate internal reworking of open lacustrine facies. The only externally-derived clasts are the black pebbles. The channelling probably records periods of lower lake

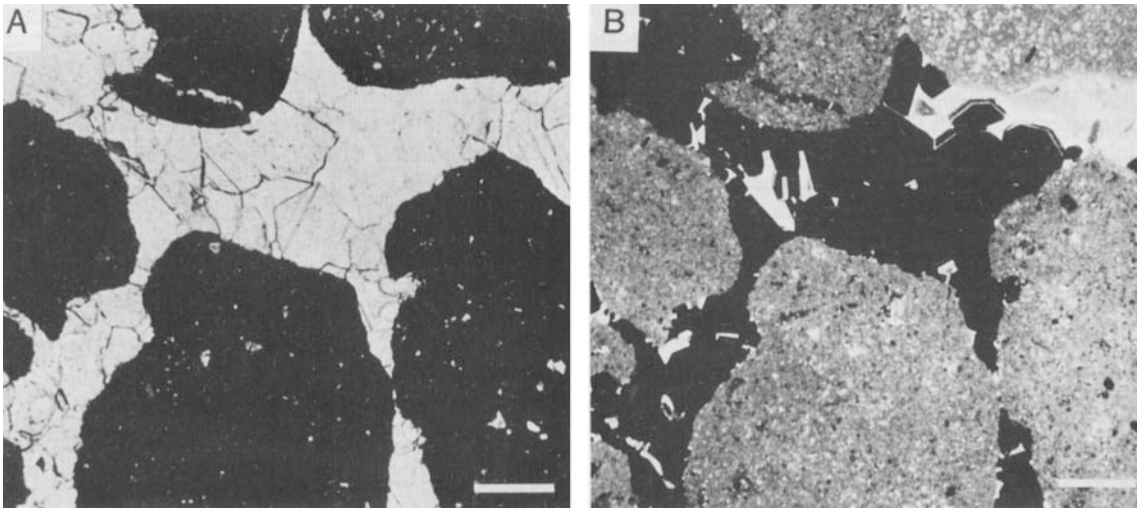

Fig. 4. Reworked lacustrine carbonate. (A) Grainstone consisting of mm-sized poorly-sorted (rounded 1–3 mm; irregular 5–30 mm) clasts of charophyte mudstone set in coarse sparry cement. Scale bar = 1 mm. Interpretation: high-energy, possibly storm reworking. (B) Grainstone under luminescence. Clasts of charophyte mudstone show dull luminescence. Most spar cement is non-luminescent, but with weak zoning; rare later generation of brightly luminescent cement filling remaining void space. Scale bar = 1 mm. Interpretation: meteoric diagenesis.

level. However, the absence of pedogenic features indicates that emergence was not prolonged. Rapid, transient shoreline retreat would have exposed open lacustrine sediments, which were then also locally eroded and reworked by streams of internal drainage plying the wide exposed lake flats.

Facies association 3: marginal lacustrine/palustrine carbonates

Microbrecciated/peloidal limestones do not generally contain faunal remains, although rare, poorly preserved charophyte stems occur within the matrix. Mottling is common, mostly from purple-red to grey, although yellow mottling also occurs. Many of the limestones are brecciated, and in thin section cavities and cracks are abundant. These are now spar-filled and display a variety of morphologies. Fine sparry cracks may be angular, or circumgranular structures developed around 0·5–2 mm rounded peloids (Fig. 5A), which rarely show a weak and irregularly concentric structure. Smaller, 0·05–0·1 mm pellets are also common. These are also partially surrounded by fine spar-filled cracks. Angular, black to mid-grey intraclasts from 2 to 5 mm (and rarely up to 30 mm) in size also occur, although they are not abundant. These locally show grey-brown rims and are associated with 0·5–1 mm subangular or subrounded red intraclasts.

Laminar horizons contain numerous predominantly horizontal, cylindrical 1 mm diameter, spar-filled cavities, which are surrounded by a lining of weakly-concentric laminated beige carbonate (Fig. 5B). Fine septae 0·1 mm across locally protrude from the cavity walls and interlink to produce intricate fabrics. The porous structure occurs rarely in discrete patches or as isolated tubules, but is more commonly developed in irregularly laminated, bedded units several cm in thickness which are laterally continuous for 0·1–5 m or more.

Limestones with geopetally-filled cavities contain fenestrae which are 2–20 mm in length and 1–5 mm in height, are elongate parallel to bedding, and show planar cavity floors but smoothly-rounded roofs (Fig. 5C). The cavity-fillings consist of single or multiple generations of fine calcite microspar (grain size approximately 10 μm), and an upper, later coarse blocky void-filling non-ferroan calcite cement (grain size 100–200 μm). Rounded peloids 0·5–1 mm across occur 'floating' in the cavities and locally show a coarsening-up trend in grain-size within a single cavity. Cavities commonly interlink to form complex networks with perched geopetal fills of internal sediment and crystal silt (Fig. 5D) or may be entirely filled with fine microspar. This hinders their recognition from the host micrite. Other sparry cavities include unlined 1 mm diameter tubular voids and rarer angular 1–3 mm cavities filled with brown spar.

Centimetre-sized carbonate nodules are abundant in some limestone beds. Larger, vertical nodular structures 5–15 cm in diameter and up to 50 cm long may be associated with rough vertical fracturing, giving rise to 'prismatic fabric'. Reticulate fabrics also occur. These show a combination of vertical nodular structures with horizontal laminar bedded units containing mm-scale cylindrical structures (see above).

Interbedded with the limestones are several 0·5–1 m rubbly red horizons, consisting of mottled, impure carbonates containing many subangular red clasts 2–10 mm in diameter. Strings of pale grey carbonate, 1 mm in diameter and 5–30 mm in length, are also common, forming individual, concentrically micrite-coated, cylindrical tubules. The red material drapes irregular basal contacts and locally passes down vertically along joints. Underlying beds have microbrecciated peloidal fabrics; overlying beds have rare red clasts 1–5 mm in size.

Green marl units 1–10 cm in thickness occur at a few localities. Samples taken from Rupelo Formation green marls were analysed by Deconinck & Strasser (1987) and found to be composed chiefly of smectite, with minor quantities of kaolinite.

Interpretation

Evidence of pedogenesis was noted by Mensink & Schudack (1982) and Salomon (1984). Mottling, desiccation brecciation, glaebule development, microkarst cavities and root structures are all common features in the Rupelo Formation.

Microbrecciated/peloidal limestones show mottling, which is characteristic of sediment subjected to repeated wetting and drying and may develop during pedogenesis as a result of fluctuating *E*h–pH conditions or through redistribution of iron oxide/hydroxide particles (Buurman, 1980). The mm-scale peloidal structures (Fig. 5A) are 'glaebules' (Brewer, 1964), nodules formed during pedogenesis through concentration of soil 'plasma' (colloidal or soluble soil material; Brewer, 1964). Desiccation shrinkage and rotation during emergent periods then results in circumgranular cracking and formation of rounded soil grains or 'peds' (individual soil aggregates; Brewer, 1964).

The smaller 0·05 mm pellets are similar to micro-pellets recorded from paleosols by Esteban & Klappa (1983) and Wright (1983) and interpreted as calcified faecal pellets. Their presence suggests the existence of a burrowing infauna.

The dark intraclasts are similar to the 'black pebbles' reported above from the wackestones and grainstones. However, the larger size of the black pebbles in the marginal lacustrine carbonates probably reflects closer proximity to the vegetated hinterland. The common alteration, especially of the smaller pebbles, to a brown-red colour is characteristic of this facies and apparently reflects the effects of pedogenesis *after* deposition. This may explain the scarcity of small black pebbles in this facies association, as possibly only the largest ones survived alteration.

The fabric of laminar horizons (Fig. 5B) is similar to that previously described as 'laminar calcrete' (James, 1972), 'laminar crusts' (Multer & Hoffmeister, 1968) or 'croûte zonaire' in the French usage (Freytet & Plaziat, 1982). However, in this case, the abundant cylindrical spar-filled cavities are associated with complex networks of fine septal structures. This alveolar texture (Esteban, 1974) is a root-associated fabric recently attributed to calcification of fungal hyphae (Wright, 1986; Phillips & Self, 1987). The cavities are interpreted as root voids. They may have been created by the horizontal root networks of subaerial or shallow-water marsh plants, or alternatively by charophyte holdfasts. When they are abundant, the bedding-parallel orientation of the cavities defines a crudely laminated fabric. Somewhat similar 'root mats' were described from the Plio–Pleistocene fluvial and marginal lacustrine deposits of Kenya by Mount & Cohen (1984). Laminar biogenic horizons with this morphology (rhizolite laminar calcretes) have been recognized from carbonate paleosols of a variety of stratigraphic ages (Wright, Platt & Wimbledon, 1988) and provide evidence for periodic colonization by plants.

The limestones with geopetal cavities (Figs 5C & 5D) are identical to carbonates with microkarst cavities described by Freytet & Plaziat (1982). The cavities may have been originally produced by root systems, but subsequent solutional enlargement is suggested by the rounded, embayed cavity margins. The cavities were then partially filled with internal sediment and crystal silt, probably during successive periods of desiccation and emergence prior to spar cementation. Internal sediment may have been derived from the cavity walls, but the coarsening-upwards size distribution of the peloids suggests that they were washed in during progressive widening.

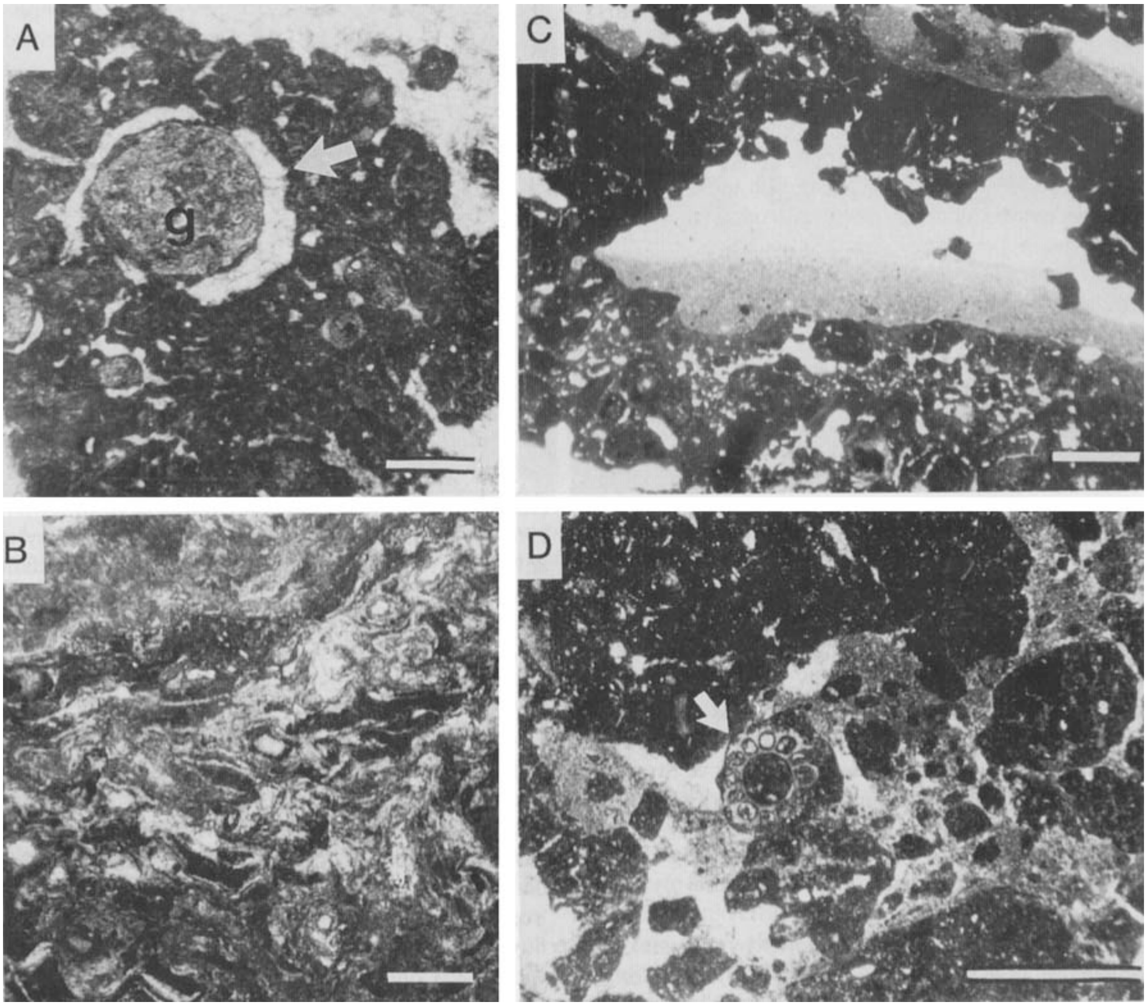

Fig. 5. Marginal lacustrine carbonates. (A) Rounded glaebules (example marked 'g') 0·5–2 mm in diameter. Partial and complete development of spar-filled circumgranular cracks (example arrowed). Scale bar = 1 mm. Interpretation: grain shrinkage and rotation on desiccation. (B) Laminar fabric showing tubular, spar-filled voids with concentric-laminated micrite lining. Scale bar = 1 mm. Interpretation: root mat (laminar rhizolite horizon) consisting of many small rhizoliths (Wright *et al.*, 1989). (C) Elongate cavity with partial geopetal fill of fine crystal silt, later spar cement. Circumgranular cracks in host sediment. Scale bar = 1 mm. Interpretation: 'pseudo-microkarst' (Freytet & Plaziat, 1982). Cavity possibly formed by root penetration; rounded margins suggest later solutional expansion. (D) Complex network of interlinked cavities containing perched geopetal fills of crystal silt. Note transverse section of charophyte stem (arrowed). Later sparry cement. Scale bar = 1 mm. Interpretation: brecciation as a result of strong development of 'pseudo-microkarst' (Freytet & Plaziat, 1982).

The crystal silt commonly postdates the peloids, favouring a later origin through precipitation, probably from vadose diagenetic fluids ('vadose silt'; Dunham, 1969).

The unlined cavities are probably small-scale invertebrate burrows. The rarer, brown-spar-filled cavities may be 'bird's-eyes', small vugs formed through shrinkage and expansion or gas bubble formation and preserved as a result of early lithification (Shinn, 1968, 1983), or may represent now-dissolved authigenic minerals.

The nodules present in the nodular limestones are interpreted as pedogenic structures. Cm-sized caliche nodules are common features of calcisols (Esteban & Klappa, 1983). Fabrics with columnar aspect were reported from marginal lacustrine facies by Freytet (1973). Vertical nodular structures are also typical features of paleosols (e.g. Cohen, 1982; Parnell, 1983; Brookfield & Sahni, 1986), and may be produced by root systems. Combinations of vertical structures (pneumatophores and geotrophic roots) with horizontal features (lateral roots, desiccation sheet cracks and bedded root mats) can give rise to prismatic and reticulate fabrics (cf. Hoffmeister & Multer, 1965). An alternative explanation comes from the work of Dubiel, Blodgett & Bown (1987), who described somewhat similar vertical structures from the continental Upper Triassic of Colorado, which they interpret as fossil lungfish burrows. However, no lungfish remains were found here.

The intercalated red horizons record supply of fine-grained terrigenous sediment onto the exposed carbonate surface. Fine sediment may have come from incursions of the alluvial plain into the central lake areas during low lake stands or as wind-blown dust. The grey carbonate stringers present within the red horizons are interpreted as isolated root traces. Their concentrically micro-laminar wall structure is similar to that present in the laminated units and their cylindrical, locally branching, morphology is identical to that of rhizocretions described from Quaternary paleosols by Klappa (1980). The red horizons are thus thought to represent paleosols developed over, and locally penetrating, karstified limestone surfaces formed during prolonged periods of shoreline retreat.

Thin green marls with smectite–illite–kaolinite mineralogies are common in Late Jurassic–Early Cretaceous marginal carbonate 'Purbeck' sequences (Deconinck & Strasser, 1987). Similar mineralogies were also reported from paleosols in the Lower Carboniferous (Mississippian) of South Wales by Robinson & Wright (1987). Illitization of smectites is commonly attributed to increasing temperature as burial diagenesis proceeds (Hower *et al.*, 1976; Nadeau *et al.*, 1985), but Eberl, Srodon & Northrop (1986) suggested that K-fixation necessary for illitization of smectites could be achieved at surface temperatures by repeated wetting and drying. This led Robinson & Wright (1987) to suggest that some mixed layer illite–smectite could be produced from smectite during pedogenesis (although this process has yet to be documented from modern soils).

Deconinck & Strasser (1987) attributed input of detrital smectite and kaolinite in the European Purbeck to the weathering of soil material and to the erosion of ancient massifs (Sladen, 1983), with the less easily transported kaolinite deposited mostly in areas proximal to sources of detrital input. In the French and Swiss Jura, Deconinck, Strasser & Debrabant (1988) noted that illite occurred in those areas nearer to marine influences, and suggested that illite was formed by conversion from detrital smectite as a result of repeated wetting by K-rich marine waters and subsequent drying in a hypersaline environment. In the case of the Rupelo Formation, the minor quantities of kaolinite present in the green marls are consistent with evidence from the carbonates of generally low detrital input. The dominance of smectite in the Rupelo Formation green marls reflects little conversion to illite, and might suggest low salinity environments with no significant influx of K-rich waters. This, in turn, would be consistent with the absence of marine indicators in the Rupelo Formation.

Facies association 4: distal alluvial

Red marls locally make up as much as 50% of the Rupelo Formation sequence. These red, or red–green mottled, calcareous and silty mudstones occur as monotonous units up to 20–40 m thick. The marls are virtually structureless both at outcrop and in thin section, and contain only rare faunal or floral remnants in the form of a few fragmented ostracod shells and broken charophyte stems.

White micritic limestones occur interbedded with the marls in lenses up to 5 m in thickness and 20 m in lateral extent.

Interpretation

The red marls are interpreted as distal alluvial sediments that were deposited out of suspension in a floodplain environment. Their structureless nature suggests thorough bioturbation. Lithologically similar sandy mudstones were reported from the Late Cretaceous–Early Tertiary of SW France by Freytet & Plaziat (1982). These deposits were also associated with shallow water marginal lacustrine carbonates and clastics, and were likewise interpreted as distal floodplain deposits. Alternatively, the red marls might represent poorly-developed paleosols, a hypothesis supported by the local presence of mottling. However, no other pedogenic fabrics were discernible.

The white micritic limestone lenses are interpreted as the deposits of isolated ponds developed in depressions on the floodplain. These ponds may have been the sites of intermittent biogenic production and/or inorganic precipitation of carbonate where desiccation led to periods of subaerial exposure, resulting in some pedogenic modification.

Facies association 5: evaporitic

Chert occurs in a 2–80 cm thick chert bed towards the top of the Rupelo Formation sequence. This bed is traceable over much of the basin. The chert may show nodular fabrics (Fig. 6A). It is generally white or translucent grey-blue. Polygonal angular voids (2–5 mm) are common and 1–5 mm angular patches of coarser silica are evident in thin section. Minor amounts of length-slow chalcedony and a few clustered 0·1 mm dolomite rhombs also occur.

Yellow limestones are associated with the cherts. These carbonates may be nodular, consisting of microspar with abundant fine sparry cracks, or, more commonly, vuggy (Fig. 6B). The vuggy limestones consist of elongate 0·5 × 2 mm calcite strings arranged in an irregular mesh network and separated by abundant angular interstitial voids 2–10 mm across, giving the rock a highly porous, sponge-like texture.

Interpretation

The chert contains minor amounts of length-slow chalcedony, which is indicative of sulphate replacement (Folk & Pittman, 1971). The cherts are thought to represent silicified evaporites. Nodules, crystal shapes and voids similar to those present here have been described by a number of authors (e.g. West, 1964; Chowns & Elkins, 1974; Tucker, 1976; Milliken, 1979; Arbey, 1980) and interpreted as evaporite silicification fabrics. The dominantly trapezoidal pseudomorph shapes are probably gypsum forms, although inclusions of sulphates are not preserved.

Features associated with subaqueous evaporites, such as depositional lamination or evidence of wave or current structures, are absent. However, a change in the net water budget, brought about by increased aridity or by tectonically-induced change in drainage may have caused a drop in water level eventually leading to the evaporite deposition in a continental sabkha environment.

There is no evidence for a biogenic silica source. However, given sufficient input of dissolved silica to lake waters, then silicification may be achieved inorganically under high pH conditions. In alkaline lakes such as the Coorong (Peterson & von der Borch, 1965) and Lake Magadi (Eugster, 1967, 1969), direct precipitation of cristobalite silica or silicification of evaporite phases is possible. However, the high limestone content of the Rupelo Formation and evidence for the presence of primary gypsum argues against highly alkaline waters (see Drever, 1982).

The common vuggy texture of the yellow limestones is consistent with evaporite solution. Dissolution of evaporite minerals (e.g. sulphates) could create an open porous fabric of this type. An alternative origin could involve dedolomitization of a cellular dolomite.

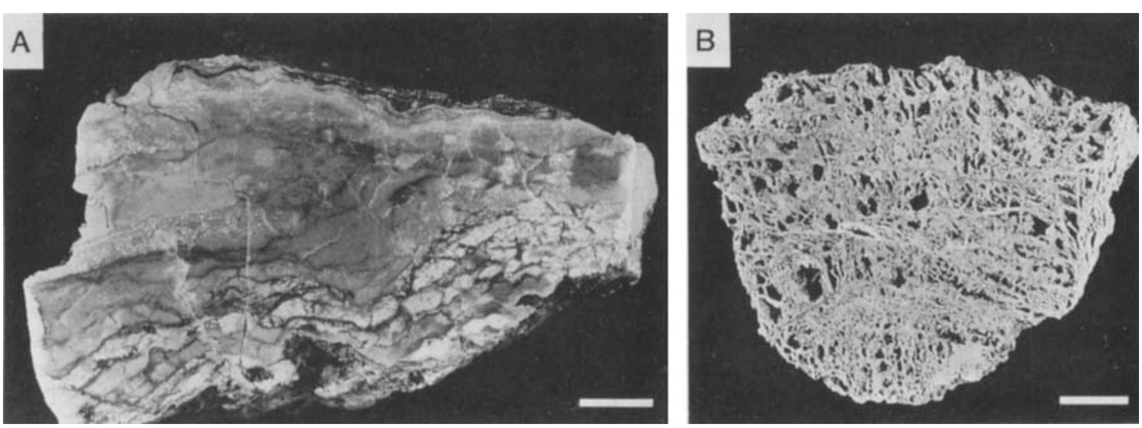

Fig. 6. Evaporitic facies. (A) White chert displaying undulating nodular fabric (cf. 'chicken-wire' texture). Scale bar = 2 mm. Interpretation: replacement of evaporites, probably sulphates, by silica. (B) Yellow vuggy carbonate showing extremely porous, open mesh fabric of 0·5 × 2 mm diameter calcite strings and interstitial angular voids. Scale bar = 2 mm. Interpretation: evaporite replacement.

FACIES ASSOCIATIONS AND SEQUENCES

Characteristic facies associations in the Rupelo Formation are outlined and interpreted in Table 1. large-scale evolution of facies in vertical sequence within the Rupelo Formation is indicated in Fig. 2.

Climate

Platt (1989) suggested that long-term climatic changes were responsible for the evolution of environments observed through time (Fig. 2; Table 2). Semi-arid conditions prevailed during deposition of the distal alluvial Las Viñas Member, and persisted through sedimentation of the palustrine Ladera Member. Deposition of open lacustrine facies (Mambrillas de Lara Member) suggests a more humid climate, but subsequent greater aridity led to the deposition of evaporites before a return to ephemeral lake carbonate deposition (Rio Cabrera Member).

Tectonics

Rapid lateral facies and thickness changes between individual fault blocks reflect the pattern of differential subsidence within the basin (Platt, 1989). Thin Rupelo Formation sequences (10 m or less) are composed entirely of marginal lacustrine/'palustrine' and distal alluvial facies. These were deposited where subsidence was gentle. The evaporitic, open lacustrine and reworked carbonate facies occur only in the thickest sequences (25 m or more). These were deposited in areas of strongest subsidence.

Regressive sequences

Marginal lacustrine facies are characteristically arranged in 'regressive' sequences (Fig. 7A). These sequences show upward increases in the degree of pedogenic modification. However, soil profiles are commonly incomplete and/or superimposed. The frequency of desiccation points to short-term climatic variation (seasonal or between individual years). The influx of red silts and marls reflects increase in terrigenous input, as a result of lake regression, climatic change or increased tectonic activity.

Graded sequences

Open lacustrine and reworked carbonate facies (Fig. 7B) show small-scale vertical variation in the

Table 1. Characteristic facies associations within the Rupelo Formation, with environmental interpretations.

Lithofacies association	Interpretation
Red marls–white limestone lenses	Periodically-inundated floodplain, ponded carbonates
Peloidal limestones–rubbly horizons–red marls	Marginal lacustrine, frequently exposed, terrigenous progradation
Green marls–root mats–white carbonates with microkarst	Marginal lacustrine, less frequent exposure
Limestone conglomerates–arenites–clastic laminated mudstones/marls	Clastic input at lake margin, river-generated density currents
Grainstones–wackestones	Open lacustrine, varying energy
Marls/mudstones with charophytes, ostracods, gastropods, bones, prints	Open lacustrine, shallow, unstratified perennial lake
Dark grey marls/mudstones, diffuse lamination	Open lacustrine, deeper water, possible oxygen-poor bottom
Grey marls–wackestones–intraformational cgls	Open lacustrine, reworking in drainage channels on emergence
Cherts–yellow limestone–yellow vuggy limestones	Desiccating lake flat, evaporitic
Wackestones–mudstones with desiccation cracks–red marls	Periodic desiccation in marginal lacustrine carbonate flat

Table 2. Interpretation of environments through Rupelo Formation time. Facies reflect variation in climate, carbonate production and clastic supply.

Member	Climate	Carbonate production	Clastic supply
Las Viñas	Semi-arid	Minor, in ponds	High, from NW
Ladera	Semi-arid	Important, freshwater, interrupted	Low
Mambrillas de Lara	More humid	Important, freshwater, more continuous	Low to zero
Rio Cabrera	Arid, semi-arid	Important later in freshwater	Low

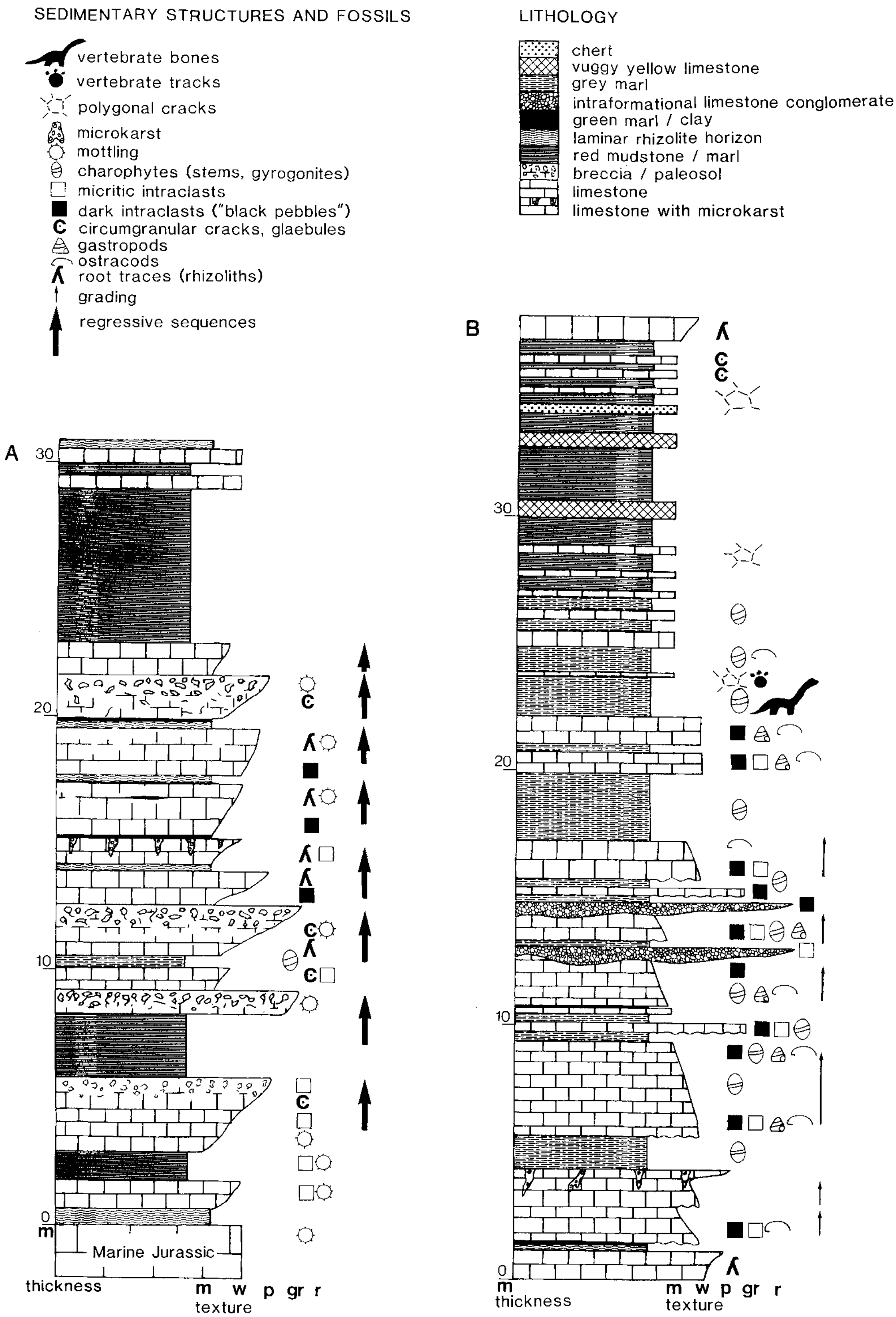

Fig. 7. Typical sedimentary logs. (A) Facies associations 3 & 4: marginal lacustrine and associated distal alluvial facies associations. Facies are arranged in shallowing upward sequences. (B) Facies associations 1, 2 & 5: open lacustrine, reworked carbonates and evaporitic. Grading represents change in energy consequent upon transgression and storm events.

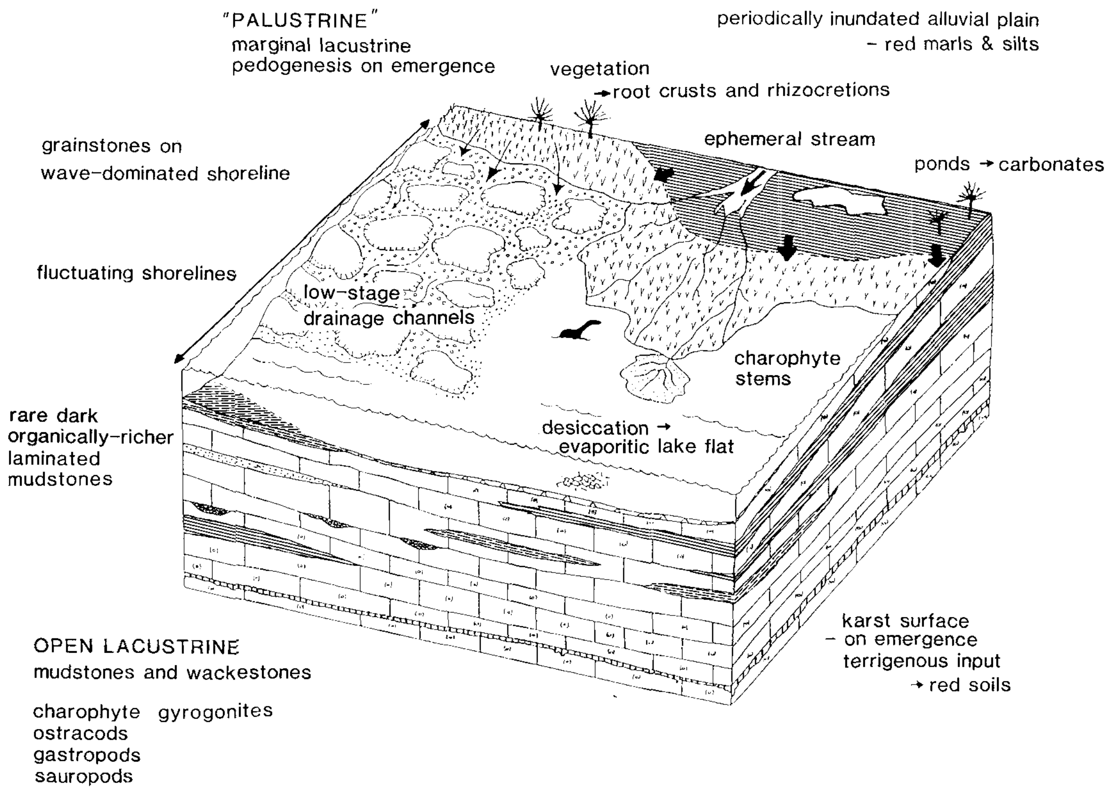

Fig. 8. Schematic environmental model for the Rupelo Formation, adapted from palustrine model of Cabrera, Cólombo & Robles (1985).

size and abundance of intraclasts. This is particularly evident in the wackestones. Grading above erosional surfaces probably reflects decreasing energy during transgression or storms.

ENVIRONMENTAL SYNTHESIS

Faunal and floral evidence indicate that the Rupelo Formation was deposited in a shallow, carbonate-producing (hardwater) lake. Figure 8 shows a schematic model for deposition during Rupelo Formation time. The main sub-environments represented in the Rupelo Formation depositional model are as follows.

Open lacustrine areas. The dominance of unlaminated deposits reflects intense bioturbation and implies shallow water depths without permanent stratification, although rare preservation of laminated fabrics may reflect periods of higher organic productivity within the lake. Carbonate derivation was dominantly from biogenic sources, chiefly from calcified charophyte stems, which were easily broken up. Some organic matter was land-derived, notably as 'black pebbles', which may represent residue from burning of terrestrial organic debris.

Lake transgressions reworked intraclasts from marginal into open lacustrine environments, and low-stage lake-flat drainage channels reworked exposed open lacustrine facies during periods of shoreline retreat. Grainstones made up of open lacustrine facies intraclasts were deposited as gravels on exposed shorelines and shoals, perhaps during storms.

Marginal lacustrine areas. The abundance of pedogenic features and the rare presence of a poorly-preserved freshwater flora in the carbonates of this facies association implies that they are lacustrine carbonates that have been extensively modified during pedogenesis. A marginal setting in a low gradient, shallow ephemeral lacustrine setting is inferred. The shorelines of low-gradient lakes (e.g. Lake Chad;

Reading, 1982) fluctuate greatly as a result of seasonal and longer-term climatic variations, so that periods of submergence and exposure alternate.

Frequent oscillations of the shoreline led to the exposure and modification of marginal lacustrine facies. Pedogenic modification resulted in loss of original fabrics and development of mottling, sparry cracks, microkarst cavities, and brecciation, as well as development of macro- and micro-scale root structures. Colonization by abundant shallow-water marsh and land plants formed a fringing vegetated zone around the lake margins, which acted as an effective barrier to terrigenous clastic input. A possible modern analogue is provided by Ruby Lake, Nevada, in the Basin and Range of the United States (Fouch & Dean, 1982), where open lake areas are surrounded by fringing marshlands with emergent aquatic plants, grasses and shrubs.

Floodplain environment. In low-gradient, shallow lakes, small-scale fluctuations in water level result in exposure of large areas, and occasional influx of fine-grained alluvial material is common. The red marls and silts of the Rupelo Formation were deposited on alluvial plains around the lake. These occasionally encroached over large areas of the basin. Deposition in the distal alluvial setting was mainly from suspension. Carbonate sedimentation was confined to ponds developed on the floodplain. Only on prolonged exposure did the alluvial systems prograde sufficiently into the central lake areas to introduce significant quantities of clastic material. However, the occurrences noted above (see facies association 1) of thin conglomerate and sandstone beds and mm-scale graded silt laminae in the NW of the basin suggests some clastic input from that direction.

Evaporitic environment. During the later part of Rupelo Formation time, periods of extreme desiccation led to the widespread establishment of hypersaline conditions and the formation of evaporites. Evaporite precipitation was associated with diagenetic silicification and dolomitization (and possibly subsequent dedolomitization).

STABLE ISOTOPES

Methods

A total of 21 carbon and oxygen stable isotope analyses were performed on selected carbonates from the Rupelo Formation. The sampling philosophy for this initial small sample suite was designed to characterize the isotopic composition of different carbonate lithofacies and components rather than investigate vertical trends in whole rock compositions, which were likely to be highly complex as a result of the heterogeneous fabrics and common superposition of pedogenic profiles. Samples were taken from only a few localities, and virtually all from a small geographical area in the NW of the basin.

Sample powder (1·5–5 mg) was drilled out under the microscope from Lakeside-mounted thin sections 150 μm in thickness using a fine engraving tool. Care was taken to sample from the micritic components; fine sparry cracks and bioclasts were avoided as far as possible. As a check on compositional heterogeneity, some analyses were controls carried out on samples drilled from different areas of the same thin section or from different thin sections cut out of the same hand specimen. Isotopic data were obtained by standard techniques (McCrea, 1950). Results were calibrated against MCS-8, a known laboratory standard (reproducibility shown in Table 3), and the values expressed in parts per thousand with reference to the PDB standard (Craig, 1957).

Results

Carbon and oxygen stable isotopic values for the

Table 3. Carbon and oxygen stable isotope data from the Rupelo Formation.

Sample	Description	$\delta^{13}C$ (‰)	$\delta^{18}O$ (‰)
316B/1	palustrine	−8·5	−5·5
339A/1	palustrine	−8·7	−6·4
339B/1	palustrine	−8·2	−5·0
341A/1	palustrine	−8·5	−5·8
341B/1	palustrine	−8·1	−5·1
B341	black pebble	−9·2	−6·7
343A/1	palustrine–root mat	−9·2	−7·2
344/1	palustrine	−9·4	−5·7
344/2	palustrine	−8·1	−4·7
V35A/1	palustrine	−8·0	−4·3
V35/2	palustrine	−8·2	−5·5
560A/1	open lacustrine	−7·1	−4·4
560B/1	open lacustrine	−7·4	−4·6
V30/1	open lacustrine–laminated	−7·5	−3·4
V39/1	open lacustrine	−7·8	−4·5
V39/2	open lacustrine	−7·9	−5·3
V39/3	open lacustrine	−7·7	−4·6
V114	open lacustrine + fenestrae	−8·5	−4·6
NP77	open lacustrine–black pebble	−9·0	−7·1
V91/1	crystal silt	−10·9	−7·4
V82B/1	crystal silt	−10·2	−8·0

Laboratory standard MCS-8 $\delta^{13}C = -0{\cdot}700$; $\delta^{18}O = -9{\cdot}177$
10 measurements: Standard deviation: $\delta^{13}C$ +/− 0·07; $\delta^{18}O$ +/− 0·17

Rupelo Formation (Table 3; Fig. 9) all lie on an approximately linear trend in the negative $\delta^{13}C$, negative $\delta^{18}O$ quadrant, with spreads of $\delta^{13}C$ from -7 to -11‰ and of $\delta^{18}O$ from -4 to -8‰.

The 'palustrine' samples showed considerable isotopic inhomogeneity ($\delta^{13}C$ +/−0·6‰; $\delta^{18}O$ +/−1·1‰). Open lacustrine carbonates were more homogeneous ($\delta^{13}C$ +/−0·2‰; $\delta^{18}O$ +/−0·3‰). Samples from the open lacustrine facies association showed heavier values than palustrine samples. The heaviest isotopic compositions were recorded from a laminated open lacustrine biomicrite. Of the palustrine samples analysed, the lightest compositions recorded were from a 'root mat' (laminar rhizolite horizon) and from black pebbles. The most negative values of all were obtained from samples of the geopetal crystal silt in fenestral cavities.

Interpretation

The compositional heterogeneity of the palustrine samples reflects their complex fabrics. These specimens contain a variety of pedogenic components including glaebules, micro-pellets, rhizolith carbonate etc., as well as fine micritic matrix. The open lacustrine samples have simpler fabrics with fewer components and show greater isotopic homogeneity.

The values obtained lie close to those of 'average freshwater limestones' (Keith & Weber, 1964) and of pedogenic carbonates (Talma & Netterberg, 1983), although they are strongly negative even within these fields. Three possible processes which might have affected the stable isotope values are:

(1) Progressive evaporitic fractionation in an ephemeral lake settling towards 'heavier' isotopic compositions (compare Lloyd, 1966; Salomons, Goudie & Mook, 1978; Oberhänsli & Allen, 1987).

(2) Progressive modification due to increasing influence of fractionated meteoric groundwaters and isotopically-light, soil-derived CO_2 in near-surface, vadose diagenetic (Gross, 1964; Allan & Matthews, 1977, 1982) or pedogenic (Beier, 1987; Cerling, Bowman & O'Neill, 1988) settings. Soil-derived CO_2 has $\delta^{13}C$ from -22 to -8‰ (Cerling, 1984).

(3) Variation in the organic productivity of lake waters. Photosynthesis results in ^{13}C enrichment of dissolved CO_2 and hence favours more positive $\delta^{13}C$ values for lake carbonates deposited during times of higher productivity and more negative values when productivity is lower (McKenzie, 1985; Oberhänsli & Allen, 1987).

Evaporitic fractionation would tend to produce isotopically lighter carbonates at times of high lake stand and isotopically heavier carbonates during low lake stands when the residual lake waters were more

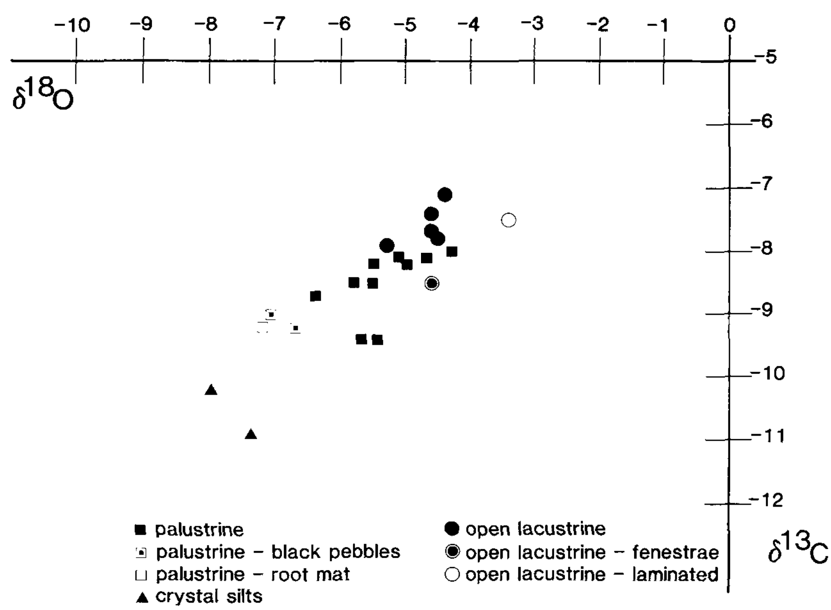

Fig. 9. Plot of carbon and oxygen stable isotope data from the Rupelo Formation, showing correlation of facies and isotopic composition.

evolved. However, the observed correlation between isotopic composition and facies shows the opposite tendency: open lacustrine limestones are isotopically heavier than palustrine limestones collected from the same locality. This trend is more consistent with processes 2 and 3. The trend is thus interpreted to represent the effects of increasing pedogenic/vadose diagenetic alteration of open lacustrine limestones, whose initial isotopic compositions reflected variations in organic productivity.

The final isotopic composition after diagenesis depends upon the isotopic composition of the initial carbonate, the composition of the diagenetic fluids and the degree of exchange. The initial isotopic composition of unmodified open lacustrine carbonate was probably close to that of the laminated lacustrine carbonate ($\delta^{13}C = -7‰$, $\delta^{18}O = -3‰$), which is likely to have been deposited during a period of relatively high organic productivity and which shows no petrographic evidence of bioturbational mixing or exposure. Since there were probably no C_4 plants during the Cretaceous, the soil carbonate $\delta^{13}C$ value would probably have been about $-12‰$ (Cerling, pers. commun., 1988). Thus the $\delta^{13}C$ and $\delta^{18}O$ values from the crystal silts, at around $-10{\cdot}5‰$ and $-7{\cdot}5‰$ respectively, are likely to represent the closest approximations to the isotopic compositions of the soil-gas charged vadose diagenetic fluids.

The isotopic compositions of the other samples represent a spectrum reflecting both lower organic productivity and variable degree of isotopic exchange with vadose diagenetic fluids. The unlaminated open lacustrine limestones show typical isotopic compositions of $\delta^{13}C = -7{\cdot}8‰$; $\delta^{18}O = -4{\cdot}5‰$. The lack of lamination reflects bioturbation in oxygenated bottom waters, and this suggests less intense organic productivity. There is little evidence of exposure. Otherwise similar open lacustrine limestones containing fenestrae have slightly more negative isotopic values, particularly in $\delta^{13}C$ ($\delta^{13}C = -8‰$, $\delta^{18}O = -4{\cdot}6‰$), suggesting some contact with isotopically light vadose diagenetic fluids.

Palustrine limestones show typical compositions of $\delta^{13}C = -8{\cdot}5‰$, $\delta^{18}O = -5{\cdot}5‰$. These more negative values reflect more extensive pedogenetic modification. The palustrine limestone samples showing the lightest isotopic compositions are from root mats and black pebbles ($\delta^{13}C = -9‰$, $\delta^{18}O = -7‰$). These soil components are likely to record prolonged contact with isotopically light soil-derived CO_2. Microscopic observation also shows slightly greater contents of organic carbon.

DISCUSSION

Palustrine limestones commonly show similar fabrics to those of calcisols; indeed Esteban & Klappa (1983, p. 40) stressed the problem of distinguishing between palustrine and pedogenic carbonates. In his comprehensive study of Quaternary calcretes from Spain, Klappa (1978) described pedogenic features including crusts, vertical roots, horizontal roots, root mats, root rock ('rhizolite'), solutional cavities, glaebular conglomerates, black pebbles (especially in coastal areas), sheet calcrete, soils, and brecciated textures. All of these occur in the Rupelo Formation and in many other 'lacustrine' and 'palustrine' carbonate sequences (see, for example, Stanley & Collinson, 1979; Freytet & Plaziat, 1982; Cabrera *et al.*, 1985).

An explanation for the similarity between palustrine and pedogenic carbonates comes from Freytet's (1973) suggestion that palustrine limestones formed through pedogenic modification of lacustrine carbonate mudstones. Stable isotope data from the Rupelo Formation supports this hypothesis. Esteban & Klappa (1983) recognized a 'continuous spectrum between lacustrine carbonates, palustrine carbonates and caliche'. The stable isotope study presented here suggests that this spectrum of fabrics is mirrored by a parallel spectrum of isotopic compositions. The fabrics reflect both the depositional conditions (laminated or unlaminated lacustrine carbonate) and the later effects of pedogenesis. The isotopic compositions are likewise interpreted as the result of variations in initial composition caused by changing lake productivity, and of secondary modification due to diagenesis in the vadose zone.

Isotopic compositions of the lacustrine–palustrine carbonates reveal that the near-surface diagenetic processes acting on freshwater carbonates after lacustrine desiccation (i.e. those associated with the formation of palustrine limestones) are geochemically analogous to the processes of meteoric vadose diagenesis known to act on marine carbonates on regression and subaerial exposure. Distinctive characteristics of the lacustrine–palustrine environment appear to be isotopically lighter initial carbonate compositions and the potential for more rapid and more frequent regression than in marginal marine carbonate settings.

CONCLUSIONS

The Berriasian Rupelo Formation of the Cameros Basin is a lacustrine–palustrine sequence deposited in a developing continental rift (Platt, 1989). Brief periods of stable lacustrine sedimentation led to uninterrupted deposition of charophyte–gastropod carbonate mudstones and wackestones, with rare laminites. However, the lake was generally ephemeral with widely fluctuating shorelines reflecting the response of a low-gradient lake margin to oscillating lake stands. Extensive areas were subject to repeated periods of exposure and strong pedogenic modification during successive intervals of shoreline retreat.

Intercalated red marls are interpreted as fine-grained distal alluvial sediments deposited on an extensive muddy floodplain fringing the lake complex. A brief phase of more intense desiccation led to the short-lived establishment of hypersaline conditions, as documented by cherts and vuggy limestones both showing evidence of evaporite replacement.

The Rupelo Formation shares many features in common with palustrine deposits described in the literature (e.g. Glass & Wilkinson, 1980; Freytet & Plaziat, 1982; Wells, 1983; Cabrera *et al.*, 1985). However, it is notable firstly for its tectonic environment (in an extensional rift rather than in a foreland basin setting), for the virtual absence of interbedded coarse clastic deposits, for the paucity of facies free from indications of pedogenic modification, and also perhaps for its age (it may represent a unique freshwater example of the European 'Purbeckian' facies).

Carbon and oxygen stable isotope compositions of the open lacustrine carbonates show variation consistent with sedimentary evidence for changes in organic productivity within the lake. Stable isotope data from the marginal lacustrine carbonates support the petrographic evidence for the action of pedogenic and vadose diagenetic processes during formation of palustrine limestones, and are consistent with an origin through progressive modification of open lacustrine carbonates during subaerial exposure.

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