Morphogenetic impact of microbial mats on surface structures of Kimmeridgian micritic limestones (Cerin, France)

P. BERNIER*, C. GAILLARD*, J. C. GALL†, G. BARALE‡, J. P. BOURSEAU*, E. BUFFETAUT§ *and* S. WENZ¶

**Université Claude-Bernard, Centre des Sciences de la Terre et Unité de Recherches Associée au C.N.R.S., no. 11, 43 Boulevard du 11 Novembre 1918, 69622 Villeurbanne Cedex, France*

†*Université Louis-Pasteur, Institut de Géologie, 1, Rue Blessig, 67084 Strasbourg, France*

‡*Université Claude-Bernard, Laboratoire de Paléobotanique et Unité de Recherches Associée au C.N.R.S., no. 11, 43 Boulevard du 11 Novembre 1918, 69622 Villeurbanne Cedex, France*

§*Université Pierre et Marie Curie, Laboratoire de Paléontologie des Vertébrés, 4, Place Jussieu, 75230 Paris Cedex 04, France*

¶*Muséum National d'Histoire Naturelle, Laboratoire de Paléontologie, 8, Rue de Buffon, 75008 Paris, France*

ABSTRACT

For several years, palaeoecological research has been conducted on micritic limestones of late Kimmeridgian age in the southern Jura Mountains. The sedimentary environment is that of a lagoon with an irregular bottom, which was repeatedly exposed. Between two stages of lime deposition, a microbial mat grew over the muddy surface, giving cohesion to the sediment, restraining erosion and preserving fossil remains and reptile tracks. Various structures at the microbial mat surface can be observed: crescentic wavy, radial wavy, torn, petee and mixed structures. They imply the presence of desiccation periods and a slight bottom slope leading to a downward sliding of the microbial mat. Such features may also be generalized to explain superficial microbial structures of other shallow carbonate-mud environments.

INTRODUCTION

Detailed sedimentological and palaeontological investigations on Kimmeridgian micritic limestones are in progress in an ancient quarry, which lies above the village of Cerin (rural district of Marchamp, Ain, France) in the southern Jura Mountains (Fig. 1). The Cerin micritic limestones were well known during the last century for their quality, and consequently the quarry was intensely exploited (Bourseau *et al.*, 1984). Numerous fossils were discovered and extracted from the bedding surface. These fossils were studied by several authors (Thoillière, 1873; De Saporta, 1891; Lortet, 1892; De Saint-Seine, 1949). They can be found mainly in the collections of the Musée Guimet d'Histoire naturelle de Lyon, but also in many other collections around the world.

Since 1975, our team has been studying not only the palaeontology but also the palaeoecology and sedimen-tology of this quarry in order to establish the depositional environment, the trapping of organisms and the taphonomy. Much data were collected on various organisms, original locomotion tracks (Bernier *et al.*, 1984, 1987), algal mats, emersion structures, etc. This information led to a new interpretation of the environment: as a lagoon overlying an ancient coral barrier reef (Bernier, 1984; Barale *et al.*, 1985), whereas it was previously considered to be a back-reef lagoon. The lagoon was episodically connected to the sea by channels. Lime mud was supplied both from the sea and from the surrounding emergent areas. Most marine organisms were transported and/or trapped in the lagoon, where they were mixed with very rare autochthonous organisms. Consequently, the marine fossils are associated with those of terrestrial animals (reptiles) and plant fragments.
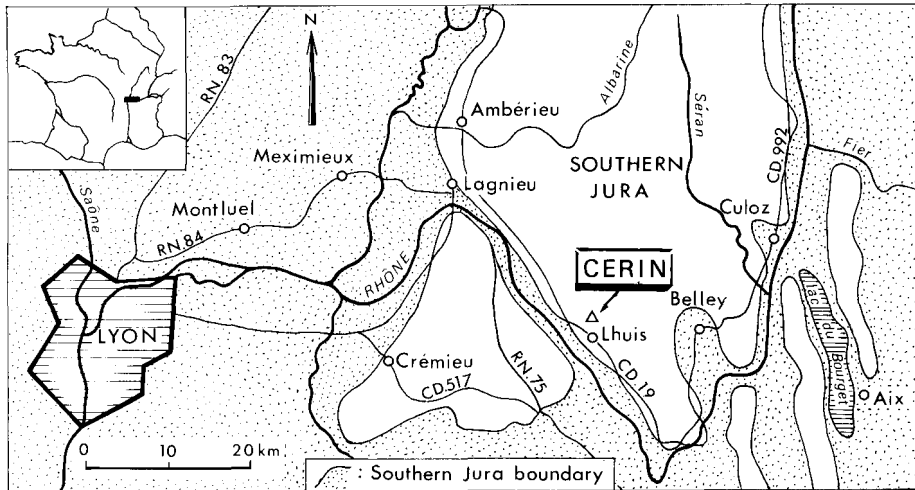
Fig. 1. Location of Cerin quarry. (□) Jurassic and Cretaceous of the southern Jura; (▨) younger sediments.

Their preservation was favoured by the presence of microbial mats (Gall *et al.*, 1985, 1986). Similar laminations have been observed and mentioned previously from the Solnhöfen area (Keupp, 1977) and from Upper Cretaceous micritic limestones in Yugoslavia (Hemleben & Freels, 1977).

LITHOLOGY OF THE MICRITIC LIMESTONES

The Cerin Formation is approximately 20 m thick and is comprised of beds of limestone, each about 10 cm thick (range of 3–30 cm). Most beds are composed of very fine micrite, displaying very occasionally larger grains at their base and frequent bioturbation in the upper part. Burrows are about 1–2 mm in diameter.

When observed under SEM, the micrite appears to be detrital, and there are no traces of coccoliths. Benthic foraminifera are very rare. Every bed surface is covered by millimetric laminations which vary from a few millimetres to several centimetres in thickness. These laminations are easily distinguishable by their yellow to reddish colour, which commonly stands out in contrast to the beige colour of the limestone.

In thin-section, the micrite is very fine-grained ($\approx 1\,\mu m$ grain diameter). The laminations display microcrystals of dolomite, which alternate with micritic layers. Iron oxides are abundant and emphasize the stratification. Some laminations display a vertical

arrangement of dolomite microcrystals (Fig. 2). Such an arrangement is probably not haphazard but is perhaps linked to the filamentous framework created by a microbial mat. Similar frameworks resulting from microbial activity have been observed by Shinn, Lloyd & Ginsburg (1969), Hardie & Ginsburg (1977) and recently by Burne & Moore (1987). After diagenesis, only dolomite microcrystals remain preserved as tracers of the former organic filaments.

The micrite commonly displays synsedimentary fractures at the top, which do not affect the upper laminations. This does not necessarily mean that the cracks pre-date the laminae, but could indicate that the laminations reacted flexibly to external stresses while the underlying semi-consolidated micrite had a tendency to break.

SLOPE STRUCTURES

The numerous structures due to sliding observed on the beds are limited to the upper laminations and never extend into the underlying micrite. The interpreted cohesion and plasticity of these upper laminations may have been produced by the filamentous framework of a superficial microbial mat. Thus, one contact between the microbial mat and the underlying calcareous mud would correspond to an interface which could be easily detached. This could be facilitated by the presence of trapped gas produced by the putrefaction of organic matter. Expanding gas
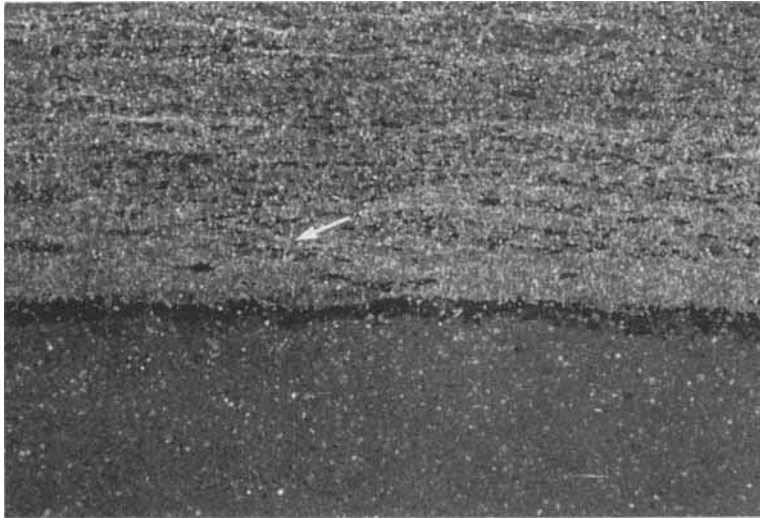
Fig. 2. Thin section showing laminations crossed by vertical filaments (arrow) now replaced by dolomite crystals: bed no. 304; magnification × 14.

bubbles created small vesicles (now filled by spar) aligned along laminations, which are now seen as birdseye structures.

During emersion, the boundary between microbial mat and lime mud functioned as a drainage zone for water, resulting in a weaker contact between these two lithologies. Gas production and water flow led to detachment of the microbial mat from the underlying micrite. A slope, albeit gentle, was then sufficient to allow the superficial sheet to slide downwards, producing various warpings. Three main structural groups can be distinguished: crescentic wavy, radial wavy, and torn structures.

Crescentic wavy structures are the most abundant. They are more or less regular sediment undulations, producing successive crescentic folds. These build up a relief. A slight asymmetry with a steeper slope on the convex part of the crescent is locally observed. Consequently, the concave part shows a more gentle slope. Fold heights vary from a few millimetres to rarely more than 15–20 mm. Wavelength is variable and in direct relationship to the height, ranging from 2–3 cm up to more than 10 cm. The arc size is very variable (30–50 cm for the most part) but can reach 1–2 m, as shown in Fig. 3.

A cursory examination of such a structure on a small surface outcrop could result in confusion between crescentic wavy structures and current ripplemarks. However, the former can be clearly distin-guished owing to their characteristic crescent shape. Such an arrangement is the result of more resistant areas occurring along the slope between the more mobile areas where downward-sliding is easier and faster. The cause of such differences in resistance is probably due to small irregularities on the bed surface. In the same way, the observation of a plain surface without superficial structures does not imply absence of a microbial mat but only the lack of any slope. Wavy and plane areas may alternate on the same surface (Fig. 3).

Some slipping areas may also have a tendency to converge. Consequently, the crescentic waves coming from different directions may meet and become interconnected (Figs 4 & 5). In some cases, this is accompanied by tears and sigmoidal cut-offs, which are the result of movements varying in intensity and direction.

Radial wavy structures show affinities to the preceding crescentic wavy structures, but are very rare and were only observed on two beds (Fig. 6). These structures consist of a succession of radial fan-shaped micro-reliefs, converging in a confluence area. The resulting fan can reach 1 m in length. Each micro-relief increases in height towards the confluence area, where it reaches about 10 mm.

This type of wavy structure could be the result of underlying morphology, showing a slightly depressed funnel shape and producing a radial arrangement of
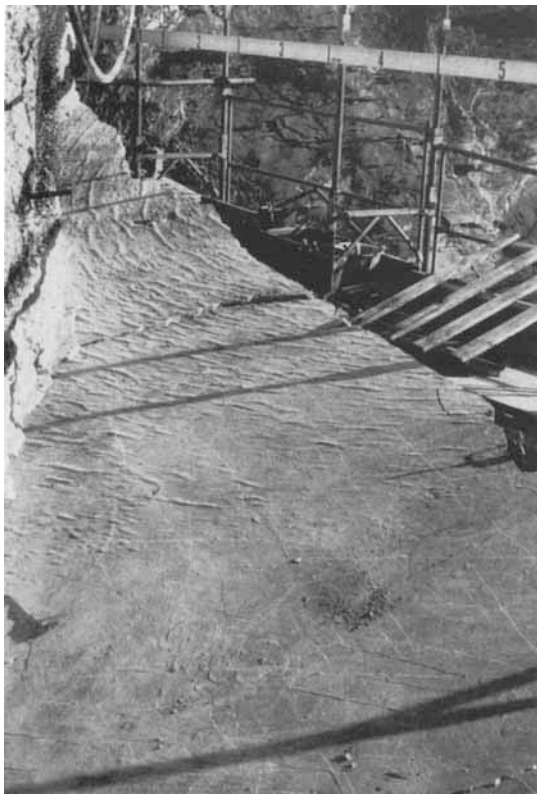
Fig. 3. Concentric crescentic wavy structures located on a very limited area of the extracted surface: bed no. 247A; southern extremity of the upper excavation; palaeoslope bottom is on the left; scale bar is in metres.

the micro-reliefs. During gas formation, the microbial mat is locally and frequently swollen. At such places, the sediment surface is disconnected from the mat and water circulation on a slight slope is made easier, eroding and channelling the surface. Then, when the microbial mat is deflated, it assumes the underlying morphology and takes a radial and crumpled shape.

While gently sliding on the slope, the microbial mat may have had a tendency to tear, producing *torn structures*. Such a phenomenon is probably facilitated by initial breaking resulting from desiccation. When tearing is complete, the microbial mat appears in tatters, the morphology of which varies from plane scraps to more or less wavy scraps, irregularly crumpled as in an accordion. These structures are another result of slipping on the bottom. They were first observed in the Cerin excavation accompanying rill-mark structures (Bernier *et al.*, 1982, Plate 1, Fig. 3).

Several characteristics apply to this type of structure. First, the tear of the microbial mat is generally not linear but irregular or sigmoidal (Fig. 7). In this last case, tearing is similar to a large natural buttonhole and comparable to a torn cloth. Furthermore, just as a torn cloth shows fraying along the tear line, the torn microbial mat shows irregularities along the tear line. These are arranged obliquely and correspond to true frayings of the filamentous microbial mat (Fig. 8). Cut-off shaving-like scraps are often associated with the torn mat, creating small reliefs without definite shape but frequently frayed themselves.

Fig. 4. Complex crescentic wavy structures. Note the superposition of several independent systems corresponding to the movement of several microbial mats or several movements of the same mat; bed surface no. 64; scale bar = 15 cm; downslope towards bottom of photograph.
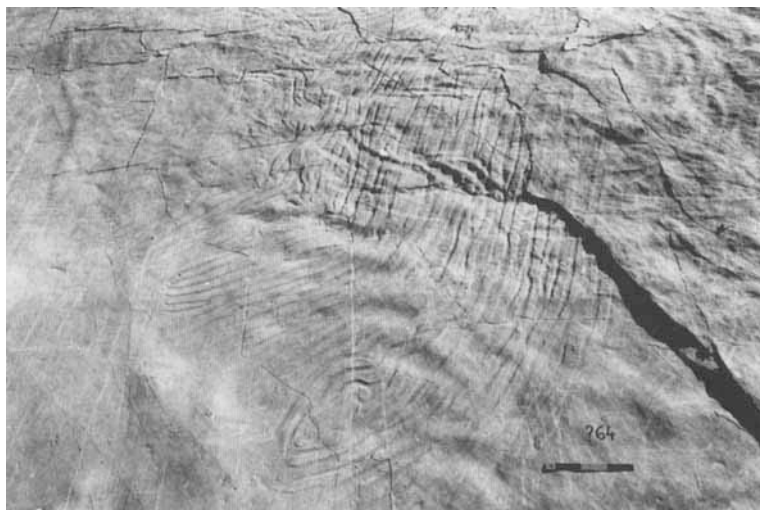
Fig. 5. Complex crescentic wavy structures: bed surface no. 64; scale bar = 15 cm; downslope towards bottom of photograph.

Fig. 6. Radial wavy structure. Note that each radial relief is made of a bundle of micro-reliefs. The arrow indicates the slope direction: bed surface no. 92; pen is 10 cm in length.

PETEE STRUCTURES

True desiccation mudcracks were identified upon the surface of some micritic limestone beds, showing a more or less regular polygonal network. However, original structures linked to microbial activity were also observed which can be compared to petee structures (Gavish, Krumbein & Halevy, 1985; Gerdes & Krumbein, 1987; Reineck *et al.*, 1990). Petee structures have a biogenic origin as opposed to tepee structures which are abiogenic. They are interpreted as the result of wind activity and slope gravity leading to undulated and wrinkled surfaces. This type of sedimentary structure is not directly related to desiccation and does not correspond to structures described by Hardie (1977) as 'ribbon-like' algal structures, which are very irregular. Shinn (1983) observed blue-green algae selectively growing on sediment-filled mudcracks constituting small polygonal reliefs (p. 177, Fig. 7A). However, at Cerin, there is no observable difference either in nature or texture of the sediment, and the subjacent layers are not broken or discontinuous. Therefore, the observed structures could not be the result of cracks. Possibly, it is a retraction of the microbial mat, as considered by Gavish *et al.* (1985) and Reineck *et al.* (1990). The polygonal structures are isotropic in development and more or less regularly arranged. As opposed to incised, sharp-edged desiccation cracks, polygonal retraction edges display a pad-shaped relief and are thus easily distinguishable from the former (Fig. 9).
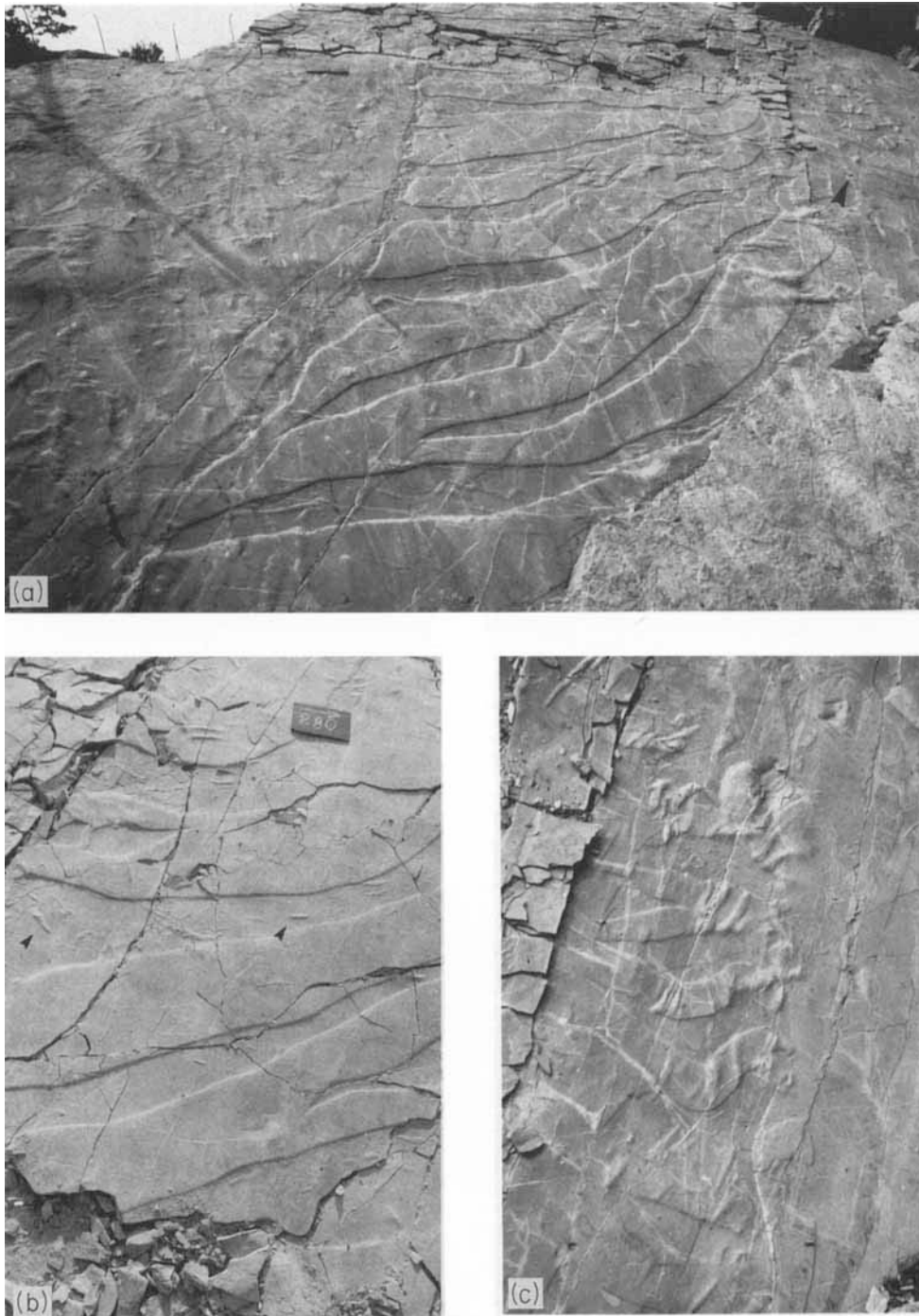
Fig. 7. (a) Torn structures. Note the wide sigmoidal tears along the rill. Scrap convexity is orientated downwards: bed surface no. 280, to the north of the upper excavation; width of photograph = *c.* 6 m. (b) Detail of the upper part of (a). Note the scraps between tears (arrow). Scale bar = 10 cm. (c) Detail of the peripheral area marked by an arrow in (a). Note the transversal undulations of each scrap and their strong convexity orientated downwards. Width of photograph = *c.* 1 m.
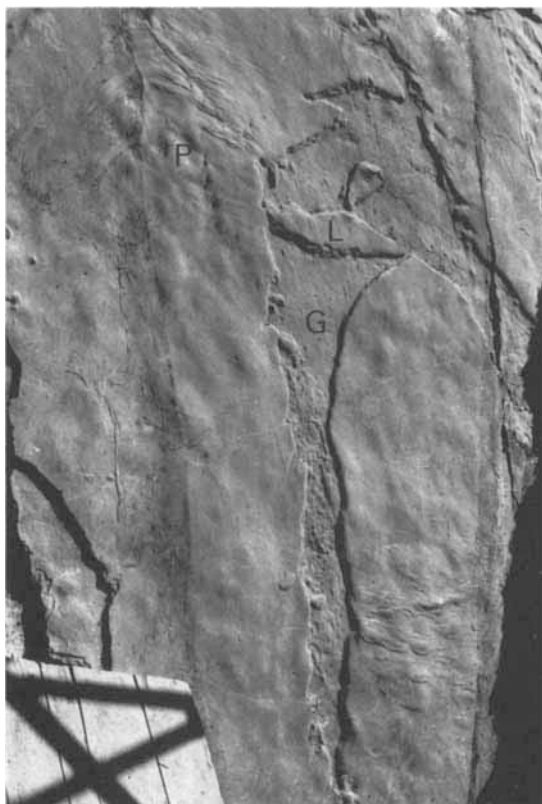
Fig. 8. Torn and crescentic wavy structures: bed surface no. 92A. G = rill filled with soft cobbles. L = scraps stopped in the upper part of the rill. P = crescentic wavy structures. Total structure length ≈ 2·5 m.

The filamentous network is sufficiently resistant and stable to prevent normal tearing and thus creates the characteristic petee structures. Polygons are variable in size and generally 5–8 cm wide (Fig. 9). The pads themselves are symmetrical. They barely reach a few millimetres in height and about 1 cm in width. When observed in section, the entire laminated part is affected by such structures. However, it is possible to observe successive stacked polygons, lamination after lamination. In this case, superimposition is not necessarily perfect. The relief caused by a pad controls the site of the following constriction, which then takes an analogous morphology and arrangement. Thus, in the same bed, petee structures are often observed slightly offset from each other.

MIXED STRUCTURES

Mixed structures are the result of the combined phenomena arising from slope and petee structures. Some bed surfaces show anisotropic, very elongate padded polygons. These are the result of two successive events: first, the microbial mat retracts producing petee structures, and secondly these petee structures slide along the slope, lengthening the polygons perpendicular to the mat movement (Fig. 10).
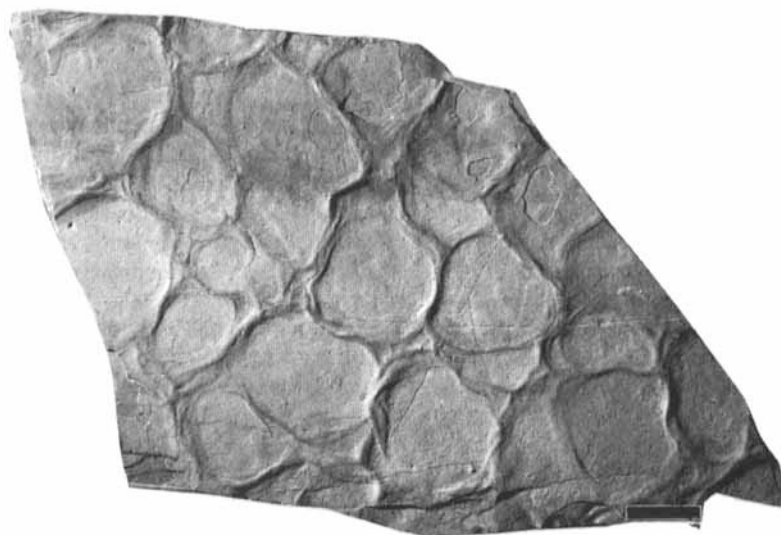

Fig. 9. Petee structures. The regular polygonal shape shows that there is no slope in this area.
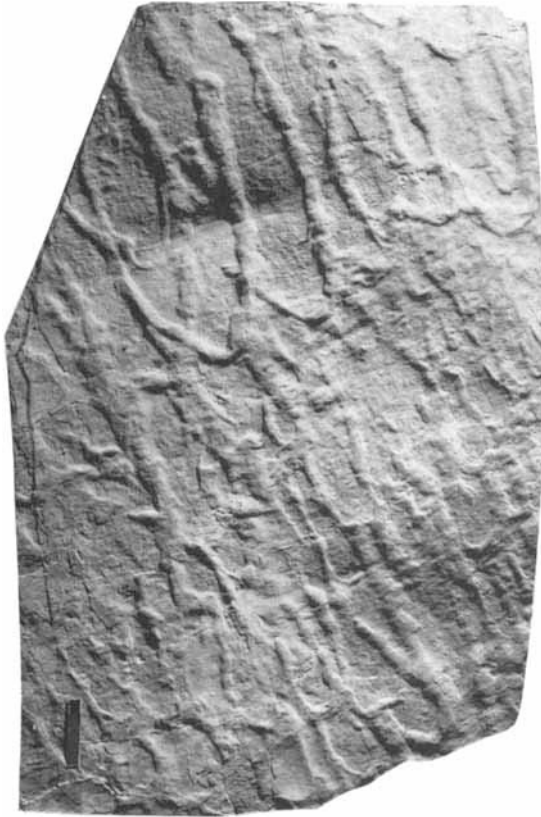
Fig. 10. Mixed structures resulting from the warping of petee structures, showing plasticity of mat: bed surface no. 113, scale bar = 5 cm.

RECENT MICROBIAL MAT ANALOGUES

Comparisons can be made between the Cerin structures and recent microbial mats developed in peritidal environments. Such structures have been described from different areas: Andros Island, Bahamas (Hardie, 1977); Florida Bay and Persian Gulf (Shinn, 1983); Red Sea sabkhas (Gavish *et al.*, 1985); southern France (Dulau & Trauth, 1982); Spain (Orti Cabo, Pueyo Mur & Truc, 1984). We have observed similar structures in the Arzeu sabkha in Algeria, in the ephemeral lakes of the Coorong region of southern Australia and in the salterns of Noirmoutier Island off the Atlantic coast of France. In the salterns, sea water runs along channels into various-sized lagoons during spring tide, where it is stored to supply the evaporative basins during the neap tide period (Fig. 11a). Accord-

ingly, there is an alternate system of sudden filling (over 3–4 h) followed by a very slow flow towards the marsh where the water evaporates and salt crystallizes. A similar water movement may be inferred for the alternating filling and emptying of the Cerin lagoon. The bottom of the natural watertanks of Noirmoutier is covered with a uniform, well-developed microbial mat, which tears along large cracks as soon as it emerges (Fig. 11b). The borders of the tanks show a very slight slope (<5°). The torn mat has a tendency to move down the slope during filling and emptying periods, thereby creating structures analogous to those described from Cerin, particularly torn structures (some of them being sigmoidal), petee structures and crescent wavy structures. When covered by water, the microbial mat tends to become disconnected from the muddy bottom due to the buoyancy of gas bubbles produced in the mat. The mat grows when submerged and slides downslope when the water retreats, tearing and crumpling (Fig. 11b). Similar torn structures were described from the South of Bretagne (France) and the Canary Islands as the result of wind or water friction, or slope gravity (Reineck *et al.*, 1990). In all of these cases, gas production, fluctuating water depth and shear stress caused by flowing water are necessary to detach the mat from its substrate.

CONCLUSIONS

The various structures described above which affect the surface and the laminations of the micritic part of the Cerin limestone beds suggest the presence of microbial mats. Microstructures point to a filamentous framework. The interpretation which had been given for one bed of the Cerin micritic limestones (Gall *et al.*, 1985) can now be applied to practically every bed in the quarry. Each period of muddy sedimentation ended with the colonization of the surface by a microbial mat. Such a development certainly plays an essential role in taphonomy, as fossils trapped in the microbial network are preserved.

At the same time, these structures indicate the presence of a slope with a slight inclination (Bernier *et al.*, 1982; Gall *et al.*, 1985), sufficient to move and tear or distort the superficial laminations. Our interpretation is supported by observations of comparable features in various present-day peritidal environments. Movement of algal mats occurs when the lagoon is emptying and drying due to water run-off or evaporation. However, some structures may originate from prevailing wind action on horizontal surfaces.
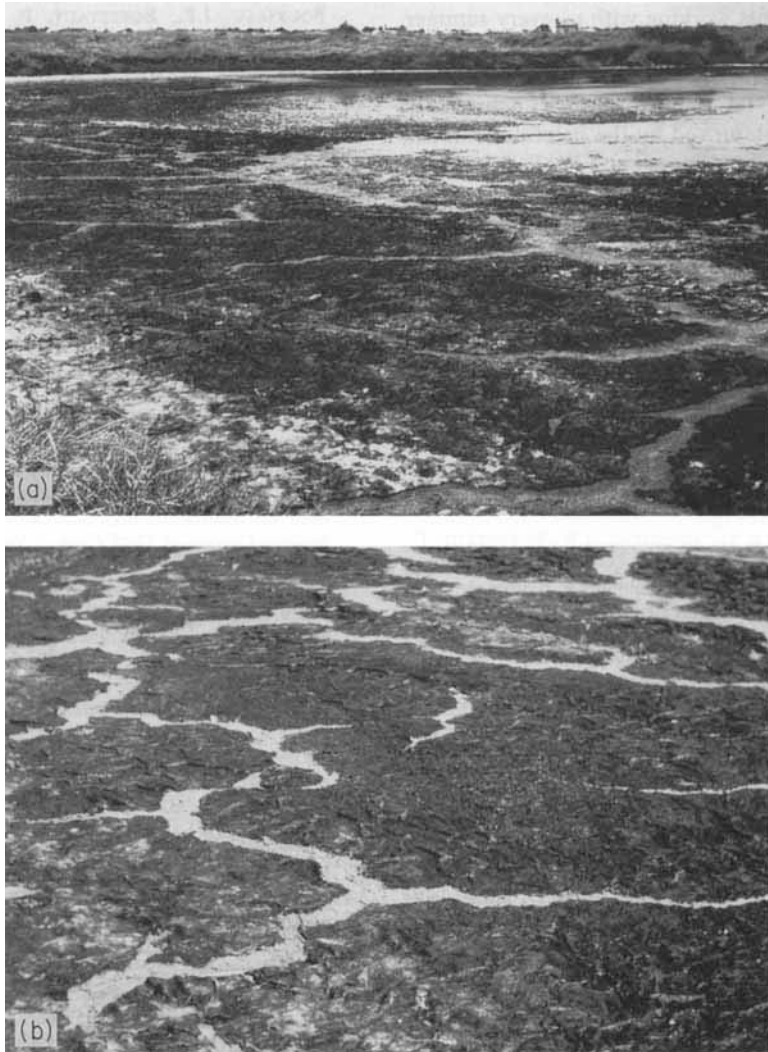
Fig. 11. (a) Recent microbial mat from the border of a saltern (Noirmoutier Island, western France). (b) Detail of (a) showing torn and sigmoidal structures of the microbial mat.

These observations are very useful for interpreting the lagoonal palaeoenvironment at Cerin and provide a well-documented inventory of biosedimentary structures, which can be used to recognize microbial mats in other shallow calcareous muddy environments.

ACKNOWLEDGMENTS

and all the students working with us every summer. We also thank P. Howlett (British Antarctic Survey, Cambridge) and J. A. McKenzie (Geologisches Institut, Zürich) for help with the English. The manuscript was improved by the helpful comments and suggestions of A. Strasser and W. E. Krumbein, and we are grateful for their careful reviews.

REFERENCES

BARALE, G., BERNIER, P., BOURSEAU, J.P., BUFFETAUT, E., GAILLARD, C., GALL, J.C. & WENZ, S. (1985) Cerin, une lagune tropicale au temps des dinosaures. *C.N.R.S., Muséum de Lyon ed.*, 136 pp.

BERNIER, P. (1984) *Les formations carbonatées du Kimméridgien et du Portlandien dans le Jura méridional (stratigraphie, micropaléontologie, sédimentologie).* PhD thesis, Université Claude-Bernard, 731 pp.

BERNIER, P., BARALE, G., BOURSEAU, J.P., BUFFETAUT, E., DEMATHIEU, G., GAILLARD, C. & GALL, J.C. (1982) Traces nouvelles de locomotion de Chélonien et figures sédimentaires associées dans les Calcaires lithographiques de Cerin (Kimméridgien supérieur, Ain, France). *Geobios*, **14**, 447–467.

BERNIER, P., BARALE, G., BOURSEAU, J.P., BUFFETAUT, E., DEMATHIEU, G., GAILLARD, C. & WENZ, S. (1984) Pistes de Dinosaures sauteurs dans les calcaires lithographiques de Cerin (Kimméridgien supérieur, Ain, France). Implications paléoécologiques. *Geobios. Mém. Sp.*, **8**, 177–185.

BERNIER, P., GAILLARD, C., GALL, J.C., BARALE, G., BOURSEAU, J.P., BUFFETAUT, E. & WENZ, S. (1987) Figures de déformation des voiles cyanobactériens à la surface des boues calcaires de la lagune de Cerin (Kimméridgien supérieur—Jura méridional–France). *Ier Congr. fr. Sédim Paris*, pp. 56–57.

BOURSEAU, J.P., BUFFETAUT, E., BARALE, G., BERNIER, P., GAILLARD, C., GALL, J.C. & WENZ, S. (1984) La carrière des calciares lithographiques de Cerin (Ain, commune de Marchamp). Vie et extinction d'une exploitation communale sur un gisement paléontologique célèbre. *Nouv. Arch. Mus. Hist. nat. Lyon*, **22**, 21–30.

BURNE, R.V. & MOORE, L.S. (1987) Microbialites: organosedimentary deposits of benthic microbial communities. *Palaios*, **2**, 241–254.

DE SAINT-SEINE, P. (1949) Les poissons des calcaires lithographiques de Cerin (Ain). *Nouv. Arch. Mus. Hist. nat. Lyon*, **2**, 357 pp.

DE SAPORTA, G. (1872–1891) *Paléontologie Française. Plantes Jurassiques* (Ed. by Masson), 573 pp.

DULAU, N. & TRAUTH, N. (1982) Dynamique sédimentaire des marais salants de Salin-de-Giraud (Sud de la France). *Géol. Méditerr.*, **IX**, 501–520.

GALL, J.C., BERNIER, P., GAILLARD, C., BARALE, G.,

BOURSEAU, J.P., BUFFETAUT, E. & WENZ, S. (1985) Influence du développement d'un voile algaire sur la sédimentation et la taphonomie des calcaires lithographiques. Exemple du gisement de Cerin (Kimméridgien supérieur, Jura méridional français). *C.R. Acad. Sci., Paris*, **301**, 547–552.

GALL, J.C., BERNIER, P., GAILLARD, C., BARALE, G., BOURSEAU, J.P., BUFFETAUT, E. & WENZ, S. (1986) Effects of cyanobacterian films upon sedimentation and taphonomy in lithographic limestones. *12th Cong. Intern. Sédim. Canberra*, p. 113.

GAVISH, E., KRUMBEIN, W.E. & HALEVY, J. (1985) Geomorphology, mineralogy and groundwater geochemistry as factors of the hydrodynamic system of the Gavish Sabkha. In: *Ecological Studies* (Ed. by G. M. Friedman & W. E. Krumbein), pp. 186–217. Springer-Verlag, Berlin.

GERDES, G. & KRUMBEIN, W.E. (1987) Biolaminated deposits. In: *Lectures Notes in Earth Sciences No. 9* (Ed. by S. Bhattacharji, G. M. Friedman, H. J. Neugebauer & A. Seilacher), pp. 1–183. Springer-Verlag, Berlin.

HARDIE, L.A. (1977) Algal structures in cemented crusts and their environmental significance. In: *Sedimention on the Modern Carbonate Tidal Flats of Northwest Andros Island, Bahamas* (Ed. by L. A. Hardie), *Johns Hopkins University Studies in Geology*, **22**, 159–177.

HARDIE, L.A. & GINSBURG, R.N. (1977) Layering: the origin and environmental significance of lamination and thin bedding. In: *Sedimentation on the Modern Carbonate Tidal Flats of Northwest Andros Island, Bahamas* (Ed. by L. A. Hardie), *Johns Hopkins University Studies in Geology*, **22**, 50–123.

HEMLEBEN, C. & FREELS, D. (1977) Algen-laminierte und gradierte Plattenkalke in der Oberkreide Dalmatiens (Jugoslawien). *Neues. Jb. Geol. Paläont. Abh.*, **154**, 61–93.

KEUPP, H. (1977) Ultrafazies und Genese der Solnhofener Plattenkalke. (Oberer Malm, Südliche Frankenalb). *Abhand. naturhist. Ges. Nürnberg*, **37**, 128 pp.

LORTET, D. (1892) *Les Reptiles fossiles du Bassin du Rhône* (Ed. by H. Georg), 139 pp.

ORTI CABO, F., PUEYO MUR, J.J. & TRUC, G. (1984) Las salinas maritimas de Santa Pola (Alicante, Espana). Breve introduccion al estudio de un medio natural controlado de sedimentacion evaporitica somera. *Rev. Inv. Geol.*, **38/39**, 9–29.

REINECK, H.-E., GERDES, G., CLAES, M., DUNAJTSCHIK, K., RIEGE, H. & KRUMBEIN, W.E. (1990) In: *Microbial Modification of Sedimentary Surface Structures* (Ed. by D. Helling, P. Rothe, U. Förstner & P. Stoffers), pp. 254–276. Springer-Verlag, Berlin.

SHINN, E.A. (1983) Tidal flat environment. In: *Carbonate Depositional Environments* (Ed. by C. H. Moore), *Mem. Am. Ass. petrol. Geol.*, **33**, 171–210.

SHINN, E.A., LLOYD, R.M. & GINSBURG, R.N. (1969) Anatomy of a modern carbonate tidal-flat, Andros Island, Bahamas. *J. sedim. Petrol.*, **39**, 1202–1228.

THIOLLIERE, V. (1873) *Description des Poissons fossils provenant des gisements coralliens du Jura dans le Bugey*, 2nd edn (Ed. by H. Georg), 5–50.