

A Jurassic counterpart for modern kopara of the Pacific atolls: lagoonal, organic matter-rich, laminated carbonate of Orbagnoux (Jura Mountains, France)

Nicolas Tribovillard, A. Trentesaux, Jean Trichet, Christian Défarge

► **To cite this version:**

Nicolas Tribovillard, A. Trentesaux, Jean Trichet, Christian Défarge. A Jurassic counterpart for modern kopara of the Pacific atolls: lagoonal, organic matter-rich, laminated carbonate of Orbagnoux (Jura Mountains, France). *Palaeogeography, Palaeoclimatology, Palaeoecology*, Elsevier, 2000, 156, pp.277-288. 10.1016/S0031-0182(99)00145-5 . hal-00089131

HAL Id: hal-00089131

<https://hal-insu.archives-ouvertes.fr/hal-00089131>

Submitted on 10 Aug 2006

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

A Jurassic counterpart for modern kopara of the Pacific atolls: lagoonal, organic matter-rich, laminated carbonate of Orbagnoux (Jura Mountains, France)

N. Tribovillard^a, A. Trentesaux^a, J. Trichet^b and C. Défarge^b

^a Université Lille 1, UMR CNRS 8577, Laboratoire de Sédimentologie and Géodynamique, bâtiment SN5 - 59655 Villeneuve d'Ascq Cedex, France

^b Université d'Orléans, UMR CNRS 6531, Laboratoire de Géologie de la Matière Organique, bâtiment Géosciences, 45067 Orléans Cedex, France

Abstract

Two types of laminated sediments are compared in this paper: the Kimmeridgian bituminous laminites of Orbagnoux (French Southern Jura Mountains) and the present-day 'kopara' of the French Polynesia atolls or Kiritimati (Christmas) Island from the Pacific Ocean. The kopara is made of laminated sediments, several tens of centimetres thick, that cover the floors of most shallow (<2 m deep) lakes and ponds on the rims of atolls in the Tuamotu Archipelago and Society Islands. The millimetre-scale laminations come from the alternation of organic-rich and CaCO₃-rich laminae. The top few centimetres host a succession of bacterial populations, from aerobic to strictly anoxic. Most carbonate grains are precipitated in situ, due to bacterial activity (s.l.). The Kimmeridgian bituminous laminae of Orbagnoux are partly made of flat stromatolites that show many similarities with the kopara. This analogy allows us to refine the interpretation of the Southern Jura platform where laminated, organic matter-rich, carbonates were deposited in many places.

Author Keywords: bacteria; Kimmeridgian; laminated sediments; (palaeo-) lagoonal environment

1. Introduction

The Kimmeridgian, laminated, organic matter (OM)-rich carbonates of Orbagnoux (a small hamlet in the French southern Jura Mountains) were deposited in a lagoonal environment, within a large carbonate platform, sheltered by a well-developed reef barrier (Fig. 1 and Fig. 2; Bernier, 1984). This site is presently mined for the organic-sulphur compounds, extracted in large amounts from this facies, and the strata are called the Laminites bitumineuses (bituminous laminites). These peculiar deposits have been extensively studied by many authors (see below). Thus, a comprehensive set of data is now available about these bituminous laminites, which allows a thorough comparison with modern, OM-rich, laminated material: the so-called kopara of the French Polynesian atolls and equivalent material from Kiritimati Island (Pacific Ocean). A modern analogue for the bituminous laminites has previously not been identified.

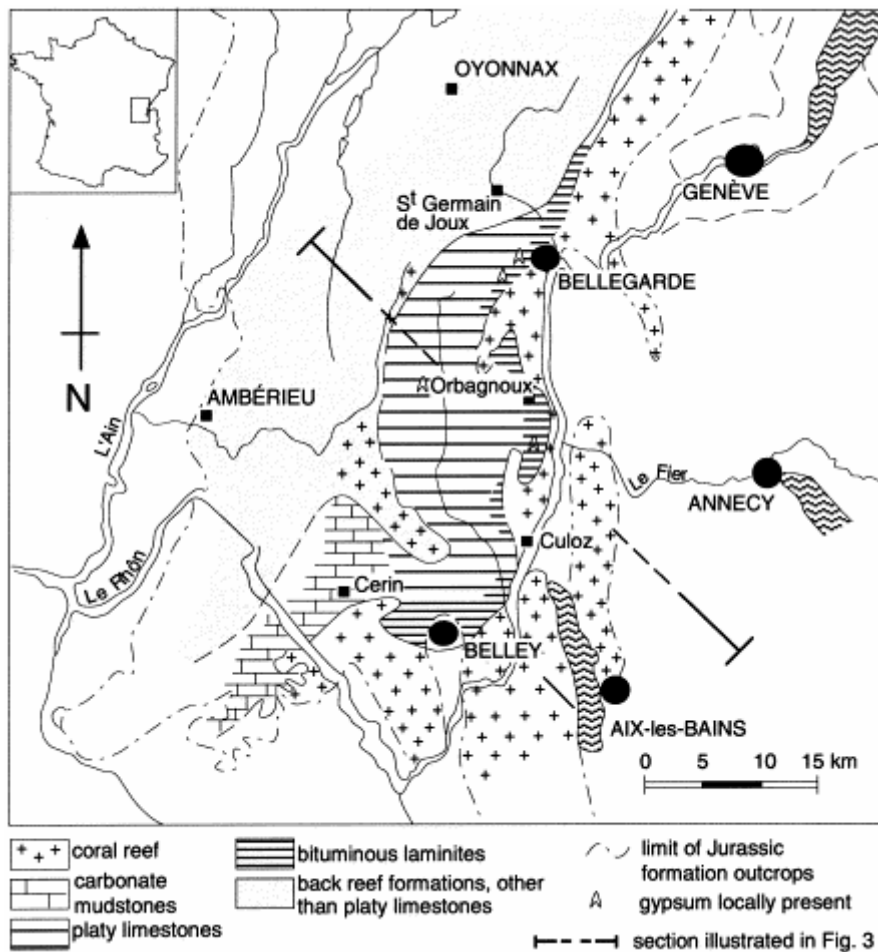


Fig. 1. Geological setting of the area studied, indicating the location of the section illustrated in Fig. 3. Redrawn from Bernier (1984).

Late Kimmeridgian was a time when lagoonal/peritidal, bacterially influenced facies were widespread (Dromart and Kazmierczak) and it is important to identify a modern counterpart for these laminated facies which have not been well represented since the Jurassic.

In the descriptive part of this paper, the emphasis is placed upon the bituminous laminites, since the kopara has already been extensively studied and numerous descriptions and photographs have been published in D; D; D; D; D; Trichet and Trichet et al., 2000.

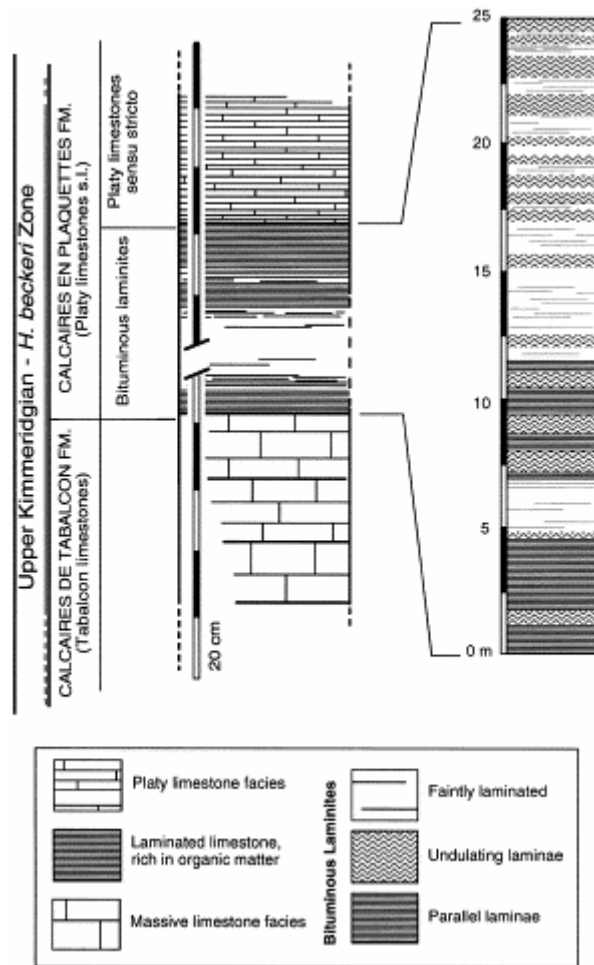


Fig. 2. Schematic lithological column of the three units studied, based on observations from the Dorche Torrent, at Orbagnoux (French map IGN, Seyssel sheet, 1:50 000; X=866.91, Y=2115.65).

2. The kopara deposits

The French Polynesian laminated sediments are flat deposits several tens of centimetres thick that cover the floors of most shallow (<2 m deep) lakes and ponds on the rims of atolls in the Tuamotu Archipelago and Society Islands (D and D). The salinity of the waters fluctuates between that of fresh and normal marine water. The millimetre-scale lamination comes from the alternation of organic- and CaCO_3 -rich laminae [Plate 1(E and F)]. The microbes are principally filamentous cyanobacteria, living within the first 3 cm below the sediment–water interface. They are accompanied by a few coccoid species and are underlain by living purple photosynthetic bacteria (D and D). The underlying sediment, the organic fraction of which consists mainly of the remains of extracellular polymer secretions of cyanobacteria and bacteria (i.e. sheaths and dispersed mucilage), hosts a vertical succession of living anaerobic bacteria, where sulphate reducers are abundant in layers underlying the purple layers, and, in deeper levels, methanogens occur. In most lakes, the superficial laminated layers lie upon older ones, which have a higher CaCO_3 content (71–86%). The carbonates forming the horizontal mineral laminae of the sediments can be distinguished into several classes on the grounds of their shape and origin processes. Most are precipitated in situ and are associated with

minor reef-derived grains and other bioclasts (molluscan shells, foraminifer tests, echinoderm skeletal parts, etc.) which were deposited during seawater incursions or carried by the wind. The precipitates can be divided into true biominerals (formed through encapsulation of living bacteria or sheath impregnation of living cyanobacteria), minerals formed by post-mortem mineralisation of cyanobacterial sheaths, and organominerals, formed in close association with the sedimentary OM and peloids (D; Trichet and Trichet).

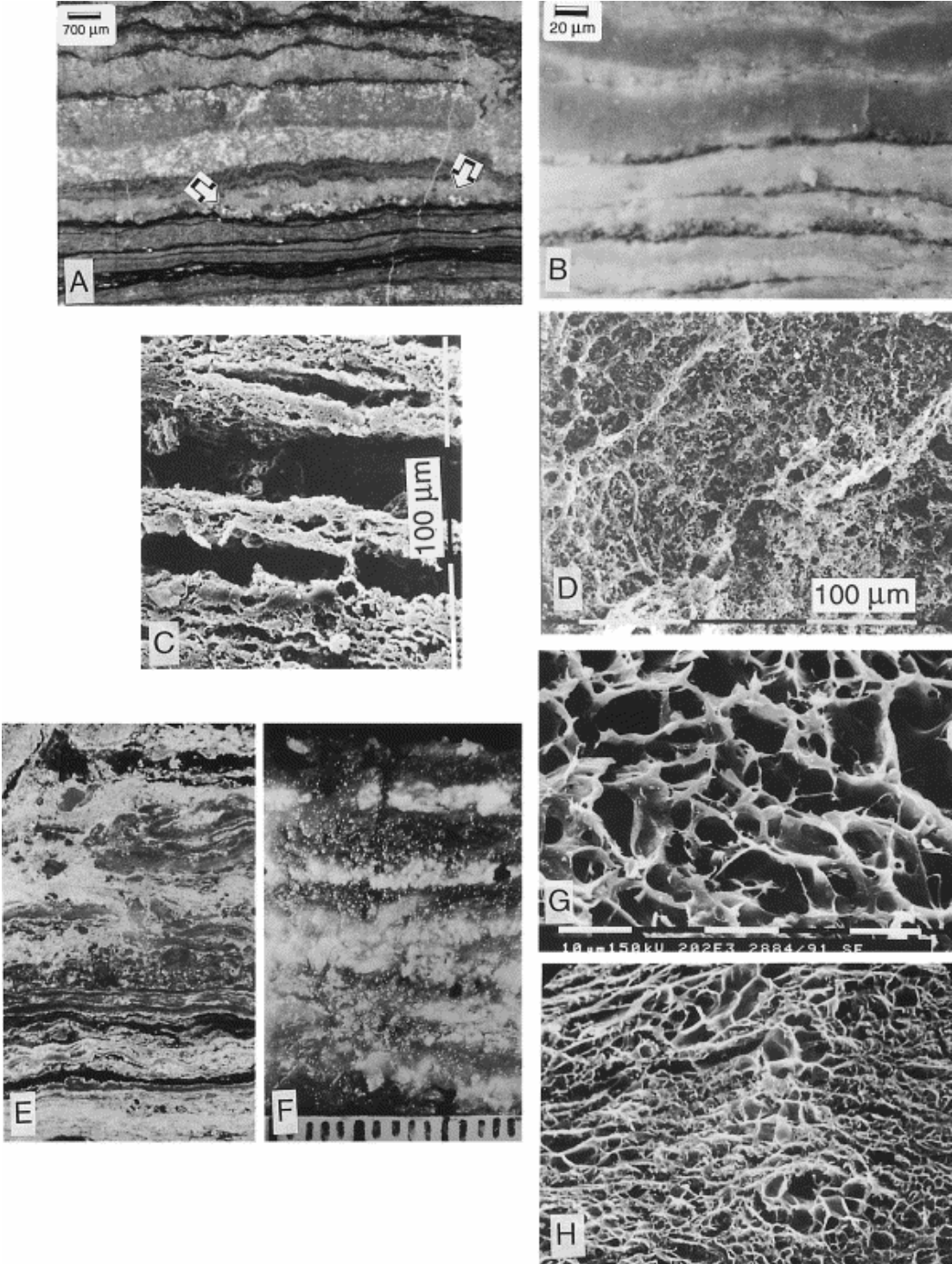


Plate 1. (A)–(D) photomicrographic images from the bituminous laminae of Orbagnoux. The samples come from the quarry along the Dorche Torrent (French map IGN sheet of Seyssel, 1:50 000;

X=866.91, Y=2115.65. (A) The stromatolitic texture of undulating laminae. The arrows indicate a horizon rich in peloids. (B) Etched sample of undulating laminae. The organic-rich seams stand out. (C) and (D) Strongly etched sample of undulating laminae with numerous organic-rich seams observed in a section normal to the stratification plane (C) and parallel to the stratification plane (D). The reticulated texture of the organic network is visible. (E)–(H) Photos of kopara samples from Rangiroa Lake R2 [French Polynesia; D and D]. (E) Thin section of resin-indurated kopara. The sample has been picked at a few decimetre depth and was already partly indurated by carbonate precipitation. The long dimension of the picture is 17 mm long. (F) Section of soft kopara down from the sediment surface. The scale divisions are millimetres long. (G) Reticulated organic network of the kopara observed through cryoscanning electron microscopy [see details in D and D]. (H) Enlarged vision of the reticulated network observed in (G). Compare with (D).

2.1. Bacterial biominerals

Aggregates of micrometre-size carbonate spheres, rods, dumbbells and ‘rosettes’, which are evocative of encapsulated bacteria, are found in the sediments. They are present within rounded microzones, generally 10–100 μm wide, that infill several contiguous alveoli of the organic network [Plate 1(G and H)]. Both the shapes and the size distribution of the individual bodies, and the clustering in space of the aggregates, are typical of bacterial precipitates (Buczynski and D). The bodies are composed of aragonite or magnesian calcite. These bacterial precipitates are major components of the buried layers of the sediments, whereas they are rare within the superficial ones in spite of the presence of numerous live bacteria.

2.2. Cyanobacterial biominerals

These biominerals are present as carbonate-impregnated tubular sheaths, which is a common mineralisation mode for filamentous cyanobacteria (Riding, 1991b). They are present as 15–30 μm broad tubes, with magnesian calcite walls 2–10 μm thick. The tubes appear to be bound to the surrounding network by organic membranes inherited from the sheaths. These biominerals are rare in the sediments.

2.3. Post mortem cyanobacterial carbonates

Cyanobacterial filaments that have undergone post mortem mineralisation have also been observed in the buried stromatolitic layers of some atoll lakes. They are present within a <0.5 cm thick lamina that has numerous weakly degraded cyanobacterial filaments, incorporated in the surrounding network. These precipitates are distinguished from the cyanobacterial Mg-calcite because: they are aragonitic; they infill the entire filament cavity; and they formed only after the trichome was dead, or had abandoned the sheath, and the cavity had been filled with membranes derived from the cell wall or the sheath, whereas cyanobacterial calcification begins during the life of the microbe.

2.4. Organominerals

Organominerals have been defined as natural minerals the precipitation of which is mediated by sedimentary organic substrates, by analogy with biominerals, the formation of which is mediated by living organic matrix (Trichet and Défarge, 1995). Such precipitates have been shown to be the dominant minerals in the superficial layers of the French Polynesian atoll lacustrine stromatolites (Défarge et al., 1994a).

They range from micrometer-size individual crystals to aggregates of high-Mg calcite (7–19 mol% MgCO₃) that are enclosed within alveoli and supported by walls of the three-dimensional organic network.

2.5. Peloids

Other carbonate precipitates observed in the sediments, in particular, in the superficial stromatolitic layer of the French Polynesian atoll sediments can be grouped under the descriptive term peloids. They are elliptical to spherical grains of magnesian calcite, 50–150 µm in diameter and up to 650 µm long, that display a radially oriented internal structure arranged around one or more centres. They have also been interpreted as being of cyanobacterial origin (Défarge et al., 1996).

Laminated sediments in Kiritimati (an island located in the equatorial area of the Pacific Ocean, formerly called Christmas Island) are found on the bottom of many of the ca. 500 shallow lakes and ponds that occupy ca. 25% of the lagoonal surface area (ca. 360 km²) of this almost completely filled atoll (Schoonmaker et al., 1985). The stromatolitic layers of the lake sediments are as much as 30 cm thick, and consist of alternating organic-rich and mineral-rich flat laminae, of millimetre- to centimetre-scale thickness (Défarge et al., 1993). The principal mineral components are calcium carbonates (calcite and Mg-calcite), accompanied by gypsum or halite in hypersaline settings (D; D and Schoonmaker).

3. The bituminous laminites

This bituminous laminite unit of Orbagnoux was extensively studied (Bernier; Bernier; Bernier; Courtinat and Riche), particularly in the Orbagnoux palaeolagoon (Gorin; Gubler; Mongenot; Mongenot; Tribovillard; Tribovillard; Tribovillard and Tribovillard). A few conclusions will be reviewed. At Orbagnoux (along the Dorche torrent, on the right bank of the Rhône River, French map IGN sheet of Seyssel, 1:50 000; X=866.91, Y=2115.65), the Laminites bitumineuses Member forms the lower part of the Calcaires en plaquettes Formation (Platy Limestone Fm.). It belongs to the Beckeri ammonite zone of Early Kimmeridgian times. It corresponds to a peculiar episode of a long lasting, regressive sequence that affected the carbonate platform of the Southern Jura during the Malm (Bernier, 1984). During this sequence, the pelagic environment of the platform (Early Kimmeridgian) was progressively transformed into palustrine environments by the end of Jurassic [Purbeckian facies; Bernier; Strasser and Strasser]. Meanwhile, during the Beckeri zone, the development of a reef barrier gradually isolated a shallow lagoon, where the laminated facies studied accumulated (Fig. 1).

The Orbagnoux bituminous laminites are made of two components: carbonate and OM. The carbonate content (calcite) varies between 75 and 96%. The organic content is higher in the dark laminae than in the light ones (4.47–8.55 wt% versus 0.65–8.03 wt%). The values of the Hydrogen Index (Espitalié et al., 1985) of the kerogens are always very high (755–966 mg hydrocarbons per g of TOC). Elemental analyses performed on the isolated kerogens indicate that organic sulphur is unusually abundant (12–17.6 wt% of the kerogens).

Within the laminites bitumineuses member, the following two subfacies alternate.

1. Parallel laminae are made of alternating, sub-millimetre scale, dark-coloured laminae. These parallel, continuous, individual layers are clustered into millimetre- to centimetre-scale laminae, which commonly appear dark, depending on the composition of the individual layers. Various macro- and microfossils occur in the parallel laminae: ammonites, benthic foraminifers and ostracods. Mass-mortality events that affected the ammonites are evident as very thin accumulations of juvenile forms of apparently the single genus *Aspidoceras*; these accumulations do not disturb the laminated structure. Under scanning electron microscopy (SEM) the light-coloured laminae are exclusively made of coccospheres and coccoliths that seem to be the only source of calcite. The dark-coloured laminae contain less abundant coccoliths and coccospheres, embedded within a matrix of structureless, gel-like, OM (Tribovillard and Tribovillard). The particles comprising this facies seem to have been derived mostly from settling mechanisms: periods of flourishing coccolithophorids led to the accumulation of light-coloured laminae, consisting exclusively of coccoliths. These periods alternated with episodes of OM accumulation. This OM was most likely derived from planktic algae (Mongenot; Mongenot and Tribovillard). The exceptional quality of lamina-scale laterally continuous deposits testifies to the absence of burrowers and the absolute calm of the depositional environment. The frequent presence of oxygen-demanding planktic and benthic organisms indicates that the water column must have remained (almost?) constantly oxic, whereas the underlying sediments were constantly bathed by anoxic, sulphidic, porewaters. The sharp chemical gradient was caused by the presence of cyanobacterial biofilms acting as a barrier between the two contrasting environments (Tribovillard and Tribovillard).

2. Undulating laminae: this facies comprises irregularly undulating, alternating light and dark-coloured, laminae, grossly parallel to the bedding plane [Plate 1(A)]. The thickness of these laminae is of the same order as each parallel laminae. Some light undulating laminae exhibit bird's eye and flat fenestrae textures. Thin-section observations show the alternation of dark laminae, consisting of bundles of very thin seams, and the light-coloured, thicker, carbonate laminae, occasionally disclosing abundant peloidal bodies. These calcite peloids have been interpreted to be of cyanobacterial origin, basing upon SEM-observed morphological features, their very homogeneous size distribution, and upon comparisons with present cyanobacterial formations (see detail in Tribovillard, 1998). Acid-etched samples clearly display the distribution of the thin organic seams, which stand out in relief [Plate 1(B); Tribovillard (1998)] as an anastomosed mesh-like network [Plate 1(C and D)]. In the undulating laminae, no coccolith were observed, but SEM observations reveal that carbonate is present as calcitic micrite grains, being almost equidimensional, their size ranging from 2 to 4 μm and also interpreted as being of cyanobacterial origin. This facies was most likely not deposited by settling mechanisms. As previously stated by Tribovillard et al. (1992), these biolaminations must have resulted from self-burial processes, *that is*, mat-by-mat build-up due to ecological changes possibly affected by water salinity, light intensity, or temperature in the absence of particle settling (Gerdes et al., 1991).

Throughout both facies, some rare, authigenic, quartz grains or clay mineral particles were detected. A few dedolomitised rhombs are interspersed within the laminites. Lastly, no gypsum crystals are preserved, although numerous crystals grew in the undulating laminae; they have been substituted for by calcite. The calcite-replaced

ghosts of gypsum crystals are small (<100 µm–1 mm), lozenge-shaped crystals, parallel to bedding plane, apparently not formed within the sediment (no displacive-growth structures can be evidenced).

The simultaneous occurrence of abundant OM and reducing conditions favoured intense sulphate reduction. Hence, much sulphide was released and trapped within the sediment, below the cyanobacterial barrier. As iron was almost absent (no terrigenous supply), sulphide could react with organic molecules (Tribovillard et al., 1994). This early vulcanisation of OM is an efficient agent of OM preservation (Fran; Sinninghe and Tegelaar).

Molecular studies were performed, either upon biomarkers of Soxhlet extracted OM and directly upon total-OM pyrolysates (Mongenot, 1998; Mongenot and Van). They displayed the presence of molecules typical of various bacterial populations; cyanobacteria, and photosynthetic anoxygenic bacteria, comparable to present *Chlorobiaceae*, that are strict anaerobes.

At Orbagnoux, both types of laminae, either parallel or undulating, are in an arrhythmic arrangement: no regular or cyclic pattern can be evidenced and until now the explanation put forward is that the driving force has been the sea-level fluctuations (Bernier and Tribovillard). The development of cyanobacterially-influenced undulating laminae was related to periods of very shallow sea level; the parallel laminae were deposited while the palaeolagoon was somewhat deeper, due to (faint) sea-level rises. The depth of the water column in the lagoon, not exceeding a few meters, could be controlled either by sea-level fluctuations or the efficiency of the coral reef as a barrier between the lagoon and the open sea (Tribovillard et al., 1992).

Lastly, such bituminous laminites also crop out at various locations on the Southern Jura palaeoplatfrom: for example, at Armailles and Saint-Champ, close to Belley, and at Forens, close to Bellegarde (Fig. 1). However the field conditions are best at Orbagnoux.

4. Interpretation

The kopara and the wavy undulating laminae of the Orbagnoux bituminous laminites show a number of common features.

1. Both facies are made of alternating laminae: OM rich/carbonate rich alternations. The depositional environments are devoid of land-derived clastic fractions both in the Orbagnoux setting and the Pacific atolls.

2. Both types of sediments are associated with strongly reducing conditions. In the kopara, the classical sequence of bacterial population succession is completed within the top few centimetres (<10 cm): the oxygenated conditions of the water column of the atolls and of the water–kopara interface are rapidly replaced downward by reducing conditions allowing the development of nitrate or sulphate reducers and of methanogens. Additionally, as strictly anoxic conditions are met just beneath the water-kopara interface, that is, still in the photic zone, anoxygenic photosynthetic purple bacteria can develop, immediately below the cyanobacteria level. Concerning

the Orbagnoux sediments, the sulphuration of the lipidic fraction of the OM (Mongenet; Tribovillard; Tribovillard and Van), together with the marked enrichment in some trace metals [V, Mo, Ni, Co, Cu, Zn, Cd; Tribovillard et al. (2000)] bear witness to the strongly reducing conditions during early diagenesis.

3. Both facies are almost azoic, in the sense that they show no (or very few) identifiable fossils. The kopara lakes are almost devoid of megafauna: shrimps and crabs, feeding most probably on non-cyanobacterial organic remains available at the lake border, are rarely present and cause only limited bioturbation of the aerobic top-few millimetres of the deposits (D and D). Only very few fish species (two known, the 'bone fish' *Chanos-Chanos* and the *Tilapia*) can live in kopara lakes, feeding strictly on the top green layer of the sediment. When present, the sediment is composed of ca.0.5–1 cm sized balls resulting from the reworking of the top sediment by fish grazing. However, the presence of the fishes in the modern lakes is unusual and essentially due to anthropogenic intervention. The laminated sediments of Kiritimati disclose levels of evaporite minerals, due to more or less episodic water confinement and supersaturation. The presence of the undulating laminae reflect unfavourable ecological conditions for the development of life: gypsum pseudomorphs testify to water confinement of the palaeolagoon that led to evaporative conditions; moreover, the severe reducing conditions of the pore waters may have episodically reached up into the water column itself, as strongly suggested, as evoked above in the description section, by mass-mortality events and the occurrence of isorenieratene derivatives, evidencing the presence of anoxygenic photosynthetic bacteria (*Chlorobiaceae*), inferring that the water column could have been anoxic, though shallow (Mongenet; Tribovillard et al., 2000 and Van).

4. Both facies were affected by intense bacterial activity, which is the cornerstone of the sediment formation, in the absence of land-derived supply and of bioclastic accumulation. Several papers have been devoted to the bacterial influence upon both texture and structures of the kopara (D; D; D; Trichet and Trichet). Numerous textures in the undulated laminae of Orbagnoux have been interpreted as the result of bacterial activity (Tribovillard, 1998):

4.1. Acid etching and SEM imaging reveal that the carbonate laminae are made of packed peloids that may represent bacterial colonies (e.g. Buczynski; Chafetz; Chafetz; Kazmierczak; Riding; Riding and Tribovillard);

4.2. This treatment also reveals organic remnants such as sheath or extra-cellular polymer secretion (Kazmierczak et al., 1996);

4.3. The etching highlights the carbonate matrix of the carbonate laminae which is composed of equant, isodimensional, micrite grains the size of average bacteria (2–4 µm), which again possibly reflects bacterial activity (Tribovillard, 1998). SEM imaging of unetched samples exhibits endolithic microbial filaments and ellipsoidal carbonate bodies, interpreted as calcified bacteria (Tribovillard, 1998).

This indicates that both facies (undulating laminae and kopara) are basically induced by bacterially mediated biochemical precipitation of carbonate, either directly or indirectly: the replacement of gypsum by calcite must have been induced by sulphate-reducing bacteria activity under reducing conditions.

5. Last but not least, acid etching discloses the reticulated texture of the OM, that is a constant feature throughout the undulating laminae as well as the kopara laminated sediments, both in French Polynesia and Kiritimati (Christmas) Island. The morphological similarity between the reticulated OM of Orbagnoux samples and that of the kopara is most striking [compare Plate 1(C and D) with Plate 1(G and H), and with Figs. 2 and 4 from Défarge et al. (1994a); Fig. 1 from Défarge et al. (1996); Plates 1 and 3 from Défarge (1997)].

This series of similarities points toward the kopara being a modern counterpart for the Kimmeridgian undulating laminae of the Orbagnoux palaeolagoon. Thus, kopara is the first modern analog of Orbagnoux.

5. Discussion

The correspondence between the modern kopara and Orbagnoux Jurassic laminites highlights and clarifies some points about the depositional environment of the Southern Jura carbonate platform during Kimmeridgian times.

First, in terms of the bituminous laminites of Orbagnoux, the analogy with the kopara allows us to reconcile two observations that are apparently incompatible. As discussed above, molecular biomarkers typical of anoxygenic photosynthetic bacteria (isorenieratene derivatives) occur both in the parallel laminae and the undulating ones (that is, associated with in situ growth and detrital laminae). The presence of such molecules is generally interpreted as indicating anoxic conditions in the water column, since these bacteria are strict anaerobes and demand to be in the photic zone. However, at Orbagnoux, the frequent occurrence — and sometimes abundance — of oxygen-demanding, planktonic, nektonic and benthic organisms within the parallel laminae facies, attests to the presence of oxygenated waters (at least, episodically). The observation of the kopara shows that anoxygenic photosynthetic bacteria can develop within the kopara, immediately beneath the cyanobacteria surface horizon, because there they can meet their requirements: daylight illumination and anoxic conditions. It is thus possible for the sediment to accumulate below an oxygenated water column and to contain biogeochemical proxies of anoxia. One requisite for this situation is that the illumination can reach the lagoon floor (shallow water depth) and pass through the layer of cyanobacterial biofilms.

Second, at a regional scale, the comparison suggests that the carbonate Southern Jura platform, protected by a well-developed reef barrier, might have resembled the complex atoll system of present-day Polynesia (Fig. 3). The extended platform could have allowed the appearance, from place to place, of small restricted environments where 'palaeokopara' could develop for some time and generate the bituminous laminites. In such a scheme, the development of the various palaeokopara pools must not necessarily have been strictly contemporaneous everywhere upon the platform. Additionally, the palaeokopara pools would have occupied small places, separated by larger carbonate zones, without laminated and OM-rich facies, but with platy limestone facies. This interpretation would explain:

1. why the bituminous laminites were not extended to the whole platform during the time of deposition of the Calcaires en plaquettes Formation but only localised in small areas; and

2. why Bernier (1984) could not be sure whether the various places on the platform where bituminous laminites accumulated were strictly coeval: no fine-scale correlation between the outcrops could be recognised.

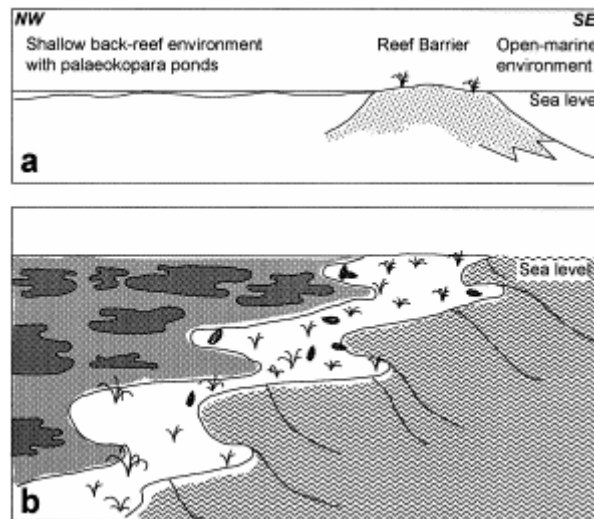


Fig. 3. Palaeogeographic sketch illustrating in (a) the approximate location on Fig. 1 and in perspective (b) the palaeokopara environment of the Southern Jura carbonate platform. The open-marine conditions were separated by a reef barrier from a very shallow platform with numerous individual ponds where palaeokopara could develop.

Third, the bituminous laminites result from the alternation of periods of grossly laminated sediment — or palaeokopara — in situ growth (undulating laminae sequences) and periods of particle settling in a quiet environment (parallel laminae sequences). The latter contain many fossils (even ammonites) and their main carbonate contributors are coccoliths. They correspond to periods during which the Orbagnoux palaeolagoon was experiencing more open-marine conditions: for instance, increased water depth could have caused decreased illumination of the bottom and, consequently, decreased cyanobacteria growth. During such a time, sedimentation would have been fed by settling coccoliths and coccospheres, as well as organic-walled (phyto-) plankton [leiospheres, dinoflagellates, etc.; Mongenot and Tribovillard]. In other words, planktonic productivity would have been the main sediment supplier. This scheme is fully compatible with what is observed in the atolls of French Polynesia: for instance, during El Niño (ENSO) events, the atolls experience dramatic sea-level rises, during which they are invaded and flooded by marine waters. These marine incursions trigger short spells of development of life forms typical of low-to-normal marine salinity (e.g. coccolithophorids that may accumulate in the kopara pools whereas they are usually absent from them). Hence, episodes of sea-level rise are recorded in the kopara sequences as proof of open-marine conditions.

Last, both kopara and palaeokopara must owe their preservation to the absence of predators, such as gastropods (ceritids are efficient cyanobacterial mat grazers that

prevent the fossilisation of stromatolites). In both cases, the cause precluding the settlement of predators must be the hostile chemical conditions: widely varying salinity, possibly hyperalkalinity, and highly reducing conditions below a depth of 1–2 cm in the sediment.

6. Conclusion

This study presents a modern analog of the Kimmeridgian environment that led to the formation of peculiar OM-rich laminated carbonates. The comparison between the modern setting and the ancient one helps understand the influence of small-scale sea-level fluctuation upon carbonate-platform lagoonal environment, recorded by the type of laminated facies: stromatolitic; undulating laminae correspond to shallowest conditions; parallel laminae record relative sea-level rises, even of very limited amplitude.

This helps envision the depositional conditions of carbonate facies rich in sulphurised OM. The sulphuration process — a key factor concerning OM storage — is usually known for pelagic deposits such as the Kimmeridge Clay Formation of England and the La Luna Formation of Venezuela (Tribovillard and Van). Thus this study shows that sulphuration can also operate in shallow peritidal environments where bacterial activity is intense.

The model established for Orbagnoux may apply to other sedimentary deposits of similar facies, whatever their age, for example, the Messinian pre-evaporitic facies of the Lorca Basin (Southern Spain) that shows striking similarities with the Orbagnoux deposits: identical sedimentary facies; comparable platform setting; and abundance of vulcanised OM (Permanyer and Rouchy).

Acknowledgements

The authors thank J. Carpentier and M. Bocquet for technical assistance. This manuscript greatly benefited from the experience of G. Gerdes, A. Strasser, J. and G. Tribble, F. Sansone; Mark Caplan improved the English of the draft. They warmly thank Cathryn Newton, Jean-Marie Rouchy and Henry Chafetz for their careful review and editing which considerably improved this paper.

References

- Bernier, P., 1984. Les formations carbonatées du Kimméridgien et du Portlandien dans le Jura méridional. Stratigraphie, micropaléontologie et sédimentologie. *Docum. Labo.Géol. Lyon* **92**, p. 803.
- Bernier, P. and Courtinat, B., 1979. La matière organique des calcaires d'arrière-récifs du Kimméridgien supérieur dans le Jura méridional. Systématique, conditions de genèse et d'environnement. *Docum. Labo.Géol. Lyon* **75**, pp. 95–117.
- Bernier, P., Gaillard, C., Barale, G., Bourseau, J.-P., Buffetaud, E. and Wenz, S., 1991. Morphogenetic impact of microbiological mats on surface structures of Kimmeridgian micritic limestone (Cerin, France). *Sedimentology* **38**, pp. 127–136.

Buczynski, C. and Chafetz, H.S., 1991. Habit of bacterially induced precipitates of calcium carbonate and the influence of medium viscosity on mineralogy. *J. Sediment. Petrol.* **56**, pp. 812–817.

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

Chafetz, H.S. and Buczynski, C., 1992. Bacterially induced lithification of microbial mats. *Palaios* **7**, pp. 277–293.

Courtinat, B., 1989. Les organoclastes des formations lithologiques du Malm dans le Jura méridional. Systématique, biostratigraphie et éléments d'interprétation paléoécologique. *Docum. Labo.Géol. Lyon* **105**, p. 361.

Défarge, C., 1997. Apports du cryo-microscope électronique à balayage et du microscope électronique à balayage haute résolution à l'étude des matières organiques et des relations organo-minérales naturelles. Exemple des sédiments microbiens actuels. *C. R. Acad. Sci. Paris* **324**, pp. 553–561.

Défarge, C., Trichet, J., Sansone, F., Tribble, J., Roibert, M. and Jaumet, A.-M., 1993. Further evidence for the participation of organic networks inherited from prokaryotes in the development of microstructures and carbonatation of modern stromatolites. Paleontological inferences. *C. R. Acad. Sci. Paris* **316**, pp. 1107–1114.

Défarge, C., Trichet, J., Maurin, A. and Hucher, M., 1994. Kopara in Polynesian atolls: early stages of formation of calcareous stromatolites. *Sediment. Geol.* **89**, pp. 9–23.

Défarge, C., Trichet, J. and Coute, A., 1994. On the appearance of cyanobacterial calcification in modern stromatolites. *Sediment. Geol.* **94**, pp. 11–19.

Défarge, C., Trichet, J., Jaunet, A.M., Robert, M., Tribble, J. and Sansone, F., 1996. Texture of microbial sediments revealed by cryo-scanning electron microscopy. *J. Sediment. Res.* **66**, pp. 935–947.

Dromart, G., 1987. Deposition of upper Jurassic fine-grained limestones in the western Subalpine Basin, France. *Palaeogeogr., palaeoclim., Palaeoecol.* **69**, pp. 23–43.

Espitalié, J., Deroo, G. and Marquis, F., 1985. La pyrolyse Rock Eval et ses applications. *Rev. Instit. Fr. Pétr.* **40**, pp. 563–579.

François, R., 1987. A study of sulphur enrichment in the humic fraction of marine sediments during early diagenesis. *Geochim. Cosmochim. Acta* **51**, pp. 17–27.

Gerdes, G., Krumbein, W.E. and Reineck, H.-E., 1991. Biolaminations — ecological versus depositional dynamics. In: Einsele, G., Ricken, W. and Seilacher, A., Editors, 1991. *Cycles and Events in Stratigraphy*, Springer-Verlag, Berlin, pp. 592–607.

Gorin, G., Gülaçar, F. and Cornioley, Y., 1989. Organic geochemistry, maturity, palynofacies and paleoenvironment of Upper Kimmeridgian and Lower Tertiary organic-rich samples in the southern Jura (Ain, France) and Subalpine massifs (Haute-Savoie, France). *Eclog.geol. Helv.* **82**, pp. 491–515.

Gubler, Y. and Louis, M., 1956. Etude d'un certain milieu du Kimméridgien bitumineux de l'est de la France. *Rev. Instit. Fr. Pétr.* **11**, pp. 1536–1543.

Kazmierczak, J., Coleman, M.L., Gruszczynski, M. and Kempe, S., 1996. Cyanobacterial key to the genesis of micritic and peloidal limestones in ancient seas. *Acta Palaeont. Polon.* **41**, pp. 319–338.

Mongenot, T., 1998. Étude pétrographique et géochimique d'un dépôt sédimentaire très riche en soufre organique (Orbagnoux, Kimméridgien supérieur). Unpublished PhD Thesis, Orleans University.

Mongenot, T., Boussafir, M., Derenne, S., Lallier-Verges, E., Largeau, Cl. and Tribovillard, N.-P., 1997. Sulphur-rich organic matter from Bituminous Laminites of Orbagnoux (France, upper Kimmeridgian) — the role of early vulcanization. *Bull. Soc. géol. Fr.* **168**, pp. 331–341.

Mongenot, T., Derenne, S., Largeau, Cl., Tribovillard, N.P., Lallier-Verges, E., Dessort, D. and Connan, J., 1999. Spectroscopic, kinetic and pyrolytic studies of kerogen from the dark parallel laminae facies of the sulphur-rich Orbagnoux deposit (Upper Kimmeridgian, Jura). *Org. Geochem.* **30**, pp. 39–56.

Permanyer, A., Baranger, R. and Lugardon, B., 1994. Oil shale characterisation in Messinian pre-evaporitic sediments from the Lorca Basin (SE-Spain). In: Curnelle, R. and Sévérac, J.-P., Editors, 1994. *Pétrologie organique Bull. Centres Rech. Explor.-Prod. elf aquitaine* **18** Spec. Publ., pp. 136–149.

Riche, A., 1904. Feuille de Lyon au 320 000ème. *Bull. Carte géol. Fr.* **13**, pp. 1–7.

Riding, R., 1991. Classification of microbial carbonates. In: Riding, R., Editor, , 1991. *Calcareous Algae and Stromatolites*, Springer-Verlag, Berlin, pp. 21–51.

Riding, R., 1991. Calcified cyanobacteria. In: Riding, R., Editor, , 1991. *Calcareous Algae and Stromatolites*, Springer-Verlag, Berlin, pp. 21–51.

Rouchy, J.-M., Taberner, C., Blanc-Valleron, M.M., Sprovieri, R., Russell, M., Pierre, C., Di Stefano, E., Pueyo, J.J., Caruso, A., Dinarès-Turell, J., Gomis-Coll, E., Wolff, G.A., Cespuglio, G., Ditchfield, P., Pestrea, S., Combourieu-Nebout, N., Santisteban, C. and Grimalt, J.O., 1998. Sedimentary and diagenetic markers of the restriction in a marine basin: the Lorca Basin (SE Spain) during the Messinian. *Sedim. Geol.* **121**, pp. 23–55.

Sinninghe Damsté, J.S., Rijpstra, W.I.C., Kock-Van Dalen, A.C., De Leeuw, J.W. and Schenck, P.A., 1989. Quenching of labile functionalisable lipids by inorganic sulfur species: evidence for the formation of sedimentary organic sulfur compounds at the early stages of diagenesis. *Geochim. Cosmochim. Acta* **53**, pp. 1343–1356.

Schoonmaker, J., Tribble, G.W., Smith, S.V. and Mackenzie, F.T., 1985. Geochemistry of saline ponds, Kiritimati (Republic of Kiritimati). In: Gabri , C., Toffart, J.-L. and Salvat, B., Editors, 1985. *Fifth International Coral Reef Congress, Tahiti, Proceedings vol. 3*, Antenne Mus um-Ecole Pratique des Hautes Etudes, Moorea, French Polynesia, pp. 439–444.

Strasser, A., 1988. Shallowing-upward sequences in Purbeckian peritidal carbonates. *Sedimentology* **35**, pp. 369–383.

Strasser, A., 1991. Lagoonal–peritidal sequences in carbonate environments: autocyclic and allocyclic processes. In: Einsele, G., Ricken, W. and Seilacher, A., Editors, 1991. *Cycles and Events in Stratigraphy*, Springer-Verlag, Berlin, pp. 709–720.

Tegelaar, E.W., de Leeuw, J.W., Derenne, S. and Largeau, C., 1989. A reappraisal of kerogen formation. *Geochim. Cosmochim. Acta* **53**, pp. 3103–3106.

Tribovillard, N., 1998. Bacterially mediated peloids in laminated, organic-matter rich, limestones: an unobtrusive presence. *Terra Nova* **10**, pp. 126–130.

Tribovillard, N., Gorin, G., Hopfgartner, G., Manivit, H. and Bernier, P., 1991. Conditions de d p t et mati re organique en milieu lagunaire d' ge kimm ridgien du Jura m ridional fran ais (r sultats pr liminaires). *Eclog. geol. Helv.* **84**, pp. 441–461.

Tribovillard, N., Gorin, G., Belin, S., Hopfgartner, G. and Pichon, R., 1992. Organic-rich biolaminated facies from a Kimmeridgian lagoonal environment in French Southern Jura Mountains — a way of estimating accumulation rate variations. *Palaeogeogr., Palaeoclimat., Palaeoecol.* **99**, pp. 163–177.

Tribovillard, N., Desprairies, A., Lallier-Verges, E. and Bertrand, Ph., 1994. Sulfur incorporation of lipidic organic matter in reactive-iron deficient environments: a possible enhancement for the storage of hydrogen-rich organic matter. *C. R. Acad. Sci. Paris* **319**, pp. 1199–1206.

Tribovillard, N., Trichet, J., D farge, Ch., Trentesaux, A., 2000. Jurassic lagoonal environments and quasi-abiotic platy limestone accumulation: microbial interventions. *Sedimentology* (in press).

Trichet, J. and D farge, C., 1995. Non-biologically supported organomineralization. *Bull. Instit. O c anogr. Monaco, spec. publ.* **14**, pp. 203–236.

Trichet, J. and D farge, C., 1997. High resolution cryo-scanning electron microscopy of modern stromatolites (Lake R2, Rangiroa Atoll, Tuamotu Archipelago). In: Neuweiler, F., Reitner, J. and Monty, C., Editors, 1997. *Biosedimentology of Microbial Buildups IGCP Project n 380Facies* **36**, pp. 195–284.

Trichet, J., D farge, C., Tribble, J., Tribble, G., Sansone, F., 2000. Christmas Island lagoonal lakes, models for the deposition of carbonate-evaporite-organic laminated sediments. *Sediment. Geol.* (submitted for publication).

Van Kaam-Peters, H.M.S., 1997. The depositional environment of Jurassic organic-rich sedimentary rocks in NW Europe. A biomarker approach. *Geol. Ultra* **153**, p. 248.