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Cover photograph: Field of putative Martian scoria cones in Ulysses Colles, Tharsis (see page 49).

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Time-travelling in the Mesozoic of Lorraine

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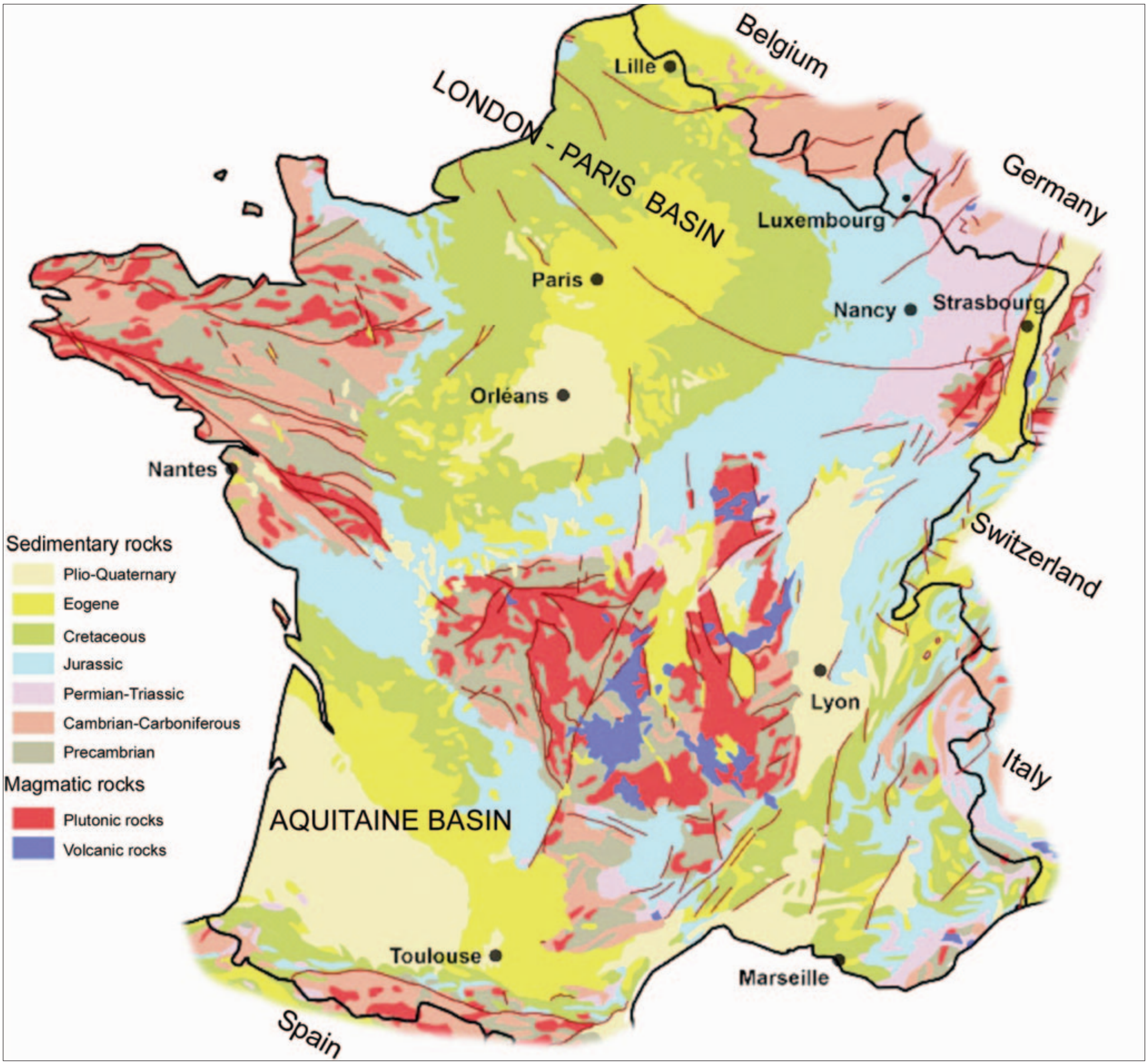
Following Etienne Skrzypek's description of the basement rocks (this issue), this article presents a general overview of the sediments deposited in Lorraine. The approach adopted here is to trace environmental changes and biodiversity crises through the stratigraphic column, illustrated by reconstructions of key episodes along the geological timeline.

If we look at the geological map of France (Fig. 1), we can see concentric outcrop belts surrounding Paris: yellow for the Tertiary, green for the Cretaceous, blue for the Jurassic, and violet for the Triassic, extending eastward toward Germany. The pattern is roughly similar in every direction. Heading north-west, one crosses the Channel and finds the same outcrop pattern in the London–Paris Basin, since Paris and London were once submerged beneath the same Cretaceous sea.

Returning eastward, from the summit of the Vosges Massif (near Strasbourg, Fig. 1), and travelling westward across Lorraine, we can observe a continuous succession of strata spanning from the beginning of the Triassic to the end of the Jurassic — representing nearly 100 million years of Earth's history.

The stratigraphic column of Lorraine (Fig. 2, *overleaf*) reveals an impressive succession of formations, their traditional names reflecting two centuries of geological study. Before beginning our journey through this geological record, it is worth pausing to consider its human and economic significance. Note, for instance, the coal resources found in the Hercynian basement beneath the French–German border; the salt deposits of the Upper Triassic (Carnian), still actively exploited today; and the iron-rich oolitic 'Minette' ores of the Lower Jurassic, once crucially important to

Figure 1 Simplified geological map of France.



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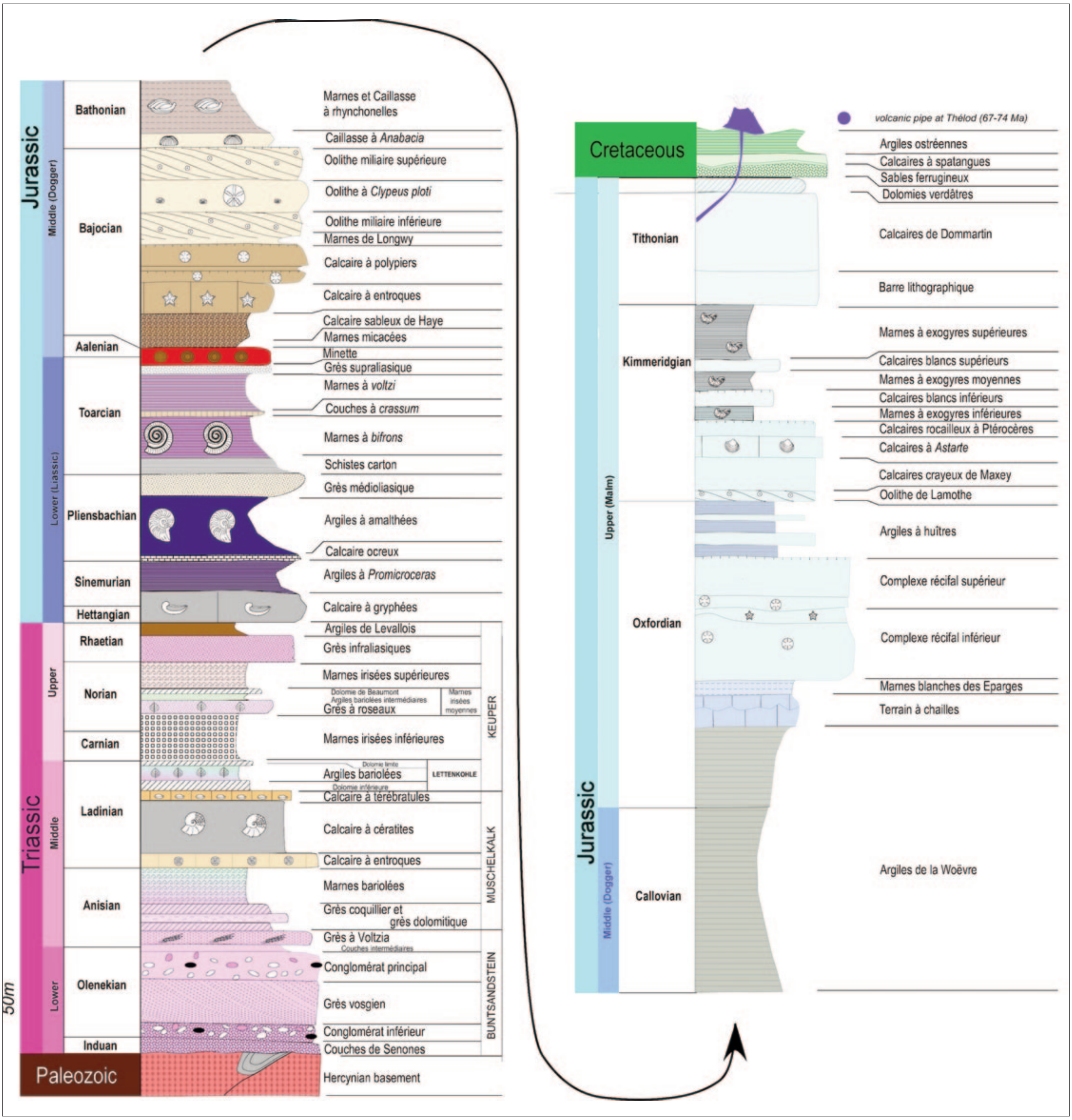
the economies of Lorraine and Luxembourg, and a point of contention in past Franco-German conflicts. Iron mining ceased several decades ago, but attention has now turned to the thick Callovo–Oxfordian clay — considered a potential repository for nuclear waste. Then we see how important this stratigraphic column is to Lorraine's heritage.

Our first stop is the Grès à Vosgien Formation, a sandstone unit that forms prominent reliefs in the Vosges landscape. No detailed reconstructions are available for this period, but we can imagine a vast braided river, transporting pink sands beneath a warm climate shortly after the greatest mass extinction in Earth's history: the Permian–Triassic mass extinction. This immense river flowed eastward toward the Germanic Sea. As conditions became slightly more deltaic, the Grès à Voltzia Formation (at the top of Buntsandstein Group) developed and created and environment for exceptional fossil preservation — what German geologists call a 'Konservat-Lagerstätte' — and provides vivid glimpses of life at that time (Fig. 3, *opposite*).

A reconstruction is always an interesting scientific tool, because it provides a basis for raising many new questions: For example, what did this stegocephalian, known only from its footprints, actually look like? Would a gallery forest be a more realistic interpretation?

Figure 2 Stratigraphic column of Lorraine.



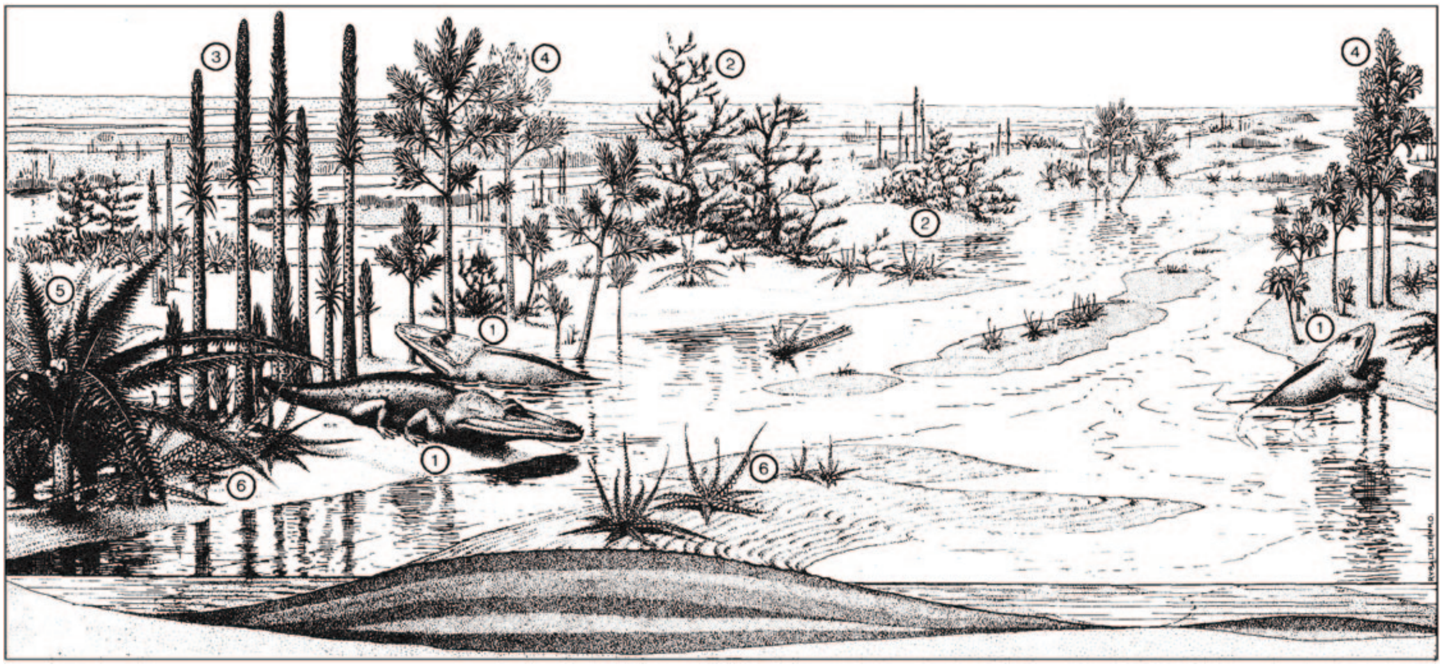


Figure 3 The Lorraine region during deposition of the Grès à Voltzia Formation: 1 Stegocephalian (amphibian); 2 Voltzia (conifer); 3 Pleuromeia (Lycophyte); 4 Yuccites (conifer); 5 Anomopteris (fern); 6 Neuropteridium (fern) (after J.-C. Gall, 1981).

Skipping forward, we reach two formations of the Muschelkalk Group: the 'Calcaire à entroques' and the 'Calcaire à cératites'. These mark a major environmental transition from fluvial to fully marine conditions.

Published reconstructions exist, but they were not specifically inspired by the Lorraine settings. For example, in Figure 4 a reconstruction proposed by Hess (1975) presents a summary, which amalgamates both formations. In this illustration, the palaeoenvironment of the Calcaire à entroques Formation is shown as a shallow sea floor teeming with crinoids (*Encrinus liliiformis*), whose stalks could reach 1.6 m in length — survivors of the Permian–Triassic mass extinction. The author suggested that some *Encrinus* could swim, probably based on analogy with certain modern crinoids that can detach themselves through autotomy, and because some of the lower stem segments are rounded. The sea floor also hosted bivalves (Limidae), gastropods, and pedunculate brachiopods.

Above the Calcaire à entroques Formation, the Calcaire à cératites Formation generally lacks crinoids, but abounds in ceratitid ammonoids. A single one is represented in Figure 4. Ceratites evolved within the restricted Muschelkalk Sea. In its phase of maximum isolation, this inland sea was connected to the Tethys Ocean only through a narrow passage in present-day Poland. The isolation of this basin fostered an endemic lineage of ceratites, a fine illustration of vicariant evolution in the fossil record. Ceratites were not the only swimmers in this Muschelkalk Sea, and the presence of marine reptiles and conodontophorids (small fish-like organisms) should also be mentioned. The transition from the Calcaire à entroques Formation to the Calcaire à cératites Formatio marks a clear deepening of the marine environment — the maximum flooding of the Triassic in Lorraine.

The upper Triassic Keuper Group represents a different world, in which there were vast, shallow lagoons of fluctuating salinity, perhaps reminiscent of the modern pink lagoon of Torrevieja, Spain. These waters, possibly tinted by pigment-producing algae such as *Dunaliella*, left behind thick salt deposits. Whether the Triassic lagoons were truly pink remains speculative — but it is a pleasing image.

The Triassic Period closed, *c*. 200 million years ago, with another major biological crisis — one of the 'Big Five' mass extinctions. This was linked to the immense volcanic outpourings of the Central Atlantic Magmatic Province (CAMP). Conodonts and ceratites vanished forever, along with numerous reptiles and amphibians. Yet from this extinction emerged new organisms, including the first true ammonites (*Psiloceras*), heralding the dawn of the Jurassic Period.

Figure 4 Scene from the Muschelkalk Sea (after Hess 1975).

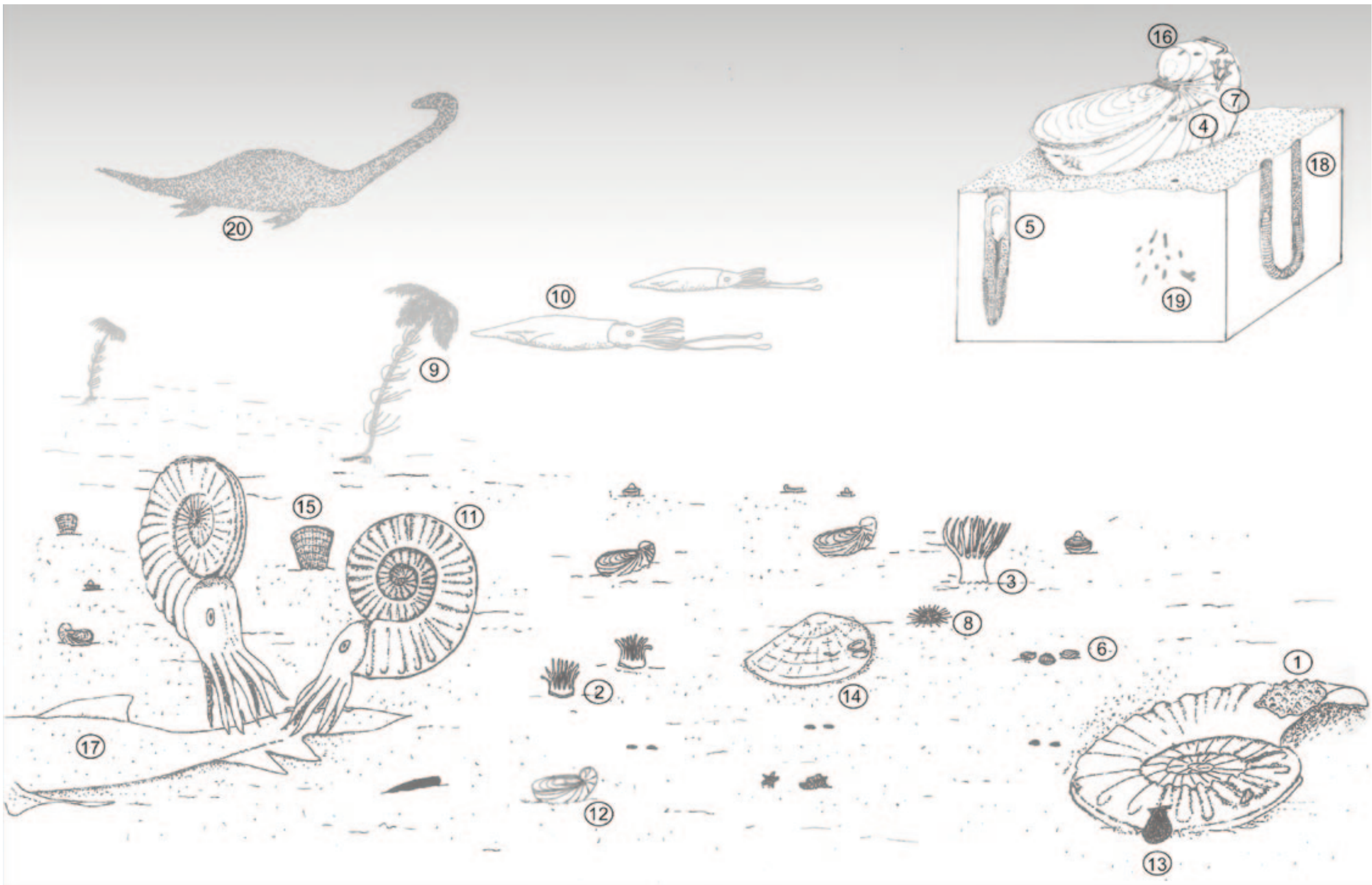


Figure 5 Reconstruction of a Sinemurian sea floor in central Lorraine (after Hanzo et al. *2000; drawing by B. Lathuilière): 1 sponge encrusting an ammonite shell; 2* Stylophyllopsis *(coral); 3 Cerianthid sea anemone producing the ichnofossil* Kulindrichnus langi*; 4* Serpula *(annelid worm) on a* Gryphaea*; 5* Lingula metensis *(inarticulated brachiopod); 6* Piarorhynchia juvenis *(brachiopod); 7 Stomatopora (bryozoan); 8 echinid; 9* Isocrinus *(life position and disarticulated columnals); 10* Nanobelus *(belemnites); 11 Arietitidae ammonites; 12* Gryphaea arcuata*; 13* Chlamys *(bivalve); 14* Plagiostoma gigantea *(bivalve); 15* Pinna *(bivalve); 16* Zapfella *(crustacean cirriped boring a* Gryphaea*); 17* Acrodus *(shark); 18* Diplocraterion *(trace fossil, probably a crustacean); 19 Chondrites (nutrition burrow); 20 plesiosaur.*

The Jurassic Period

The overlying formation, the Calcaire à gryphées Formation is the first Jurassic unit in central Lorraine. It is comparable to the Blue Lias of the Dorset coast in the UK, with its rhythmic alternations of marls and limestones. The emblematic fossil *Gryphaea arcuata*, 'the drosophila of palaeontologists' — as Stephen Jay Gould famously called it because of the interest this fossil aroused in evolutionary studies — laid on the bioturbated seafloor (Fig. 5).

Besides *Gryphaea arcuata*, many other bivalves can be seen on the sea bottom, such as the large *Plagiostoma gigantea* or the half-buried Pinna. But several other endobenthic bivalves would have been hidden in the mud. In the background, crinoids of the genus *Isocrinus* are filtering a higher part of the water column. And in comparison to previous Triassic environments, new swimmers had evolved, and true ammonites (illustrated is a tall is Sinemurian Arietitidae). Also shown in the background are some belemnites. Sharks (*Acrodus*), ichthyosaurs and plesiosaurs were also present at this time. The depth is estimated at several tens of metres. In northern Lorraine, the sea was shallower, giving rise to sandy deposits such as the Grès d'Hettange Formation.

Moving upward in the stratigraphic succession, the Pliensbachian–Toarcian boundary is marked by a double-step mass extinction. The second phase corresponds to the Toarcian Oceanic Anoxic Event (TOAE), recorded in the Schistes-carton Formation. This global event, triggered by volcanic activity in the Karoo–Ferrar Large Igneous Province, profoundly altered marine ecosystems. Among the emblematic victims of this mass extinction was a group of huge bivalves, the lithiotids, which build enormous reefs — for example as are found in Morocco or in Italy. In these low-latitude reefs, corals have also suffered severely, as recently documented. In Lorraine, the Amaltheidae disappeared with the last *Pleuroceras*, a group of boreal ammonites.

At the end of this Toarcian Stage, a sedimentary event of great importance for the history of Lorraine occurred: the Minette Formation, an oolitic ironstone widely mined since the middle of the 19th century.

In Figure 6 (*opposite*) we are facing the shore; the basin is behind us. Megaripples of rusty colour made of iron ooids can be seen advancing to cover the grey mud deposited in a distal position. These ooids formed on the sea floor, and were moved by tidal currents, bringing iron from the emerged land. In the foreground, the muddy substrate is mostly occupied by bivalves, among them *Gryphaea ferruginea*, a descendant of the previously mentioned ancestral *Gryphaea arcuata*. Occasionally, a sunken tree trunk was deposited and created a suitable substrate for bivalves such as *Modiolus*. In this scene,

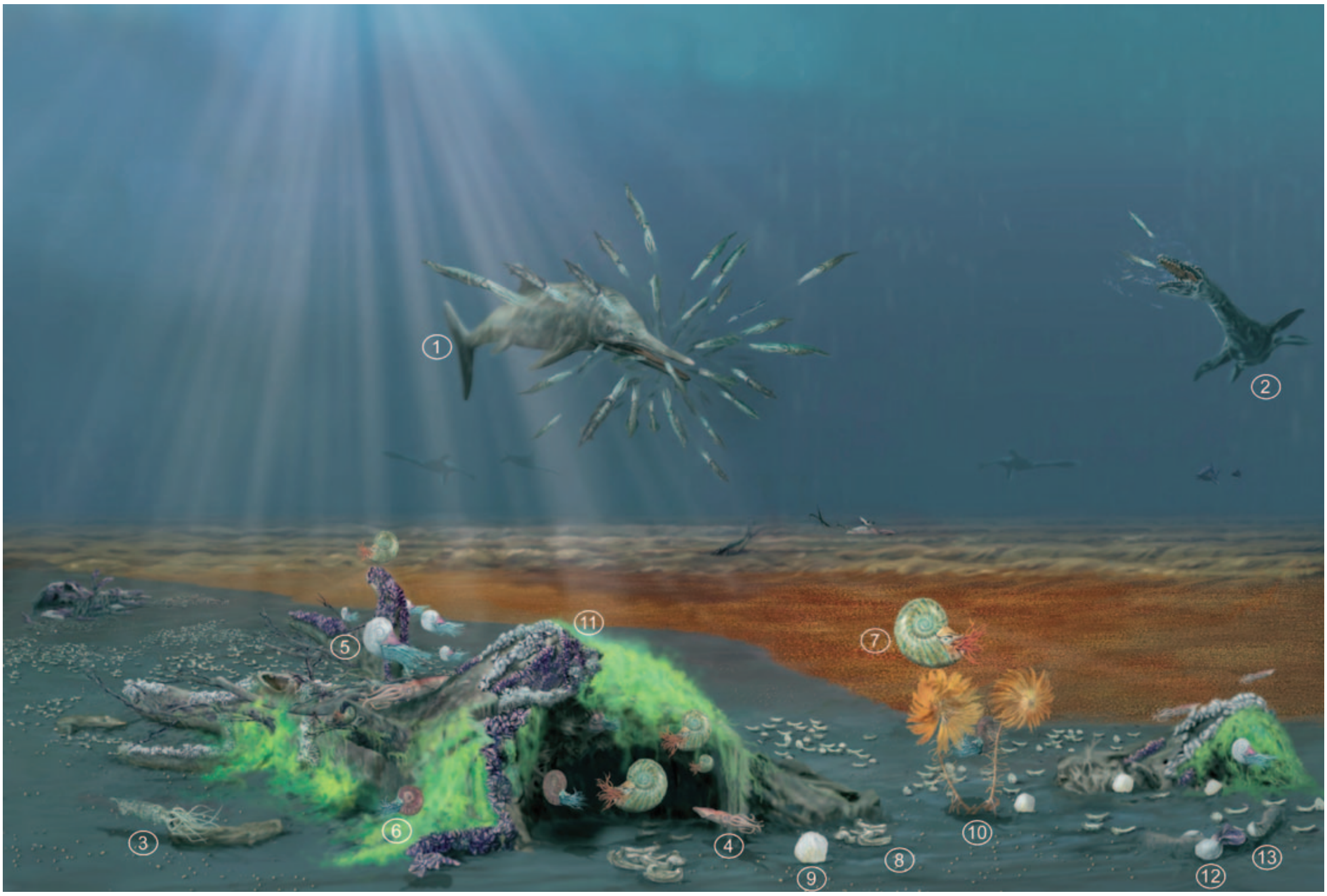


Figure 6 Scene from the Late Toarcian (Minette Formation) (drawing by Pascal Laheurte; scientific supervision by B. Lathuilière): 1 Ichthyosaur; 2 Plesiosaur; 3 Acrocoelites *(belemnite), 4* Dactyloteuthis *(belemnite), 5* Dumortieria moorei *(ammonite), 6* Pleydellia aalensis *(ammonite); 7* Pleurolytoceras wrighti *(ammonoid); 8* Gryphaea ferruginea *(bivalve); 9* Pinna *(bivalve); 10* Isocrinus *(crinoïde); 11* Modiolus *(bivalve); 12,* Inoceramus *(bivalve); 13* Oxytoma *(bivalve).*

the green colour is a means to represent non-fossilised green algae and emphasise the high phosphorus and nitrate content of the water. Indeed, mesotrophic waters are the best explanation for an abnormal, very high proportion of swimmers in such a shallow environment. Among these swimmers, an ichthyosaur and a plesiosaur are represented eating belemnites, but ammonites are also illustrated.

The stratigraphic development from this Minette episode to the next one is precisely this kind of progressive change in the nutrient content. The structure of the ecosystem shifted toward oligotrophic conditions, culminating in the Bajocian coral reef episode of the Calcaire à polypiers Formation, a much more favourable situation for the production and preservation of carbonate skeletons.

In the reconstruction presented in Figure 7 (*overleaf*) low relief reefs emerge from the calcareous sand or from the mud according to sedimentary input deposited by the last storm. These reefs are mostly built of platy corals that formed a tiered framework, with numerous cavities in which a diverse fauna could live, sometimes in accordance with their sciaphilic preferences. Here and there, some rare branching phaceloid corals found their place among platy corals. The setting resembles modern mesophotic reefs, which grow some tens of meters below the sea surface under low light levels, and beyond the reach of fair-weather waves. Between the reefs, crinoids (Isocrinidae) were filtering the water, and soft-bottom bivalves and large gastropods of the genus *Bourguetia* evolved. Soft algae have also been hypothetically drawn, but their exact shape is unknown; only a witness of their existence remains at the fixation points of some epiphytic small fossilised organisms. Among swimmers, a shark has been pictured, the teeth of which have been fossilised, and also a big (500 mm) nautilid of the genus *Cenoceras*.

A next development in the stratigraphic succession is represented by the Argiles de la Woevre Formation, which is an equivalent in part to the English Oxford Clay. The work of the French national agency for nuclear waste (ANDRA) to install a laboratory here 500 m underground has provided evidence of the content of this formation. The reconstruction shown in Figure 8 (*overleaf*) shows a dark environment, a soft grey-black substrate of clay, marls and silts inhabited by a scarce benthic fauna (here artificially densified for artistic emphasis). The descendants of previously mentioned *Gryphaea* (here *G. dilatata*) are significantly present, reclining on the soft bottom beside *Pinna*, and other a pectinid bivalve. A *Bourguetia* snail is shown crawling through the soft grey clay; and rare crinoids are also illustrated, as well as some crustaceans (known only from scarce partial remains). The swimmers are represented by cephalopod ammonites of the genus *Cardioceras*; and there are also belemnites. Both are known for their boreal biogeography, which indicates that the temperature was rather cool rather than tropical, on a calm sea bottom, deeply situated below any disturbance from the actions of the storm wave base.

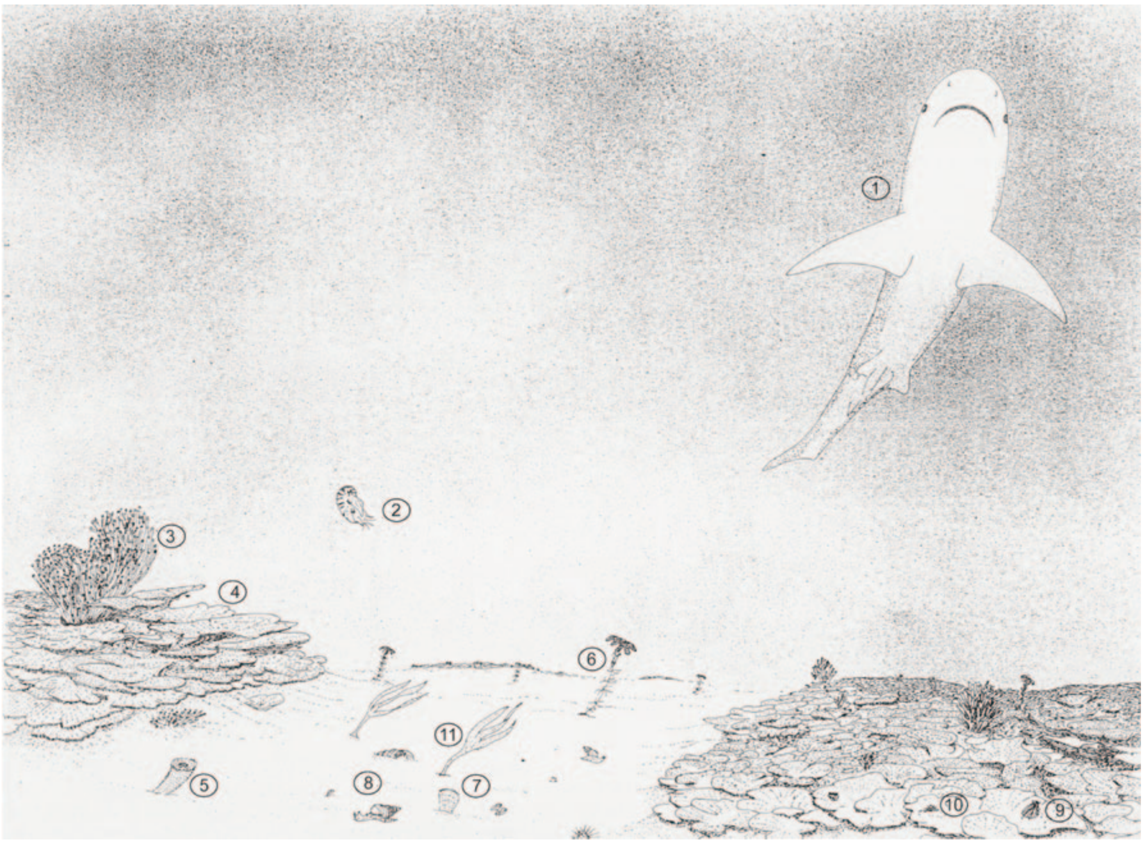
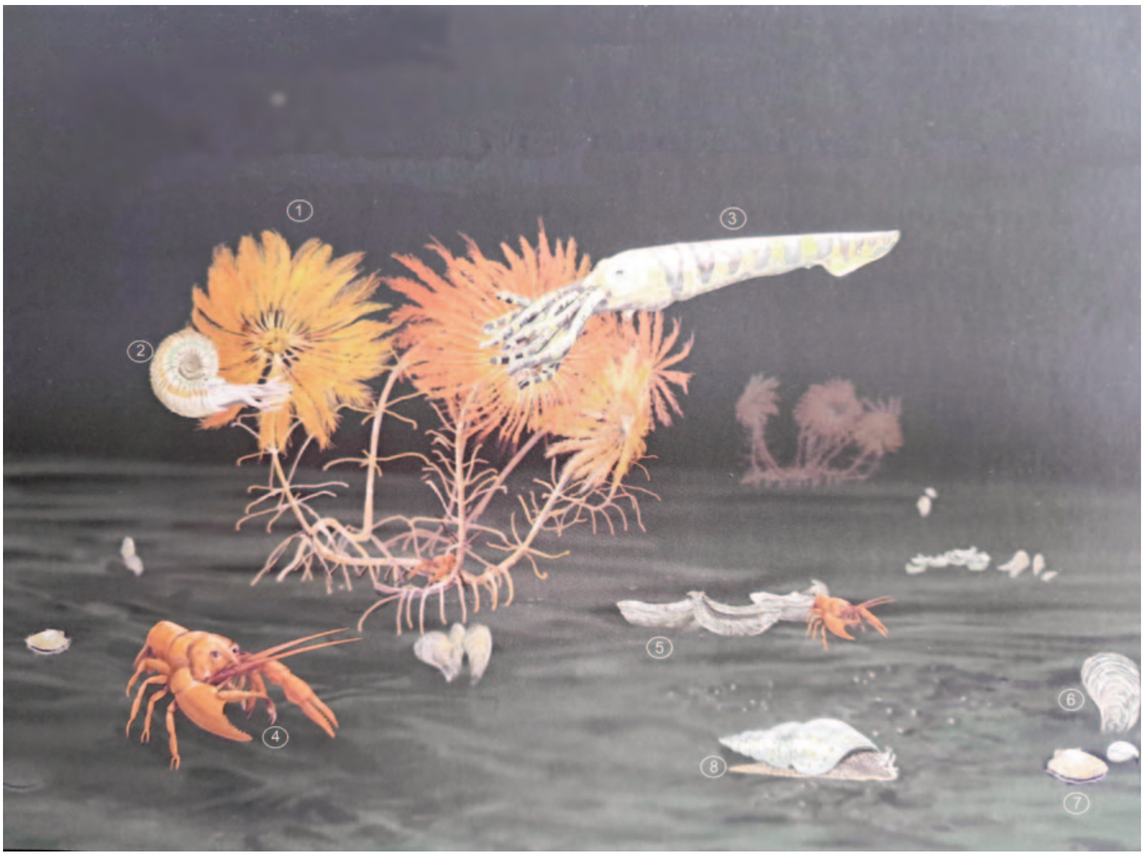


Figure 7 Reconstruction of a Bajocian reef in Lorraine (drawing by B. Lathuilière): 1 Acrodus *(shark); 2* Cenoceras *(nautilid); 3* Cladophyllia *(branching coral); 4 lamellar corals (mainly* Isastrea bernardiana*,* Periseris elegantula *and* Thamnasteria mettensis*); 5 sponge; 6* Isocrinus *(crinoid); 7* Pinna *(bivalve); 8* Bourguetia *(gastropod); 9* Chlamys *(bivalve); 10,* Caenocidaris cucumifera *(sea urchin); 11 soft algae.*

Figure 8 Early Oxfordian sea floor in Lorraine (drawing by P. Laheurte; scientific supervision by B. Lathuilière for ANDRA): 1 Isocrinus *(crinoide); 2* Cardioceras *(ammonite); 3* Hibolites *(belemnite); 4 decapod crustacean; 5* Gryphaea dilatata *(bivalve); 6* Isognomon *(bivalve); 7 Pectinidae (bivalve); 8* Bourguetia *(gastropod).*



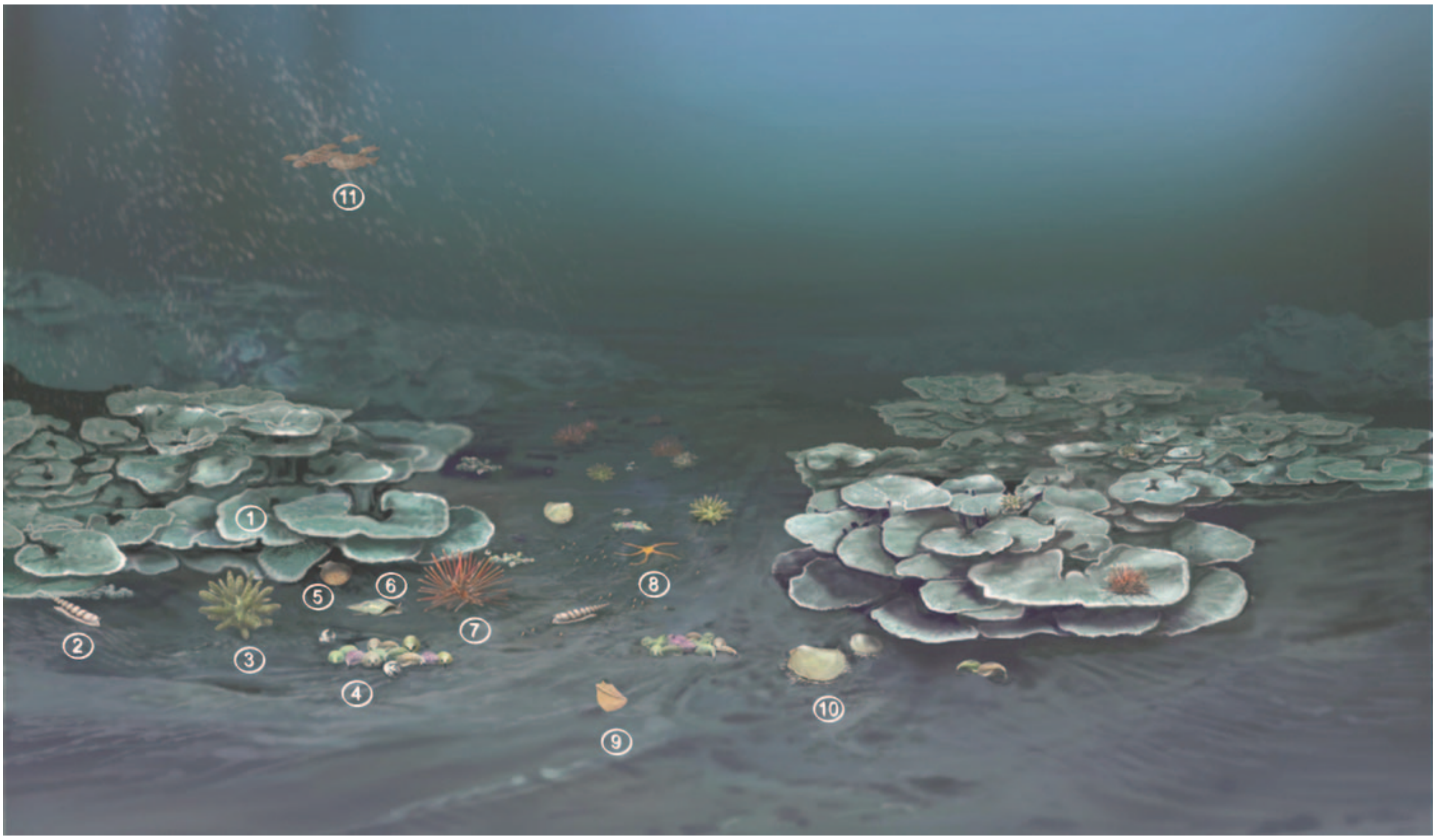


Figure 9 A scene of the Middle Oxfordian life in Lorraine at the beginning of the reef-building episode (drawing by P. Laheurte; scientific supervision by B. Lathuilière for ANDRA): 1 platy corals (dominated by Dimorpharaea*); 2* Nerinella *(gastropod); 3* Paricidaris *(sea urchin); 4* Ornithella *(brachiopod); 5* Chlamys *(bivalve), 6* Bourguetia *(gastropod), 7* Hemicidaris *(sea urchin), 8 ophiurid, 9* Trigonia *(bivalve), 10* Plagiostoma *(bivalve); 11* Lepidotes *(actinopterygian fish).*

The English Corallian beds also have an equivalent in which corals and reefs have flourished more favourably in Lorraine due to their more suitable palaeolatitude. The next reconstruction (Fig. 9) is precisely the beginning of the reef-building episode. This beautiful drawing by P. Laheurte shows a mesophotic environment comparable to Bajocian reefs, but the corals in this reconstruction mainly belong to the genus *Dimorpharaea*, a group well adapted to such a pioneering environment in low-light levels, and with a moderate nutrient content in the water.

The benthos was significantly more abundant than in the previous episode, the temperature was higher, and the depth shallower, beyond the action of fair-weather waves but under the stress of storms. The tiered and interlocking framework of the corals also provided a habitat for a world of small organisms that bored, incrusted or nested into cavities, such as numerous typical sea urchins and pectinid bivalves. Brachiopods also lived in groups in the gaps between the coral zones.

By the Late Oxfordian, lagoonal environments prevailed, as reconstructed in Figure 10 *(overleaf*). These were brightly lit and shallow, with stromatoporoids and chaetetid sponges, and nerinean gastropods thriving in clear, carbonate-rich waters.

The Marnes à exogyres Formation of the Kimmeridgian provides the evidence for a final reconstruction, shown in Figure 11 *(overleaf*). The final constructional process in this stratigraphic succession created the a widely extended, flat, very shallow platform of the Calcaire à astartes Formation, which was subsequently inundated. Following this, the platform was inhabited by numerous small oysters of the genus *Nanogyra* (previously identified as *Exogyra*). They lived on a marly soft substrate with many other bivalves. The environment was also inhabited by abundant swimming organisms (ammonites *Orthaspidoceras*, and Actinoptery-gian fishes), which is interpreted as a consequence of maximum flooding. In Lorraine, the Jurassic story ends in the Tithonian with a long emersion episode, which is also known in the UK as Purbeckian and Wealdian deposits.

Reflections on environmental and biological evolution

Using the rubric of 'time travel' and reconstructing helps us to understand the big picture of these changing environments in which several biological and environments changes occurred. The first phase, at the end of the Permian, was the most dramatic of all. The second phase was the Triassic-Jurassic boundary extinction, and the final phase is represented by the Pliensbachian-Toarcian boundary.

We understand that volcanic events controlled these biological events, in particular the extinction events that we can recognise in the stratigraphic column — especially for the CAMP (Central Atlantic Magmatic Province) at the end of the Triassic, and the Karoo-Ferrar Large Igneous Province.

We also hypothesise that sea-level changes also produced significant transformations of the ecosystems noted in the stratigraphic column. Focusing on second-order cycles, starting with continental fluviatile sediments, we have identified a maximum flooding within the Calcaire à cératites Formation, a maximum regression at the end of the Triassic, and a subsequent a transgression culminating in the Toarcian.

Afterwards, a further maximum regression is evidenced in the Minette Formation and in the Aalenian erosional surface at its top. A maximum flooding occurred during the Late Bajocian after

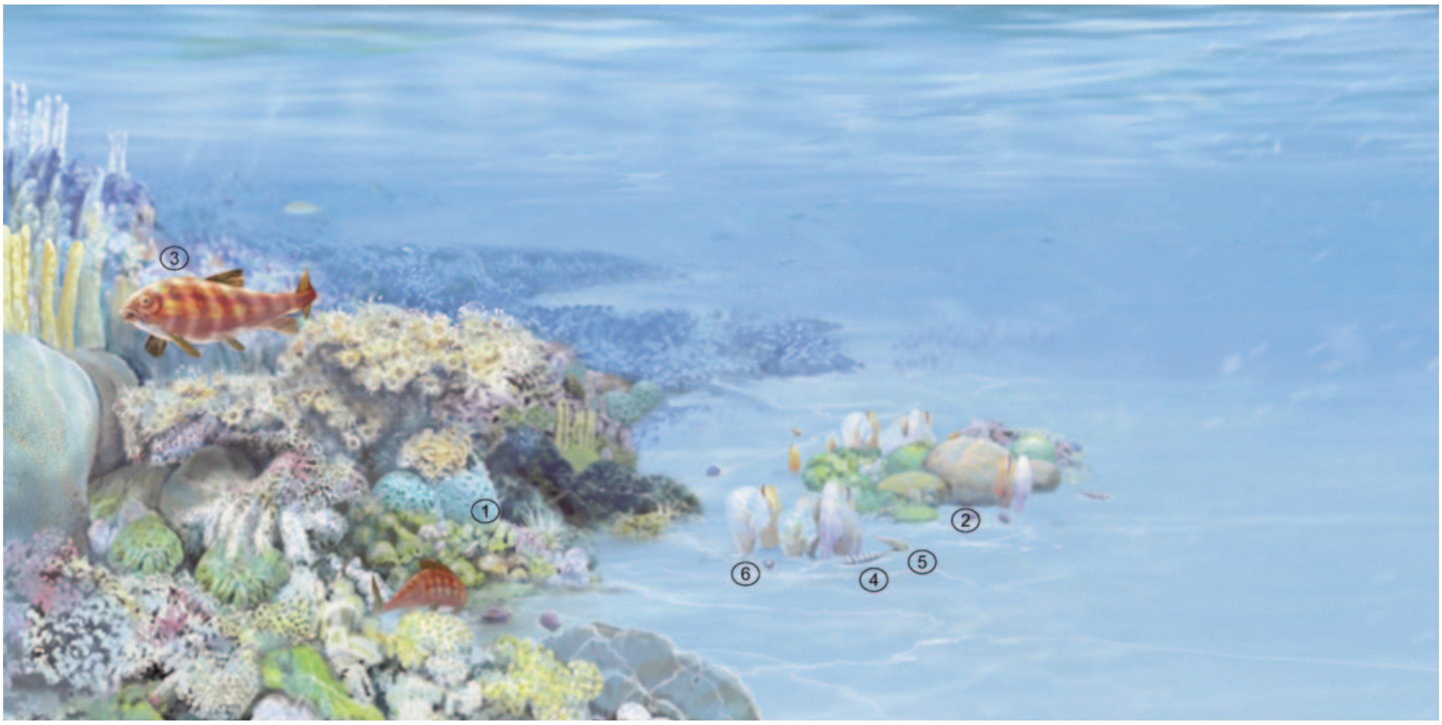


Figure 10 A scene of the Upper Oxfordian life in Lorraine at the end of the reef-building episode (drawing by P. Laheurte; scientific supervision by B. Lathuilière for ANDRA): 1 dome shaped corals (for example Complexastrea*); 2 sponges with skeleton (for example* Ptychochaetetes *or* Disparistromaria*); 3* Lepidotes *(actinopterygian fish);4* Nerinella *(gastropod); 5* Cossmannea *(gastropod); 6* Pinna *(bivalve).*

Figure 11 Reconstruction of the Kimmeridgian sea floor during deposition of the Marnes à exogyres Formation (drawing by Pascal Laheurte; scientific supervision by B. Lathuilière): 1 Orthaspidoceras *(ammonite); 2 shark; 3* Pinna *(bivalve); 4* Nanogyra virgula *(bivalve); 5* Etallonia *(crustacean); 6* Eryma *(crustacean); 7* Lepidotes *(actinopterygian fish).*

the described reef-building episode, which was immediately followed by a maximum regressive at the end of the stage.

During second-order scaled cycles in the Bathonian and Callovian the sea-level increased up to the Early Oxfordian, in the clayey episode that deposited the Argiles de la Woevre Formation.

The final maximum regressive episode described in our time-travelling is represented by the Calcaire à astarte Formation; and the ultimate maximum flooding c is represented by the Marnes à exogyres Formation. These second-order cycles were global events hypothetically caused by changes in the volumes of land and sea created by mid-ocean ridges.

All these events had a great impact on the Lorraine sedimentation. However, the effects of dynamic climatic events must also be considered. We must also try to decipher the potential impacts of climate represented in the stratigraphic column. Even if data with an appropriate granularity are still insufficient, we can point to the end of the Triassic, an important warming event caused by the CAMP activity — for which the term ‘hothouse climate’ has been used — and which was followed by a cooler Liassic period.

We should also point out that the Bajocian reefs developed despite their high latitude, and their indication of a warm period. Following this, an episode called ‘the cold snap’ has been identified during the Early Oxfordian, just before the warming attested by the large development of coral reefs along the northern Tethyan margin during the Middle Oxfordian. With these few examples, we can hypothesise that such climatic events interplay with the other factors described above..

To seek a single, universal cause for these environmental shifts would be simplistic. In summary, the stratigraphic column of

Lorraine emerges as a complex narrative — woven from the interplay of volcanism, sea-level change, climate events, and biota, each with its own feedbacks.

The ancient Greeks might have explained such complexity through their pantheon: Nemesis punishing prosperity, Hades stirring the volcanoes, Poseidon raising and lowering the seas, and Aeolus governing the winds. Perhaps, even today, sedimentary geology still resists a truly monotheistic theology!

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