Published in Journal of Paleolimnology 27 : 221-237, 2002,
which should be used for any reference to this work

Lacustrine and palustrine carbonate petrography : an overview[1]*

Pierre Freytet[1] & Eric P. Verrecchia[2]
[1]*41 rue des Vaux mourants, 91370 Verrières le Buisson, France*
[2]*Institut de Géologie, Université de Neuchâtel, rue Emile Argand 11, 2007 Neuchâtel, Switzerland*
(E-mail: Eric.Verrecchia@unine.ch)

Key words : paleolakes, nonmarine carbonates, petrography, pedogenesis, stromatolites, calcretes

Abstract

Lacustrine limestones were formerly identified by their faunistic (*limnea*, *planorbis*) and floristic (Charophytes) content. For 30 years, indications of pedogenesis have been found in many lacustrine deposits, and consequently the concept of palustrine limestone was defined.

Lacustrine fabrics are not that numerous: varved, laminated, homogeneous, peloidal, brecciated, gravelly, bioturbated (burrows), bioclastic, algal, and stromatolitic. Detrital beds are sometimes present and are interpreted as bottomset deposits. Palustrine fabrics result from exposure and pedogenesis of lacustrine mud. The main processes involved in this evolution are: cracking, with planar, curved, craze and skew planes, colonization by plants resulting in root traces, marmorization (redistribution of iron due to water table fluctuation), and redistribution of carbonates (needles, subspherical or cylindrical vertical nodules, carbonate coatings, early and late diagenetic crystals, *Microcodium*). Carbonate palustrine features can be associated with other minerals: palygorskite, gypsum, or silica. Alternation of lacustrine sedimentation and exposure/pedogenesis leads to the pseudo-microkarst facies resulting from enlargement of the complex network of root traces and horizontal cracks. The voids in the pseudo-microkarst facies are infilled with a polyphased internal sediment composed of carbonate and vadose silt and phreatic and vadose cements. Traces of exposure and pedogenesis are less in evidence in lacustrine bioclastic sands and algal-stromatolitic limestones. Finally, under certain conditions, the surficial laminar horizon and its associated perlitic crust (ooids) develops on palustrine muds and form a desert stromatolite.

Introduction

Terrestrial sediments are often composed of carbonates and their study allows paloenvironmental and paleogeographic reconstruction. The aim of this paper on ancient lacustrine deposits is to propose a short synthesis of petrologic features allowing the reconstruction of the depth, shape and type of paleolakes. Preservation of organic matter is linked to the redox conditions and the mineral paragenesis reflects the nature and proportion of ions in the lake water. Consequently, the sediments must be studied as a whole, but in this paper only carbonates will be described. The essential part of this paper concerns the petrography (fabric description) of lacustrine and palustrine carbonates. This overview is illustrated by thin sections of palustrine and lacustrine limestones from the Stephanian to the present. The purpose of this overview is to provide an illustrated and pedagogic tool for the researcher interested in terrestrial carbonate petrology.

The usefulness of the depth and boundary fluctuations in lake evolution has long been recognized (Gilbert, 1885; Fayol, 1888; Forel, 1901; Figure 1). Flat-

---

[1] Paper dedicated to Professor Claude Monty, sedimentologist and stromatophile.

*This is a series of papers to be published in *Journal of Paleolimnology* that were contributed from the keynote speakers at the 2nd International Congress of Limnogeology, held May, 1999, in Plouzane, France, and organized by Dr. Jean-Jacques Tiercelin.

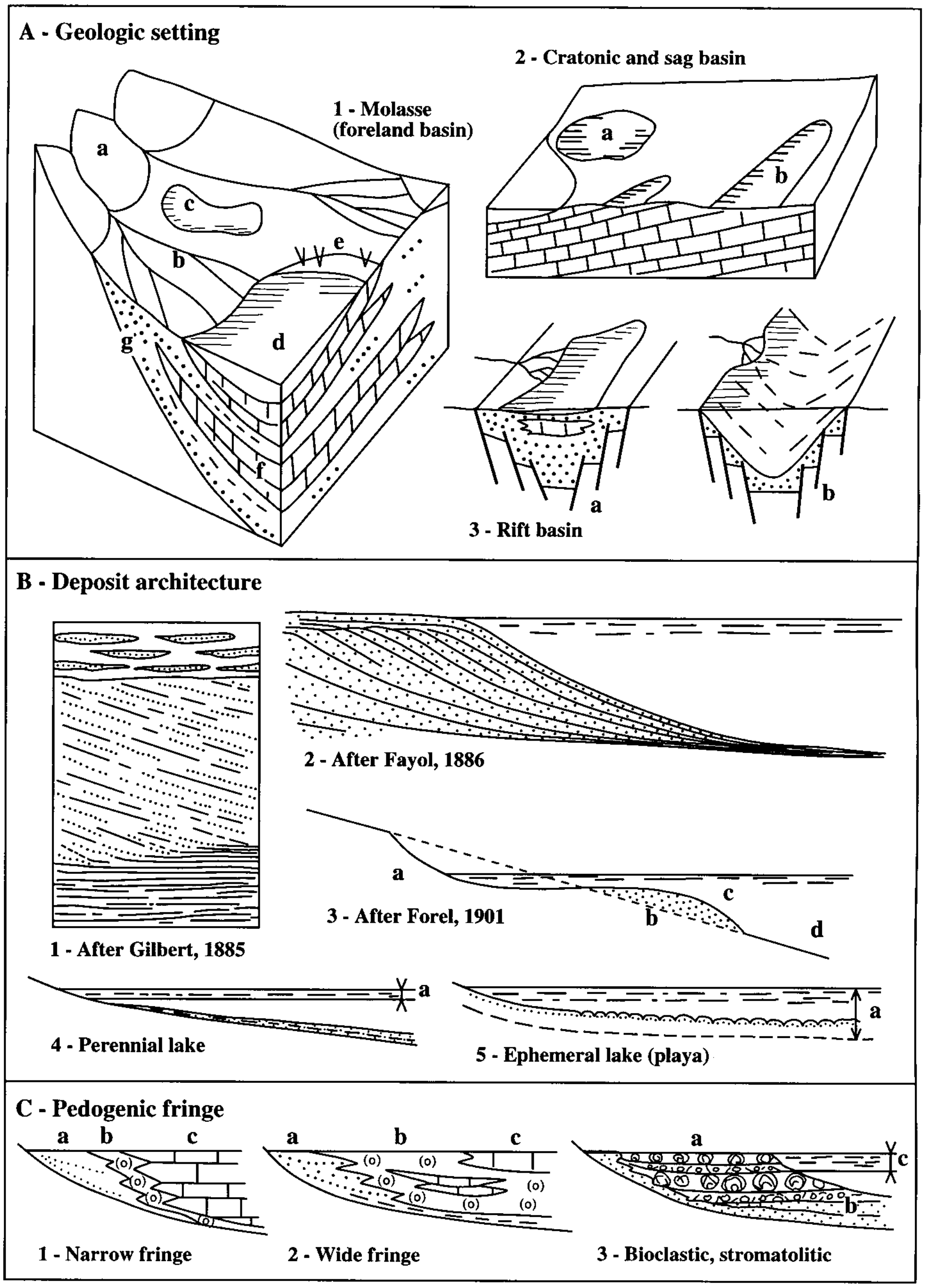


Figure 1. Geologic lacustrine nomenclature. (A) geologic setting (from Freytet and Plaziat, 1982, Figures 50 & 51). 1, molasse – foreland basin: (a, hinterland; b, alluvial fan; c, lake between two alluvial fans; d, distal lake; e, swampy edge of a lake; f, lacustrine limestone; g, alluvial deposits (conglomerate and sandstone in channels, mudstone in flood plain). 2, cratonic or sag basin: a, epicontinental (thalassic/athalassic lakes); b, subsidence area on erosional surface. 3, rift basin: a, sedimentation rate equals subsidence rate (shallow lake); b, sedimentation rate is lower than subsidence rate (deep lake). (B) depth and lake boundary variation. 1, deep lake with deltaic infilling, Pleistocene model (from Gilbert, 1885); 2, deep lake with deltaic infilling, Stephanian model (from Fayol, 1886); 3, deep lake with bench system (from Forel, 1901): a, 'beine d'érosion'; b, 'beine d'accumulation'; c, 'mont'; d, 'plaine'; 4, perennial shallow lake (ramp system from Platt and Wright, 1991): a, fluctuation of water lake level; 5, ephemeral shallow lake (playa lake, ramp system from Platt and Wright, 1991): a, fluctuation of water lake level, with total exposure of the lake bottom. (C) pedogenized fringe (from Freytet, 1973): 1, narrow; 2, wide: a, alluvial deposits; b, palustrine limestones; c, lacustrine limestones; 3, stromatolitic margin of a lake, with: a, layers of stromatolite (bioherms); b, layer of oolitic-bioclastic sand; c, fluctuation of lake level.

bottomed lakes (when emerged) include precious traces of pedogenesis (Freytet, 1971, 1984; Freytet & Plaziat, 1982) and stromatolitic facies (Freytet & Plaziat, 1982; Verrecchia & Freytet, 1987; Figure 1). The difference between flat-bottomed lakes and variable boundary lakes is described by Platt & Wright (1992) by the use of the term 'bench system' and 'ramp system'.

All submerged sediments are covered by a biologic felt identified by Forel (1901, p. 234). This felt is composed of Chlorophyceae and cyanobacteria fixed on rooted or floating plants and on littoral zone sediments, and by filamentous bacteria in the deep zone of the lake (abyssal community of Forel, 1901, p. 140). The word 'felt' (exact translation of Forel's concept) is rarely used today (Bradley, 1929; Johnson, 1937; Freytet &Verrecchia, 1998). However, numerous synonymous terms have been proposed through lack of knowledge of Forel's work : periphyton, algal mat, biofilm, microbiolite, or microbial ecosystem. This felt can be impregnated or encrusted by carbonates and is at the origin of the lacustrine mud or marl after reworking. This felt is fairly resistent to currents. It can be compared to Bahamian mats, which can 'withstand direct current velocities three to nine times as high as the maximum tidal currents (13 cm/sec)' (Neuman et al., 1970, p. 274). In intertidal environments, the algal felt protects sands during neap tide currents (< 25 cm/sec). The sand can be removed if the biological mat is chemically destroyed (Boer, 1981).

Therefore, this biologic felt influences the sediments' behaviour in the deep zone of lakes as well as when the sediments are emerged. In addition, a biologic felt also develops on emerged sediments when they are not covered by phanerogams. This felt protects the sediments against erosion. In ancient sediments, it can be calcified and is described as desert stromatolite or laminar horizon.

The three main carbonate terrestrial environments (lacustrine, palustrine, and aerial stromatolitic) are presented using facies and microfacies description of their respective deposits. This overview mainly emphasizes the relationships between petrographic features and the evolution of the environment.

Lacustrine facies and microfacies (Tables 1 & 2)

Lacustrine chalk and marl

Muds form the main lacustrine sedimentary deposits. A second type of lacustrine deposit is known as marl (carbonate content varying between 20 and 80% wt, the other components being fine siliciclastic particles and/or organic matter). Marl is a accumulation of biochemically precipitated carbonates by cyanobacteria, Chara, diatoms, planktonic organisms, epiphytic organisms on leaves of aquatic plants, and small animals. Finally, lacustrine chalk, which has a similar origin to marl, is deposited in the pelagic zone of the lakes. All of these sediments are characterized by a homogenous and mainly micritic fabric due to intense bioturbation: they constitute the parent material for further pedogenic transformation resulting in palustrine limestones.

Varves

Varves (De Geer, 1912) are seasonal sediment deposits related to glaciers. They are also used to describe sediments organized as couplets deposited in non-glacial environments. For example, in Lake Zurich (Kelts & Hsü, 1978), couplets 2–5 mm thick are composed by a first layer of 'organic substrate, blue-green algae, iron sulfides [and] fine mineral detritus', which is a late autumn and winter deposit, and a lighter colored layer formed by diatom frustules, produced by early spring blooms. The second layer is composed by big calcite crystals (up to 30 µm) with rare diatoms (late spring) followed by a micritic layer with aggregates of plankton, including dinoflagellates and diatoms (summer and autumn). Diatom species are not the same from one season to another. Calcite forms during whitings (diatom and more rarely cyanobacteria blooms) when the lake waters are stratified. In the case of Green Lake (New York State, meromictic lake with deepwater brines ; Brunskill, 1969; Thompson et al., 1990), couplets form in the monimolimnion below 16 m. From November to May, a dark layer composed of organic matter forms (0.2 mm thick). From June to October, the organic matter is associated with calcite (micrite and aggregates of crystals up to 64 µm in length) forming a lighter colored layer 0.5 mm thick. Calcite forms during whitings due to the coccoid cyanobacteria *Synechoccocus* sp. In the sediments, the cells are included in big sparitic crystals. Examples of varves from Lake Lamayuru (Ladak, Himalyas & Fort et al., 1989) are shown in Figure 2.

Some stromatolites built by diatoms, often associated with cyanobacteria, are morphologically similar to varves, with a light sparitic layer and a dark layer, rich in organic matter. These stromatolites, with 50 µm thick laminations, have been described by Winsborough and Golubic (1987) in Germany, 'on a seep of carbon-

Table 1. Lacustrine facies and microfacies (textures) – modern and ancient

Sedimentary structures	Main features	Formation
Varves (glacial/non glacial)	Couplet (0.1 mm –several cm) – dark (micrite + organic matter) – light (sparite + micrite)	Seasonal
Turbidities	Single layers ().1 mm–several m) homogeneous or graded bedding	Irregular periodicity slumpings, landslides upper- inter-underflow reworked material (waves, currents)
Laminated micrite – laminated limestones	Laminations (fossiliferous or not) (laminations of micrite, microsparite, bioclasts, very small stromatolites, pellets)	Irregular periodicity – micrite: *in situ* precipitation, or whitings – microsparite, sparite: whitings, reworking of stromatolitic coatings on leaves, *Chara* – pellets: pelagic animals, reworking of shore deposits
Massive micrite – massive limestones	Fossiliferous or not possible local preservation of laminations	Burrowing of various intensity recrystallization
Breccia (monogenic)	Lensoid, variable in thickness	Irregular periodicity reworking of desiccation breccias
Dropstones	Any lithology	Irregular distribution, ice rafts
Fossiliferous micrite – fossiliferous limestones	Micritic limestone with ostracodes, molluscs (*Corbicula*, *Limnea*, *Planorbis*), charophytes – bioturbations	*In situ* preservation (biocoenosis), or post-mortem reworking (thanatocoenosis)
Algal, stromatolitic limestones (see also Table 2)	Mudstones with bioclasts, sandstones, boundstones	*In situ* fossilization (biocoenosis), or post-mortem reworking (thanatocoenosis)

ate saturated water flowing over scarpment ledge' of a quarry (Winsborough & Golubic, 1987, p. 196, Figure 2) and in Mexico, 'in the bed of shallow streams' (Winsborough & Golubic, 1987, p. 196, Figures 9–16). Sparite crystals developed on diatom stalks are common features of travertines (literature summarized in Freytet & Verrecchia, 1998). The sparitic laminated travertines associated with diatoms are common in mountain streams. Sparitic laminations with diatoms (*Cymbella*) alternating with organic laminations of *Lyngbya calcarea* (Figures 2d & 2e) were observed coating a cement block on the Saône River bank (France). The structures of the samples from Germany, Mexico, and France surprisingly resemble varves although the samples came from fluvial environments.

*Turbidites (*senso lato*)*

Varved sediments can be interrupted by layers of different thicknesses composed of graded bedding. These structures cover a large part of the lake bottom and can be correlated from core to core. Many turbidite deposits can occur in one year, showing an irregular pluri-annual periodicity. These turbidites (*senso lato*) have several origins:

1. sediments close to shore or on the slope put into suspension by landslides due to natural mechanical instability or an earthquake;
2. fluvial sediment input of detrital material into a lake (Sturm & Matter, 1978). When the river water has a higher density than the surficial waters of the lake, the river water with the sediment in suspension dives to the lake bottom and spreads out (underflow). If the river water has an intermediate density, it interstratifies between the lake waters that have the same density within the water column (interflow). If the river water is less dense that the lake water, it spreads out on the surface of the lake (overflow);

Table 2. Algal limestones, algo-laminated sediments, stromatolites: textures

Elements	Lacustrine limestone (aqueous) facies	Palustrine limestone (subaerial) facies
Algae (bioclasts, tufts, builtups)	Algal limestones with phreatic cements – mudstones, dismicrite, fossiliferous micrite – arenite, rudite; boundstone – wackestone, packstone, grainstones – phreatic cements	Algal limestones with – exposure features: desiccation cracks, root traces, pedalogical nodules – vadose cements
Algo-laminated sediments	Laminated limestones with – planar beds – possible calcification of filaments and felt – phreatic cements	Laminated limestones with – planar horizontal cracks (between two successive felts) – roots, nodules – vadose cements
Algo-laminated sediments (alternation of exposures and submersion = playa lake)		Laminated limestones with – polygones, vertical cracks; – roots, pedologic nodules – vadose cements
Mobile builtups: spherulites, oolites, encrusted shells and leaves, *Chara* stems, oncolites	Bioclastic sands, bioclastic limestones, oolitic limestones, etc. – mudstones, dismicrite, fossiliferous micrite – arenite, rudite; boundstone – wackestone, packstone, grainstones – phreatic cements	Bioclastic sands, etc. – roots, pedologic nodules – vadose cements
Fixed builtups: floors, domes, columns; encrustation of mosses, reeds, *Indusia*	Stromatolitic limestones, boundstones – phreatic cements	Stromatolitic limestones, boundstones – microkarstification – vadose cements
Complex association of various types of buildups	Stromatolitic bioherms, biostromes – phreatic cements	Stromatolitic bioherms, biostromes – microkarstification – phreatic cements

3. waves due to a storm or epilimnion or mixolion currents can erode the lake bottom and put fine particles into suspension. The depth of possible erosion is controversial (Hawley & Lee, 1999). Suspended sediments settle out more easily during periods of water stratification.

Micritic-laminated and -layered limestones

In thin section, micrite is exceptionally homogeneous. It mainly appears as juxtaposed irregular or rounded clusters called pellets, pelletoids, peloids, and clots (Figures 2f–2k). Micrite can also include dispersed microsparitic crystals, bioclasts, and quartz grains. Four main types of laminations can be observed:

1. lamination with algal filaments preserved in a peloidal or clotted micritic matrix. Fossilization of filaments is exceptional although the biological felt is widespread on lake bottoms (Figure 4d);
2. laminations of peloidal or clotted micrite, mixed or not with exogenic material (quartz, microstromatolites, shell debris, wood);
3. laminations of peloidal or clotted micrite enriched in bioclasts, encrusted leaves, deposited in layers, emphasizing the overall lamination;
4. laminations constituted by the accumulation of shells (Figure 3a).

Microsparitic and sparitic crystals can be observed in micritic limestones but are only visible in thin section. They mainly correspond to:

1. isolated crystals or polycrystals dispersed in peloidal clotted micritic matrix;
2. crystals or polycrystals forming regular, planar or undulating, continuous laminae;

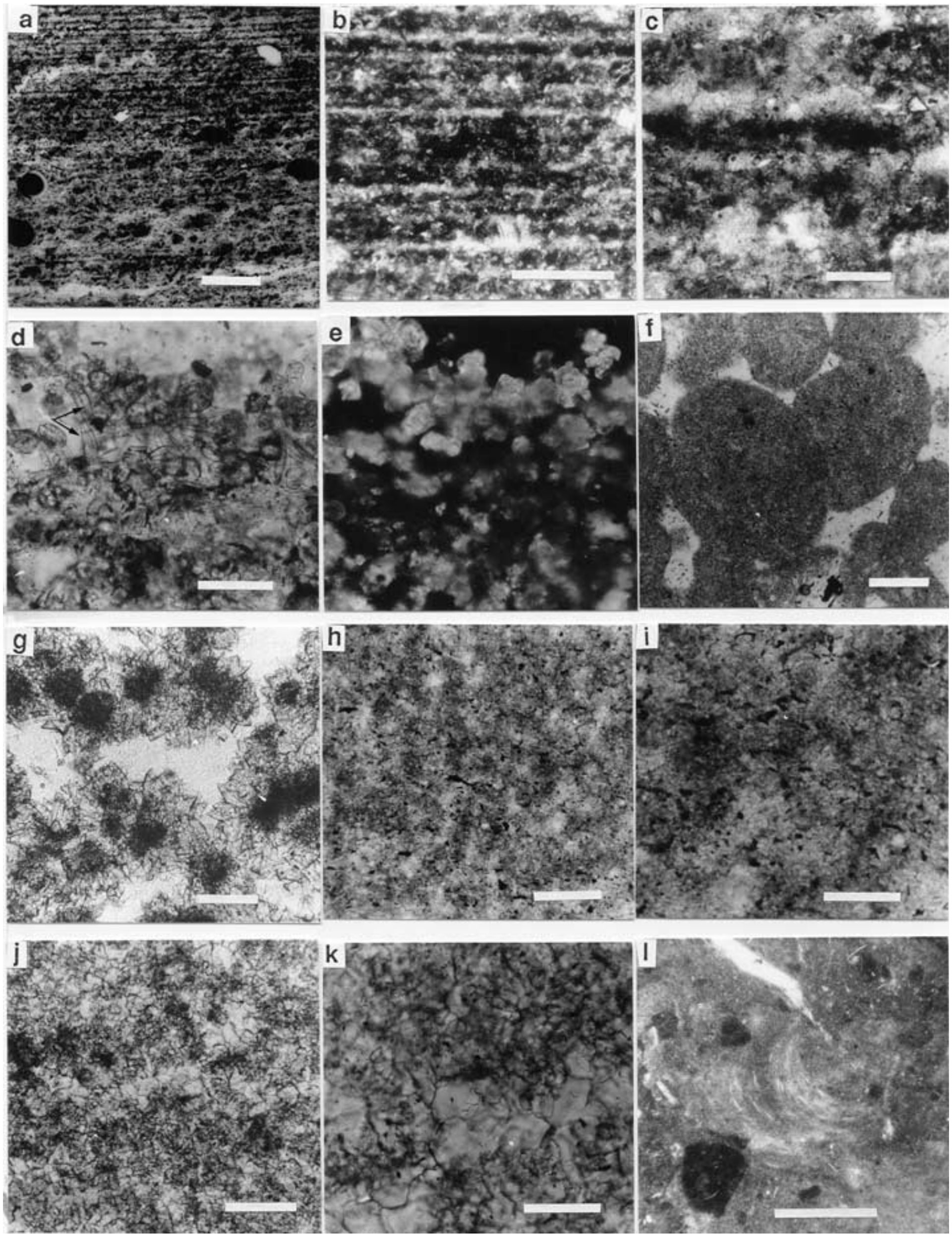


Figure 2. Varves, peloids and clots, burrows. (a), varves, negative photo. Lamayuru Lake (Fort et al., 1989). Dark circles are sections of gyrogonites, which do not disturb the laminae; compaction of the varval sediment is early. Scale bar: 1 mm. (b), detail; lamination boundaries are irregular. Scale bar: 500 µm. (c), detail of b; dark laminations are constituted by peloidal-clotted micrite; light laminations are composed of sparite; irregular boundaries. Scale bar: 100 µm. (d), laminae composed of sparite with preserved diatoms frustules (arrow), polarized light (PPL). Edge of the Saône River, France. Scale bar: 50 µm. (e), same as d, in crossed-polarized light (XPL). Crystals of sparite are 15–30 µm in size, important porosity. (f), fecal pellets in a clotted fabric. Montpensier, Limagne of Allier, Central France, Oligocene. Scale bar: 100 µm. (g), dark and clotted peloids surrounded by scalenohedral crystals. Stromatolitic limestone (travertine), Pleistocene, Wadi Nahari, Egypt (Freytet et al., 1994). Scale bar: 100 µm. (h), peloidal micrite with scattered crystals of microsparite and light micritic-microsparitic cement between peloids (probably fecal pellets). Fuveau, Southeastern France, Upper Cretaceous. Scale bar: 100 µm. (i), detail of h: peloids are micritic and clotted or microsparitic. Scale bar: 50 µm. (j), peloidal micrite with large patches of sparite. Château-Landon Limestone, Upper Eocene, Paris Basin. The pelloids are remains of filamentous algae (well preserved Figure 4d). Scale bar: 100 µm. (k), detail of j, wide crystals of sparite including dark remains, as in Figure 2g. Scale bar: 50 µm. (l), burrow (striotubule) in a peloidal- clotted micrite. St Ouen Limestone, Bartonian, Paris Basin. Scale bar: 500 µm.

3. microsparitic crystals infilling residual porosity between peloids or clots, and crystals growing on the peloidal wall;
4. crystals or polycrystals with a fibro-radial internal structure;
5. secondary crystals replacing ostracod or gastropod shells;
6. isolated rhombs dispersed in a micritic matrix;
7. finally, the spectacular case cited by Brunskill (1969, p. 841): '*Daphnia pulex* . . . was frequently observed with its gut full of brilliantly refractile small calcite crystals. The concentration of the small crystals into fecal pellets would hasten sedimentation'.

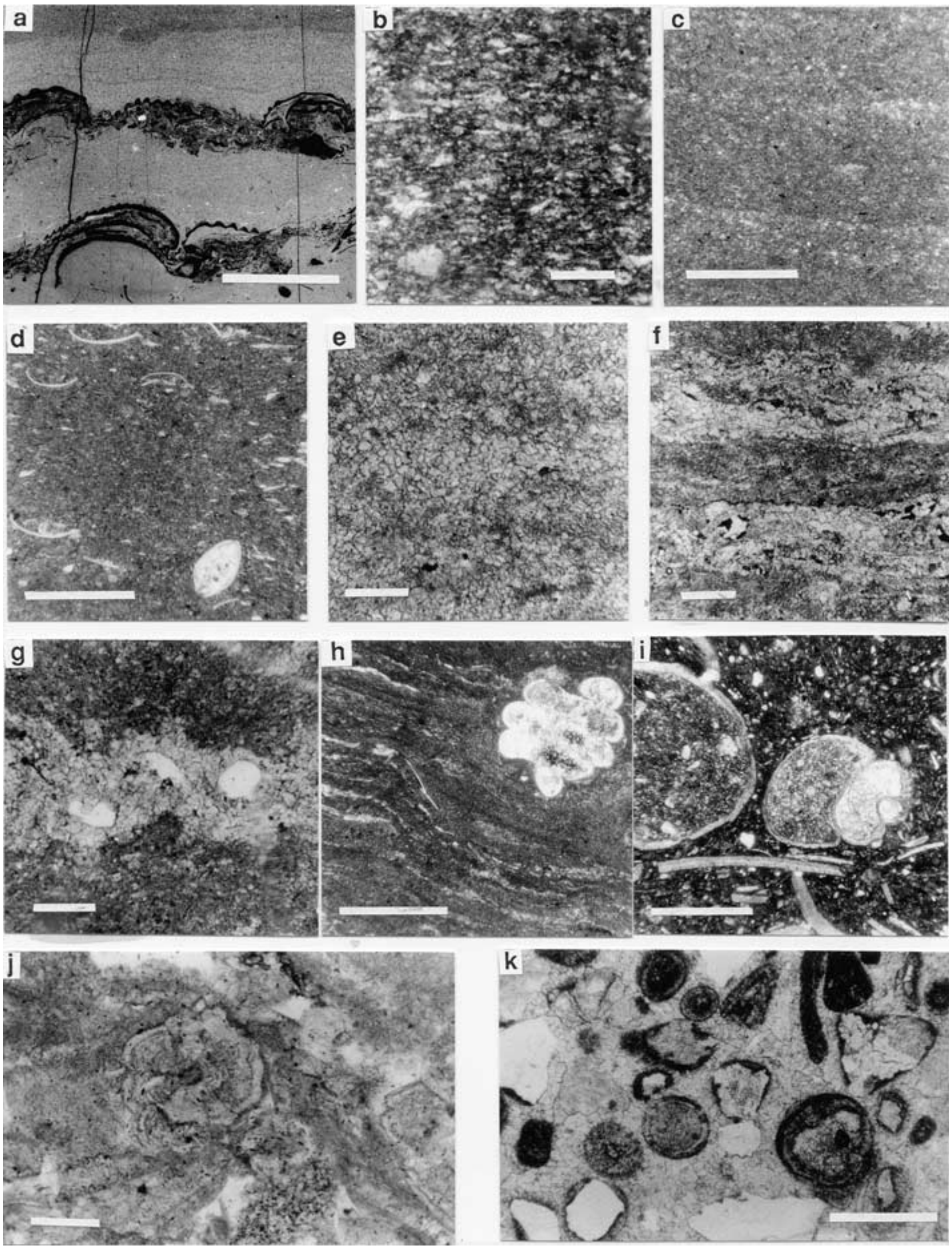
Part of the microsparite and sparite is due to recrystallization of shells (ostracods, gastropods) or to dedolomitization of dolomite rhombs. Other crystals can be interpreted as early phreatic cements. Crystals cementing clots and peloids can be primary or result from recrystallization of the light micrite. Crystals associated with laminae are primary and related to whitings or biologic felts. The fibro-radius crystals are interpreted as microstromatolite fragments (Figures 3j & 3k). Finally, some monocrystalline grains are identified as *Microcodium* fragments (Figure 5j) or gyrogonite fragments (Freytet & Plaziat, 1982).

The succession of laminae formed by micrite and microsparite-sparite is unpredictable (Figures 3a–3h). The laminated appearance can only be due to the variation of the bioclasts' contents or to the compaction rate of pellets. The periodicity of lamination is not easy to reconstruct. The irregular successions of these types of laminae contrast with the extreme regularity of varves. Micritic lacustrine limestones can also be completely without laminae. These are qualified as massive or homogeneous. This absence of internal structure mainly results from burrowing of various intensity (Figure 2l). In thin section, bioturbations are all of the same type, from Stephanian to Pleistocene: gallery infillings (from 0.2 mm–3 cm in diameter) are formed by stacked watch glasses (striotubules from Brewer, 1964; Freytet & Plaziat, 1982), with alternating color and grain size. In thin section, bioturbation exhibits circles and concentric ellipses emphasized by differences in grain size and by the orientation of the bioclasts (ostracod shells). Surprisingly, burrowing organisms never penetrate into marl stratification joints even when they are very thin. The reason for this behaviour is unknown, but it is possible that the higher siliciclastic content could annoy the animals.

Other biologic remains

Micritic limestones including biologic remains (Figures 3a–3i) are classified by the dominant macroscopic organisms present: limestones with ostracods, *Cypris*, *Planorbis*, gyrogonites or *Chara* stems. Associated bioturbations often appear as structured infillings (striotubules; Figure 2l). However, there is uncertainty between the following terms: pellets, pelletoids, peloids, and clots (Figures 3c–3e). The pellets-peloids are 50 µm–1 mm in diameter. They can have several origins: true fecal pellets (*foeces*) of planktonic (*Artemia gracilis*, Eardly 1938; *Daphnies*, Brunskill, 1969) or benthic (*Oligochaeta*, Tevesz et al., 1980) organisms; foeces and pseudo-foeces (branchial secretions) of bivalves (*Dreisenia polymorpha*, Mac Issac & Roche, 1995) or gastropods (Dudgeon, 1982). Some grains identified as pseudo-pellets could be purely mechanical in origin (Fahraeus et al., 1974). In marine environments, some peloids are thought to be bacterial in origin (Chafetz, 1986).

The word 'clot' is used to describe very small objects (10–20 µm in diameter) with an homogeneous internal fabric. Whatever their size, pellets are always grouped in a clotted fabric. Fecal pellets can result from a homogenizing pass through the gut of limnivorus organisms by mud before being excreted as a pellet. These pellets are rich in bacterial colonies that could be the origin of clots. If the micrite is related to a whiting, bacteria colonize and reorganize the crystals after settle-out on the lake bottom. In the case of travertines, there are no traces of the initial micritic sediment : clots are very dark and bristling with phreatic sparitic crystals (Figure 3g). Some of these crystals include dark clusters interpreted as bacterial remains (Freytet et al., 1994), similar to features described by Chafetz (1986) in marine environments. In addition, the progressive transition from a micritic tube around a filament to aggregates and then isolated clots has been observed in some freshwater stromatolites including well-preserved algal filaments. This feature is diagnostic in distinguishing the genus *Ponsella* (with solid filaments) from the genus *Ponsinella* (with hollow filaments) although the filaments have the same habit (Freytet , 1997, 1998). In conclusion, the term 'clots' should be used to designate the smallest grain found in a homogeneous fabric, 'peloid' or 'pelletoid' to describe micritic grains of unknown origin, and 'fecal pellets' for foeces, i.e., true animals excretions.



Algae, stromatolites and related deposits

A precise definition of stromatolites can be proposed using a synopsis on crystallizations associated with present-day freshwater algae (Freytet & Verrecchia, 1998) and fossil algae (Freytet, 1997, 1998; Freytet et al., 1999):

> Stromatolites are laminated rocks, resulting from the induration of biological felts, trapping and binding particles and precipitating minerals. A biological felt is a complex biocoenosis including bacteria, cyanobacteria, eucaryotic algae, Fungi, small Invertebrates. It can cover a mineral (shell) or biological (moss) substrate, that can be enclosed in the whole buildup. In a biological felt, one or two species are predominant, but a great number of other species are present, in low quantity, and can form local, important populations. The framework of the felt is defined by the irregular, seasonal growth of the pre-

dominant species, or/and the seasonal succession of different biocoenosis. The primary mineralization (oxalates, micrite, diverse types of sparite) is linked in a specific or generic manner to the organisms of the framework, or to their epiphytes. Early recrystallization in sparite of precise types is generally characteristic of a particular biocoenosis (Freytet et al., 1999, p. 32).

The lacustrine environment includes a wide variety of buildups, microfacies, and fabrics (Table 2):

1. algal limestones are those that contain algal remains identifiable in terms of species or genus. They are not included in stromatolites as bioclasts or boundstones, such as *Cladophorites incrustans* buildups from the Oligocene of Germany and France;
2. the algo-laminated sediments (Figure 4) are formed by flat layers over a large surface area. In an aqueous environment, the biological felt is continuous and not disturbed by desiccation cracks. Filaments may or may not be fossilized (Figure 4d). With exposure, laminae exhibit desiccation cracks (Figures 3b, 3e & 3f): they are then considered to be a palustrine limestone with planar cracks. In environments that undergo alternate submergence and exposure, the aquatic biologic felt is broken by vertical and planar cracks. A new biological felt can grow over and coat the cracks (algal sediments from Bahamas, Black, 1933, Figure 4, type C);
3. stromatolites *sensu lato* can be divided into two sets:
   - mobile buildups: spherulites (submillimeter-scale with only microlaminae, Figure 3j; spherulites are 'any more or less spherical body or coarsely crystalline aggregate with a radial internal structure arranged around one or more centers, varying in size from microscopic grains to objects many centimeters in diameter, formed in a sedimentary rock. . .', Bates & Jackson, 1980), oolites (millimetric, Figure 3k), oncolites (up to 30 cm), encrusted shells (ostracods, molluscs), encrusted leaves and stems of aquatic plants (phanerogams, *Chara*, and big algal filaments);
   - stationary buildups: only stromatolitic material (undulated river substrates, domes, columns, cauliflowers), or that resulting from encrusted substrate material (mosses, twigs, branches, larval tubes of *Phryganes*, bullrush in its living position). In all of these buildups, algal filaments can still be observed and identified, allowing the initial biocenocese to be reconstructed (Freytet, 1997, 1998, 2000; Freytet et al., 1999).

In conclusion, the term stromatolitic buildup should be used to describe stromatolites *sensu* Kalkowski (entire buildups), as well as stromatoids (buildup fragments, oolites, a few millimeters in diameter and concentric), oncoids and oncolites (bigger than oolites) algo-laminated sediments, travertines, bryoherms, and phytoherms.

Figure 3. Laminations, fossiliferous limestones. (a), negative enlargement of a limestone slide showing micritic (upper part), fossiliferous (shells of *Corbicula concinna*) and microsparitic layers (dark on the photo). Fuveau, Provence, Southeastern France, Upper Cretaceous. Scale bar: 5 mm. (b), coarsely laminated micrite, with scarce remains of ostracod shells and scattered crystals of microsparite. Manosque Basin, Southeastern France, Oligocene. Scale bar: 100 µm. (c), thin layers of microsparite in a pelloidal-clotted micrite, suggesting a cross bedding. Same basin as b. Scale bar: 1 mm. (d), remains of ostracod tests in a peloidal-clotted micrite. When valves are still connected, the central part of the void is infilled with drusy calcite. Same basin. Scale bar: 1 mm. (e), lamina of peloidal micrite alternating with equant microsparite. Same basin as e. Scale bar: 100 µm. (f), lamina of dark micrite alternating with equant microsparite due to reworking of crystals developed on charophyte leaves. Same basin as e. Scale bar: 100 µm. (g), detail of a crushed *Chara* stem showing a thick sparitic coating. The coating results from the calcification of epiphytes as well as possible recrystallization. These crystals are easily reworked, probably constituting the microsparite-sparite observed in photos b, c, e, f, g and h. Scale bar: 100 µm. (h), lamina of dark micrite and microsparite related to ostracod tests and charophyte encrustations on leaves and stems. A, gyrogonite has fallen to the bottom of the lake disturbing noncompacted laminae (different from varves, Figure 2b). Cesseras, Languedoc, Southern France, Middle Eocene. Scale bar: 1 mm. (i), black limestones with well preserved shells; the matrix is a peloidal micrite. Thézan, Languedoc, Southern France, Upper Cretaceous. Scale bar: 1 mm. (j), sparitic cement in a bioclastic sandstone; grains are remains of stromatolitic encrustation of leaves. In the center, spherulite showing small internal laminae. In XPL, spherulites show either a black cross extinction (fibro-radial fabric) or a patched extinction due to adjacent crystals formed by recrystallization of fibers. This feature is characteristic of mineralization by the alga *Broutinella arvernensis* (*forma corollata*) (Freytet, 1998, 2000). Gergovie, Limagne of Allier, Central France. Scale bar: 100 µm. (k), oolitic sand with quartz grains in a sparitic cement. Oolite fabric is similar to those of spherulites and buildups made by *Broutinella arvernensis* (Freytet, 1998, 2000). Chaptuzat, Limagne of Allier, Central France. Scale bar: 500 µm.

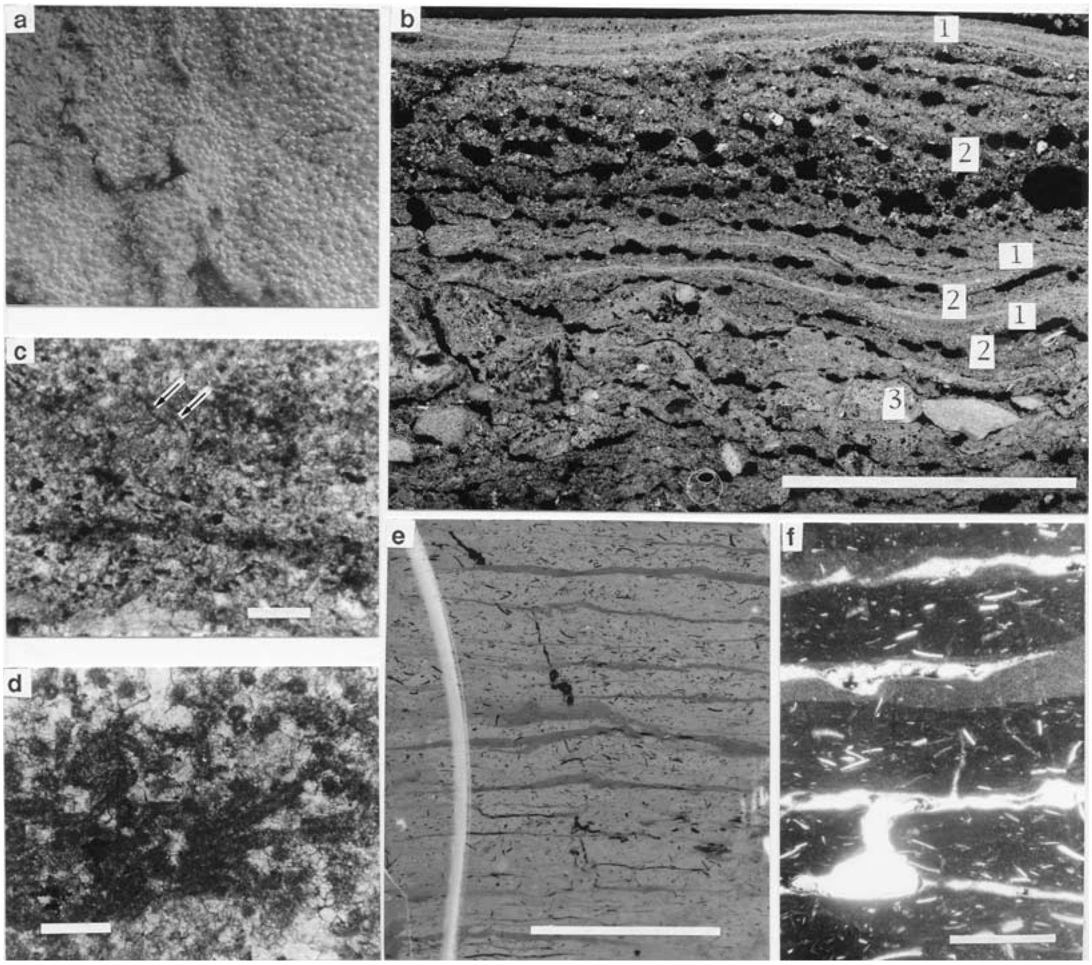


Figure 4. Biological felts and planar, horizontal cracking. (a), living algal felt, with bubbles of oxygen produced during photosynthesis. Modern small puddle, on the floor of a limestone quarry, Southern France, field size (photo width : 10 cm). (b), negative shot, section of a 'potential stromatolite', developed on the bottom of a small puddle (floor of a limestone quarry). Note the alternation of (1) sets of thin, dark, compact laminae and (2) laminae including rounded vesicles (bubbles). In the lower part of the thin section, the cracks are planar and curved, which is an indication of the formation of biologic aggregates (3). Southern France. Scale bar: 5 mm. (c), detail of upper laminae, with preserved filaments (arrow). Same location as b. Scale bar: 100 µm. (d), layer of filaments (*Ponsinella plicata*, Freytet, 1998) preserved between layers of peloidal micrite cemented by sparite . Château-Landon Limestone, Upper Eocene, Paris Basin. Scale bar: 100 µm. (e), negative enlargement of a thin section, micrite with remains of ostracod tests, and planar horizontal cracks, infilled with light microsparite (grey) and sparite (black). St Ouen Limestone, Bartonian, Paris Basin. Scale bar: 5 mm. (f), detail of e. Micrite is very dark, including white rectangular remains of ostracod tests ; horizontal cracks are partly infilled by light microsparite (in grey) and sparite. Residual voids appear in white. Locally, oblique planes (skew planes) can be observed. These cracks result from desiccation of a material formed by alternation of biologic felts and biomicrite layers (wackestone texture). Scale bar: 500 µm.

Palustrine facies and microfacies: sedimentary and pedogenic processes (Table 3)

A landscape approach

Many permanent lake shores are occupied by swamps (hydromorphic soils, bog soils). The central part of ephemeral lakes is often occupied by haline soils. Morrison (1964) believes that: 'much of the history of ancient basins, and particularly their post-extent, may in many cases be quickly determined by soil studies'. For example, Eardly & Gvosdetsky (1960, pp. 1333–1334) describe a 225 m-long core in Great Salt Lake as containing eleven paleosols, identified by their macroscopic features: solonetz, brown steppe soil, bog soil, brownish grey loam soil, dark brownish grey sand silty loam soil, immature soil on mudflow and immature soil on loess material. These soils are sometimes very rich in carbonates and are true palustrine limestones. The study of fluvial and lacustrine sediments in thin section allow sedimentary and pedologic features to be identified (Brewer, 1964). The use of thin sections allow the demonstration of the association of pedologic processes with fluvial and lacustrine deposits ('cyclothème sédimento-pédogénétique', Freytet, 1964; 'pedogenetic fringe' in lacustrine environments, Freytet, 1971, 1973, 1984; Freytet & Plaziat, 1982). The main types of pedologic features encountered in exposed lacustrine shores are briefly presented : marmorization, cracking, root traces, vadose cements, nodulization, and unusual crystals. Both sedimentary and pedologic nomenclatures are used to describe palustrine limestone features.

Marmorization (mottling, Figure 5a)

When the iron content of sediments is > 2% and if water table fluctuations occur, ferrous iron moves easily and fixes as ferric iron. The result is a sediment with mottled pink, purple, red, and yellow patches in the accumulation area of ferric iron, and grey or white in the area depleted in iron. Manganese and calcium can also migrate with iron, resulting in a complex fabric of mottled patches and ferrogeneous nodules.

Cracking (Figures 4 & 5)

Freytet & Plaziat (1982) describe vertical joint planes, horizontal joint planes, skew planes and curved planes in paleosols developed on fluvial deposits and lacustrine muds. Vertical joint planes are usually organized in a polygonal network. Isolated prisms are often deformed in cups, concave-upward. The association of vertical planes and curved planes indicates the desiccation of a biologic felt impregnated with crystals. These shapes have been described in Fresh Creek Lakes, North Andros, by Black (1933). These 'algal heads of type D' are formed by *Scytonema* sp. and *Aphanocapsa* sp. laminae.

Horizontal joint planes are always linked to a biologic felt. They can be due to oxygen bubbles or fermentation gas. They can also develop between two successive generations of biological felt. During aerial exposure of these sediments, single or sets of biologic felts can separate due to desiccation (Figures 4e & 4f). Vertical and skew planes can crosscut this horizontal network. The crack infillings are composed of internal detrital sediments, pellets, vadose silt, microsparite, light micrite, vadose cements, early phreatic sparite or late diagenetic sparite. Curved cracks develop around areas of differentiated matrix, either by early diagenetic or mechanical restructuration (bioturbation) or by plasma segregation (pedological nodules, Figure 5b).

Root traces

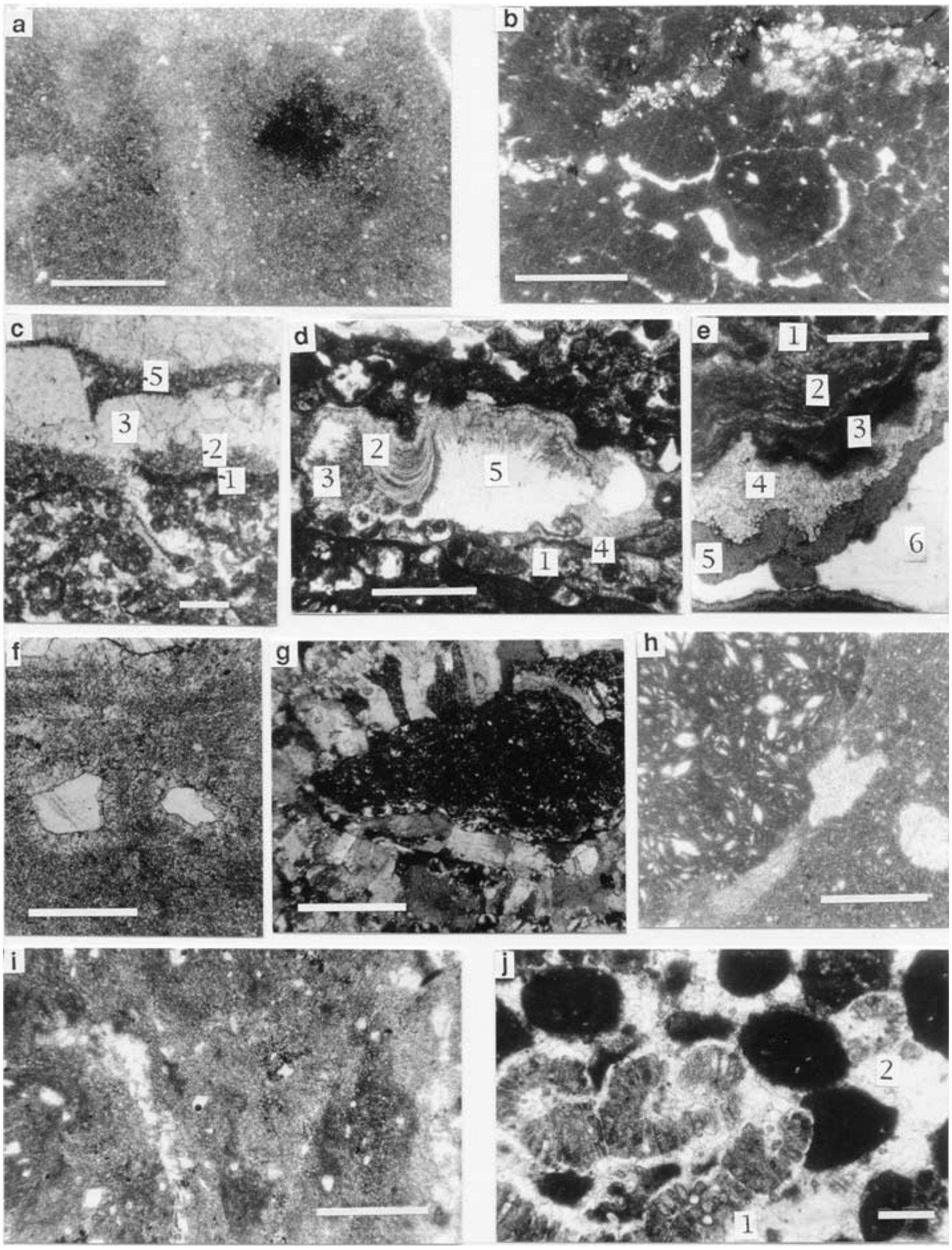
Klappa (1980) gives a list of terms that designates five basic types of rhizoliths: root moulds (voids), root casts (infilling of voids), root tubules (cemented cylinders around roots), rhizocretions ('pedodiagenetic' mineral accumulation around roots), and root petrification (mineral impregnation of plant tissue). Such root traces are common in palustrine limestones. Root traces can be complex. The root void can be enlarged and infilled by internal sediment, a vadose silt, various cements (coatings, calcitans, vadose or phreatic cements), impregnation of soil matrix (subcutanic feature), various types of recrystallization and cone-in-cone crystallizations formed by bacterial colonies associated with roots (Permian from Spain, Aassoumi et al., 1992).

Two different sets of root trace features can be distinguished: (1) subcutanic features *sensu lato* that form inside soils and have a complex fabric and (2) root hollows that can be mechanically enlarged and infilled by various materials and described as pseudomicrokarst. Subcutanic features include infillings, soil matrix, and skeleton grains, which surround the root. Their internal fabric is similar to those of subspherical nodules found on lake shores and fluvial floodplains.

The term 'pseudomicrokarst' was proposed by Plaziat (in Plaziat & Freytet, 1978; Freytet & Plaziat, 1982, pp. 71–75, Figures 42 & 43). It is a 'pseudo' karst because it results from mechanical erosion and not dissolution of the sediment. It is a 'micro' karst because the size of the features is only a few centimeters to a few decimeters. Pseudomicrokarst is a common and widespread feature of lacustrine and palustrine limestones. It is commonly misinterpreted in the literature as a brecciated limestone. Its origin is related to long-rooted grass colonization of a mud, recently exposed. This pioneer step for pedogenesis evolves into a complex facies, which can have 17 successive different stages in void infillings (Figure 5b).

Coatings, cutans, and cements

Pore walls are usually coated. In subaerial environments, meteoric vadose cements appear as micritic or microsparitic coatings, generally thicker on the pore ceiling than on the floor. These cements as called an-



isopaquous. In phreatic environments, sparitic cements have the same thickness in all directions. These two types of cements can alternate, indicating fluctuations in the water table. Vadose and phreatic micritic or microsparitic cements can result from pedogenesis: they are classified as calcitans.

The problem of needle-fiber calcite in terrestrial environments has been discussed by Verrecchia & Verrecchia (1994). The presence of needle-fiber calcite in a fossil calcrete, travertine, or palustrine limestone often corresponds to a present-day contamination by Recent fungi. Nevertheless, recrystallization features can be observed in thin section and show all the intermediate steps between needle bundles and radiating microsparite (Figure 5d). The only way to be sure that this vadose cement is primary is by its fossilization pattern e.g., by silica (Figure 5e). Misinterpretation of needle-fiber calcite led to the 'lichen stromatolite' facies, which is only a travertine of any age including present-day needle-fiber calcite.

Other crystals

Nodules in palustrine limestones can undergo complex and repetitive phases of recrystallization, leading to crystallarias (Figure 5i). Palustrine limestones also include crystals of dolomite, dedolomitization features, gypsum (Figure 5j), palygorskite, silica (Figure 5e) and structures associated with salt crusts (teepees and pseudo-anticlines).

Microcodium *(Figure 5j)*

This mysterious feature (synthesis in Freytet & Plaziat, 1982) is formed by prisms of 1 mm-high calcite, grouped into corn-cob colonies or in centimeter to decimeter scale laminae. It corrodes limestones in terrestrial and underground environments (karstic caves, limestone pebbles in fluvial channels, pedologic nodules and carbonate silts from floodplains, exposed lacustrine muds). Reworked isolated prisms can be found in lacustrine deposits. Corn-cob colonies have been observed corroding elements of desiccation breccia or nodules. In the literature, the age of the corroded rock and the age of the corrosion are commonly confused. *Microcodium* are described from the Devonian to the Miocene. The *Microcodium* described in Quaternary calcretes are confused with cyanobacterial spherulites and calcified root cells. Their origin is still uncertain : perhaps symbiotic association of bacteria with fungi or root calcification of certain plants.

Desert stromatolites: the laminar horizon and associated ooids – perlitic crust (Table 4)

The laminar horizon is composed of thin micritic laminae with irregular undulation. These laminae include microsparitic layers and isolated or fused spherulites (Verrecchia, 1994). These latter layers are often confused with *Microcodium* or root traces (see discussion in Verrecchia et al., 1995, 1996). The laminar horizon covers all substrate irregularities and forms small columns (Figure 6a), penetrating into vertical cracks to a depth of 2 m. These cracks can open and be infilled by the laminar horizon a number of times. The laminar crust also coats horizontal cracks associated with the vertical ones, leading to parallel-piped clusters coated on all sides (Freytet & Plaziat, 1982). The laminae of the layers can coat the intergranular porosity of a sand or the curved cracks around nodules. Such nodules are called pedologic ooids, ooidic crusts or perlitic crusts. The process involved in their formation was demonstrated in the Beauce limestone, Oligocene of the Paris Basin, France (Freytet & Plaziat, 1982). Laminar horizon and perlitic crust can occur cyclically in lacustrine deposits or on pediments (Freytet & Plaziat, 1982; Verrecchia & Freytet, 1987).

In the literature, the laminar horizon is considered as an important constituent of calcretes and is rarely interpreted as a surficial horizon (Kahle, 1977). It is mainly described as an accumulation horizon related to pedologic leaching processes. This misinterpretation

Figure 5. Palustrine limestones. (a), patch of marmorization (mottling) in a calcitic nodule. The iron-bearing crystals are irregularly distributed. In the field, grey patches are reddish, and black patches dark-red. Their boundaries are diffuse (forming 'globular halos' in pedologic terminology). The enclosing material is micrite and some microsparite due to recrystallization, and rare quartz grains in white. Alaric Mountain, Languedoc, Southern France, Maastrichtian. Scale bar: 1 mm. (b), curved cracks in a nodular material; some nodules are composed of smaller nodules, also surrounded by curved cracks. Many generations can be enclosed in a single nodule. Alaric Mountain, Languedoc, Southern France, Maastrichtian. Scale bar: 1 mm. (c), pseudomicrokarst fabric: a peloidal-bioclastic mud contains enlarged root traces, infilled by a complex sediment: 1, micritic, dark coating (compacted internal sediment); 2, vadose silt; 3, sparry phreatic cement; 4, dissolution surface at the top of crystals; 5, vadose silt; sparry phreatic cement. St-Jean-de-Minervois, Languedoc, Southern France, Middle Eocene. Scale bar: 1 mm. (d), Recent complex vadose cement in a void inside an Oligocene limestone (peloidal -bioclastic); 1, internal sediment at the void bottom; 2, stalactitic cement formed by radial, laminated microsparite (recrystallization of tufts of needles); 3, dark, micritic, vadose cement; 4, dark, micritic internal sediment; 5, well preserved needles. Phase 1 is Oligocene, phases 2–5 are Recent. Teilhède, Limagne of Allier. Scale bar: 500 µm. (e), vadose cements: 1, peloidal-bioclastic limestone; 2, laminated dark/light cement; 3, dark, homogeneous, micrite; 4, equant sparite, irregular layer (probably due to recrystallization of needles); 5, chalcedony cement; 6, residual void. Montaigu-le-Blin, Miocene, Limagne of Allier, Central France. Scale bar: 500 µm. (f), aureoled quartz, a conventional feature of 'calcretes', in a microsparitic-peloidal micritic matrix. Albas, Languedoc, Southern France, Maastrichtian. Scale bar: 1 mm. (g), palygorskite nodule, aureoled by radiating, palisadic calcite. The enclosing material is a sparitic - microsparitic limestone. St. Maixent, Deux-Sèvres, France, Oligocene. Scale bar: 1 mm. (h), striotubule infilled by dark micrite in a peloidal-clotted micrite; the internal curved structure is emphasized by small gypsum pseudomorphs (gypsum crystals have been replaced by sparite). Puivert, Plantaurel, Southern France, Dano-Montian. Scale bar: 1 mm. (i), complex nodule showing patches of dark, clotted micrite (initial sediment) and patches of microsparite and sparite, indicating a succession of recrystallizations – cracking – infillings steps. Assignan, Languedoc, Southern France, Maastrichtian. Scale bar: 1 mm. (j), *Microcodium*. 1, corn-cob (longitudinal section) and 2, rosette (transversal section) in a brecciated gravelly limestone; the colonies of *Microcodium* clearly corrode the dark, micritic grains, and the early, sparitic cement. Thézan, Languedoc, Southern France, Maastrichtian. Scale bar: 1 mm.

Table 3. Palustrine facies and microfacies

Features, sediments and rocks	Features, processes *Pedologic terminology in italics*	Equivalent terms in the literature (lacustrine model of calcretes)
Marmorized limestones	Fe hydromorphic soil dynamic leading to patches of various colours (*globular halos*, *glaebules*)	Mottled limestones (calcretes *pro parte*)
Cracking:		
– horizontal cracks	– desiccation of a mud influenced by algal felts (*joint planes*)	Brecciated limestones (calcretes (*parte*)
– horizontal and oblique cracks	– idem (*joint and skew planes*)	
– curved cracks	– desiccation of a mud showing a nodular framework (associated with skew and joint planes: (*craze planes*)	Nodular limestones (calcretes *pro parte*)
Root traces:		
– cylindrical, solid, vertical	– filling of a root hole, induration of the soil material around the root (*subcutanic feature*, *cutanes*, *nodules*)	– rhizocretions, rhizoliths, rhizomorphs, petrified roots, fossil mangrove, pedotubules (calcretes *pro parte*)
– cylindrical or irregular, empty, vertical	– root hole enlargement, mechanical and chemical infillings; pseudomicrokarst	– brecciated limestones (calcretes *parte*)
Cements:		
– anisopachous vadose cements (micritic, bioclastic and stromatolitic limestones)	– coating of micrite and microsparite (*calcitans*, *organo-calcitanes*)	– vadose cements, meteoric diagenesis, calcretization of travertines
– isopachous phreatic cements (micritic, bioclastic and stromatolitic limestones)	– coatings of sparite (geodic, drusy) (*calcitans* or *crystallaria*)	– phreatic cements
– needles of calcite	– *calcitans* or *crystallaria*	– in micritic limestones: nedles – in stromatolites: lichen stromatolites
Crystallization:		
– nodules – crystallaria	– nodulization/recrystallization during hydromorphic processes (*nodules* and *crystallaria*)	– nodular limestones, limestones with recrystallization (calcretes *pro parte*)
– aureoled grains (quartz, nodules of palygorskite)	– crystallization during hydromorphic processes	– aureoled quartz (calcretes *pro parte*)
– diagenetic sparite	– geodes in ostracod double test, spire of gastropod shell; replacive sprite in gastropod shell	– geodes, druses, replacive sparite (meteoric diagenesis, calcretes *pro parte*)
– vadose silt (crystals 15–30 µm in	– reworking of diatom sparitic felt length)	– meteoric diagenesis, calcretes *pro parte*
Microcodium (Devonian to Pleistocene)	Enigmatic feature, corrosion of limestones, nodules, calcitic muds	– meteoric diagenesis, calcretes *pro parte*
Limestones with palygorskite nodules, gypsum, salt crust	Complex hydromorphic pedogenesis (*crystallaria*)	– restricted environments, salt marshes (calcretes *pro parte*)

is related to the fact that the laminar horizon is often buried under aeolian or fluvial sediments in Plio-Pleistocene outcrops. The profile is then interpreted as a single soil instead of the succession of different sedimentary layers of various ages.

According to the conventional terminology, palustrine limestones, with or without the laminar horizon, belong to the 'lacustrine model of calcretes'. However, the term calcrete is rarely used accurately and is often applied as a synonym for a formation that is 'carbon-

Table 4. Desert stromatolite features

Sediments and rocks	Processes, features	Equivalent terms in literature
Limestones with laminar horizon – planar lamination – coating on parallel-pipes – coating on vertical cracks	Desert stromatolite, calcification of a surficial biologic felt micritic or miscroparitic laminae, spherulites	Laminar horizon (calcretes *pro parte*)
Limestones with ooid crust, perlitic crust	Coating of pedologic nodules rounded by curved planes	Pisolitic caliche, vadose pisolites (calcretes *pro parte*)

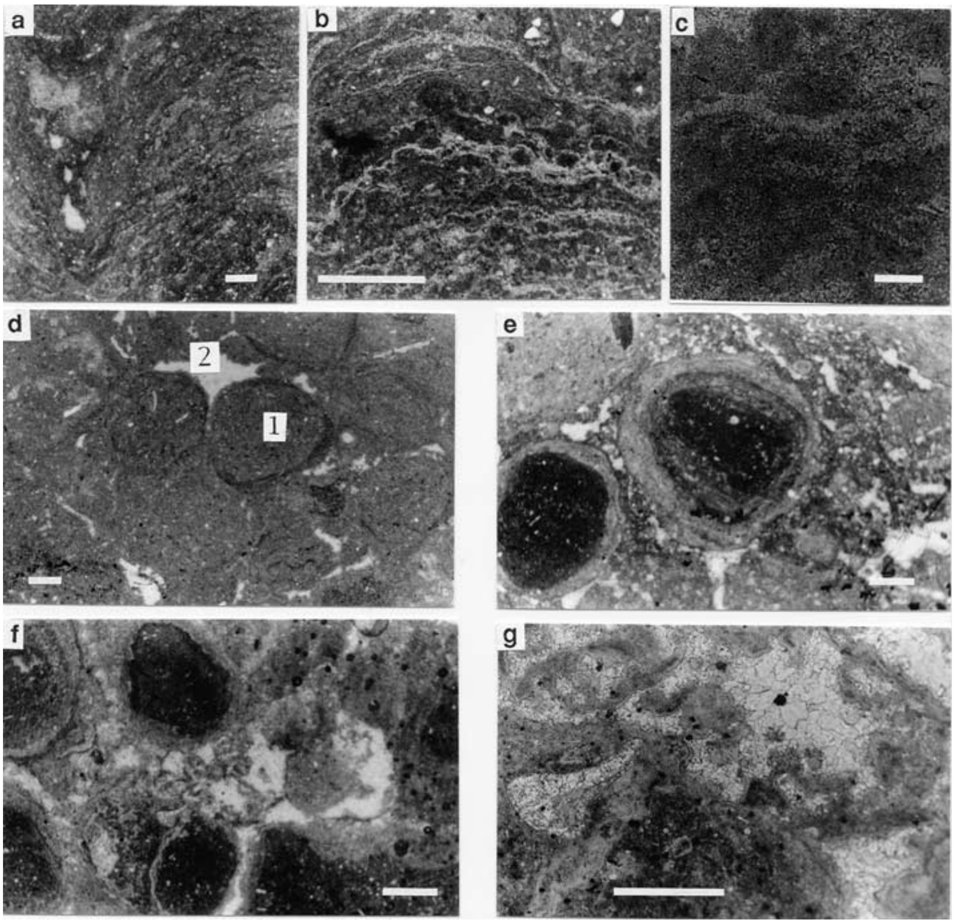


Figure 6. Desert stromatolites, Beauce Limestone, Oligo-Miocene, Paris Basin. (a), columns developed in a laminar horizon, with internal sediment and residual cavities (infilled or not by sparite). Scale bar: 1 mm. (b), detail of a. Laminar horizon formed by an alternation of dark, clotted micritic layers, and light, microsparitic layers; these layers form undulations, and small, adjacent domes and hemispheres. Scale bar: 1 mm. (c), detail of b, showing the extreme irregularities of the layers; locally, the microsparitic layer is formed by palisadic crystals. Scale bar: 100 µm. (d), nodules of clotted micrite (1) are isolated from the matrix and surrounded by a dark material. They are described as ooids, pearls or vadose pisolites in the literature; some residual cavities are partly infilled with digitations of laminar horizon (2). Scale bar: 1 mm. (e), free ooids formed by a nucleus of dark, clotted micrite (initial sediment) and coated by several layers of laminar horizon-like material ; the residual porosity is partly infilled by peloidal internal material. Scale bar: 1 mm. (f), similar free ooids; a large cavity is infilled with flexuous digitations of laminar horizon-like material. Scale bar: 1 mm. (g), detail of the infilling material, showing the undulating digitations, clearly laminated; residual voids are infilled with phreatic sparite. Scale bar: 1 mm.

ate in a terrestrial environment'. This is why 'calcrete' is not described as a specific facies in this paper. In addition, Tables 3 and 4 show the equivalence between pedologic and sedimentary terms (which are used in this study) and those used in the literature to describe features identified in calcretes.

Conclusions

Lacustrine limestones are laminated or homogenous and sometimes include burrows, remains of *Chara*, gastropods, ostracods and algae. In some cases, breccia is present, indicating remote deltaic sedimentation. Subaerial exposure of lacustrine mud and fluctuations of water table lead to the formation of palustrine limestones. They are characterized by marmorization (mottling), nodulization and pedogenic recrystallization, clay authigenesis (for example palygorskite), desiccation cracks, traces of burrows and roots, and a specific feature, the pseudomicrokarst. The laminar horizon develops under subaerial conditions and forms layers on various types of subsrates: this horizon is not related to leaching processes occurring in carbonate soils but is a true stromatolite. It constitutes the last step in a palustrine sequence before the next flood.

Conclusions

The depth, shape, and type of three main carbonate terrestrial environments (lacustrine, palustrine, and aerial stromatolitic) can be reconstructed through the petrographic description (facies and microfacies) of their sediments. It is critical to distinguish aquatic from subaerial petrographic features. In particular, when lacustrine carbonate mud is exposed, it undergoes many microstructural changes due to the influence of pedogenesis. This type of process leads to the formation of palustrine limestones.

Identification of different facies, their comparison, and their relationship to each other is fundamental to paleogeographic reconstruction. For instance, the succession of facies in the Beauce limestone (Tertiary, Paris Basin) allows the demonstration of the flooding and desiccation of ephemeral lakes at the centimeter scale. In addition, the petrography of terrestrial carbonates is a excellent tool to understand the relationship between environments, sediments, and bios.

Acknowledgements

We wish to thank two anonymous reviewers and Dr. E. Gierlowski-Kordesh for their helpful comments, which greatly improved our manuscript. Special thanks to Dr. Alonso-Zarza who encouraged the first author to present his work at the Brest conference.

References

Aassoumi, H., J. Broutin, M. El Wartiti, P. Freytet, J.-C. Koeniguer, C. Quesada, F. Simancas & N. Toutin-Morin, 1992. Pedological nodules with cone-in-cone structure in the Permian of Sierra Morena (Spain) and Central Morocco. Carbonates & Evaporites 7: 140–149.

Bates, R. L. & J. A. Jackson, 1980. Glossary of Geology. American Geological Institute, Falls Church, 751 pp.

Black, M., 1933. The algal sediments of Andros Islands, Bahamas. Phil. Trans. Lond. B. 222: 165–192.

Boer, P. L. de, 1981. Mechanical effect of microorganisms in intertidal bedform migration. Sedimentology 28: 129–132.

Bradley, W. H., 1929. Algal reefs and oolithes of the Green River Formation. U.S. Geol. Survey Prof. Paper 154-G: 203–223.

Brewer, R., 1964. In Fabric and Mineral Analysis of Soils. John Wiley, London, 470 pp.

Brunskill, G. T., 1969. Fayetteville Green Lake, New-York. II, Precipitation and sedimentation of calcite in a meromicric lake with laminated sediments. Limnol. Oceanogr. 14: 830–847.

Chafetz, H. S., 1986. Marine peloids: a product of bacterially induced precipitation of calcite. J. Sed. Petrol. 56: 812–817.

De Geer, G., 1912. A geochronology of the last 12,000 years. 11th Intern. Congr. Geol. 1910: 241–253.

Dudgeon, D., 1982. An investigation into some physical and biotic effects of flooding on reservoir mud previously subjected to a period of aerial exposure. Hydrobiologia 97: 27–35.

Eardly, A. J., 1938. Sediments of Great Salt Lake, Utah. Am. Assoc. Petrol. Geol. Bull. 22: 1305–1411.

Eardley, A. J. & V. Gvosdetsky, 1960, Analysis of Pleistocene core from Great Salt Lake, Utah. Bull. Geol. Soc. Am. 71: 1323–1344.

Fahraeus, L. E., R. M. Slatt & G. S. Nowlan, 1974. Origin of carbonate pseudopellets. J. Sed. Petrol. 44: 27–29.

Fayol, H., 1886. Résumé de la théorie des deltas et histoire de la formation du bassin de Commentry. Bull. Soc. Géol. Fr. XVI: 968–978.

Forel, F. A., 1901. Le Léman, monographie limnologique, III. F. Rouge, Lausanne, 715 pp.

Fort, M., D. W. Burbank & P. Freytet, 1989. Lacustrine sedimentation in a semi-arid alpine setting: an example from Ladakh, Northwestern Himalayas. Quat. Res. 31: 332–350.

Freytet, P., 1964. Le Vitrollien des Corbières orientales: réflexions sur la sédimentation 'lacustre' nord-pyrénéenne; divgation fluviatile, biorhexistasie, pédogénèse. Rev. Géogr. Phys. Géol. Dyn. VI: 179–199.

Freytet, P., 1971. Paléosols résiduels et paléosols alluviaux hydromorphes dans le Crétacé supérieur et l'Eocène basal en Languedoc. Rev. Géogr. Phys. Géol. Dyn. XIII: 245–268.

Freytet, P., 1973. Petrography and paleoenvironments of continental carbonated deposits with a particular reference to Upper Cretaceous and Lower Eocene of Languedoc, Southern France. Sed. Geol. 10: 25–60.

Freytet, P., 1984. Les sédiments lacustres carbonatés et leur transformation par émersion et pédogénèse. Importance de leur identification pour les reconstitutions paléogéographiques. Bull. Centre Rech. Explor.-Produc. Elf Aquitaine 8: 223–247.

Freytet, P., 1997. Non-marine, Permian to Holocene algae from France and adjacent countries I. Ann. Paleontol. 83: 289–332.

Freytet, P., 1998. Non-marine, Permian to Holocene algae from France and adjacent countries II. Ann. Paleontol. 84: 3–51.

Freytet, P., 2000. Distribution and paleoecology of non marine algae and stromatolites : II, the Limagne of Allier, Oligo-Miocene lake (Central France). Ann. Paleontol. 86: 3–57.

Freytet, P. & J.-C. Plaziat, 1982. Continental carbonate sedimentation and pedogenesis – Late Cretaceous and Early Tertiary of Southern France. In Purser, B. H. (ed.), Contrib. Sedimentology, Schweizerbart'sche Verlag, Stuttgart, 12, 217 pp.

Freytet, P. & E. P. Verrecchia, 1998. Freshwater organisms that build stromatolites: a synopsis of biocrystallization by prokaryotic and eukaryotic algae. Sedimentology 45: 535–563.

Freytet, P., F. Baltzer, O. Conchon., J.-C. Plaziat & B. H. Purser, 1994. Signification hydrologique et climatique des carbonates continentaux quaternaires de la bordure du désert oriental égyptien (côte de la mer Rouge). Bull. Soc. Géol. Fr. 165: 593–601.

Freytet P., N. Toutin-Morin, J. Broutin, P. Debriette, M. Durand, M. El Wartiti, G. Gand, H. Kerp, F. Orszag, Y. Paquette, O. Ronchi & J. Sarfati, 1999. Paleoecology of non-marine algae and stromatolites – Permian of France and adjacent countries. Ann. Paleont. 85: 99–153.

Gilbert, G. K., 1885. The topographic features of lake shores. Ann. Rep. U.S. Geol. Survey 5: 69–123.

Hawley, N. & C. H. Lee, 1999. Sediment resuspension and transport in Lake Michigan during stratified period. Sedimentology 46: 791–805.

Johnson, J. H., 1937. Algae and algal limestone from the Oligocene of South Park, Colorado. Bull. Geol. Soc. Am. 48: 1227–1235.

Kahle, C. F., 1977. Origin of subaerial Holocene calcareous crusts: role of algae, fungi, and sparmicritization. Sedimentology 42: 413–435.

Kalkowsky, E., 1908. Oolith und Stromatolith im norddeutschen Bundsandstein, Z. Deutsche geologische Gesellschaft, Berlin, 60: 68–125.

Kelts, K. & K. J. Hsü, 1978. Freshwater carbonate sedimentation. In Lerman, A. (ed.), Lakes, Chemistry, Geology, Physics. Springer, Berlin, 295–323.

Klappa, C. F., 1980, Rhizoliths in terrestrial carbonates: classification, recognition, genesis and significance. Sedimentology 27: 613–629.

Mac Issac, H. T. & P. Rocha, 1995. Effects of suspended clay on Zebra mussel (*Dreisena polymorpha*) foeces and pseudofoeces production. Arch. Hydrobiol. 135: 53–64.

Morrison, R. B., 1964. Lake Lahontan: geology of the southern Carson Desert, Nevada. U.S. Geol. Survey Prof. Paper 401, 165 pp.

Neumann, A. G., C. D. Gebelin & T. P. Scoffin, 1970. The composition, structure and erodability of subtidal mats, Abaco, Bahamas. J. Sed. Petrol. 40: 274–297.

Platt, N. H. & V. P. Wright, 1992. Lacustrine carbonates : facies models, facies distribution and hydrocarbon aspects. In Anadon, P., L. Cabrera & K. Kelts (eds), Lacustrine Facies Analysis. IAS spec. publ. 13. Blackwell, Oxford, 57–74.

Plaziat, J. C. & P. Freytet, 1978. Le pseudomicrokarst pédologique: un aspect particulier des paléopédogénèses développées sur les dépôts calcaires lacustres dans le Tertiaire du Languedoc. C. r. Acad. Sci. Paris D 286: 1661–1664.

Sturm, M. & A. Matter, 1978. Turbidites and varves in Lake Brienz (Switzerland): deposition of calstic detritus by density currents. In Matter, A. & M. E. Tucker (eds), Modern and Ancient Lake Sediments. IAS. spec. publ. 2. Blackwell, Oxford, 147–168.

Tevesz, M. J. S, F. M. Soster & P. L. McCall, 1981. The effects of size selective feeding by Oligochaetes on the physical properties of river sediment. J. Sed. Petrol. 50: 561–568.

Thompson, J. B., F. G. Ferris & T. H. D. Smith, 1990. Geomicrobiology and sedimentology of the mixolimnion and chemocline in Fayetteville Green lake, New York. Palaios 5: 52–75.

Verrecchia, E. & P. Freytet, 1987. Interférence pédogénèse sédimentation dans les croûtes calcaires – Proposition d'une nouvelle méthode d'étude: l'analyse séquentielle. In Fédoroff, N. (ed.), Soil Micromorphology. AFES, Paris, 555–561.

Verrecchia, E. P., 1994. L'origine biologique et superficielle des croûtes zonaires. Bull. Soc. Géol. Fr. 165: 583–592.

Verrecchia, E. P. & K. Verrecchia, 1994. Needle-fiber calcite: critical review and proposed classification. J. Sed. Res. A64: 650–664.

Verrecchia, E. P., P. Freytet, K. Verrecchia & J.-L. Dumont, 1995. Spherulites in calcrete laminar crust: biogenic $CaCO_3$ precipitation as a major contributor to crust formation. J. Sed. Res. A65: 690–700.

Verrecchia, E. P., P. Freytet, K. Verrecchia & J.-L Dumont, 1996. Spherulites in calcrete laminar crust: biogenic $CaCO_3$ precipitation as a major contributor to crust formation – Reply. J. Sed. Res. A66: 1041–1044.

Winsborough, B. M. & S. Golubic, 1987. The role of diatoms in stromatolite growth: two examples from modern freshwater settings. J. Phycol. 23: 195–201.