

# Benkovac Stone (Eocene, Croatia): a deep-sea Plattenkalk?

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**Abstract** In contrast to Solnhofen-type conservation Lagerstätten, the platy limestones of the Benkovac Stone of the Eocene of Croatia contains a variety of trace fossils. They belong to the *Nereites* ichnofacies, characterized by a suite of highly specialized ichnogenera, turbiditic preservation, and distinctive pre-event versus post-event communities. In siliciclastic rocks, this ichnofacies stands for turbiditic deep-sea sediments. Also unusual is the lack of body fossils. The only exceptions are occasional plant debris and *Benkovacina concentrica* n. gen., n. sp., which is affiliated with xenophyophorian Foraminifera. These giant protozoans survive on present deep-sea bottoms, but they were also common on the shallow-marine biomats in Ediacaran times. These findings contradict the current shallow-marine interpretation, which is based on the regional geologic setting and sedimentary structures typical for tempestites. Thus, the Benkovac Stone would be an ideal place to test the reliability of ichnological versus sedimentological depth criteria in an entirely calcareous sequence.

**Keywords** Lithographic limestone · Trace fossils · *Benkovacina* n. gen. · Xenophyophorian Foraminifera · Ichnofacies · Palaeobathymetry

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## Institutional abbreviations

- GPIT Collection of the Institut für Geologie und Paläontologie, University of Tübingen (Germany)  
YPM Yale Peabody Museum's collection, Peabody Museum of Natural History, Yale University, New Haven (CT, USA)

## Introduction

Platy (and partly lithographic) limestones of the Solnhofen type range among the most famous conservation Lagerstätten. Historically, their environmental interpretation has changed from tropical beaches to quiet waters below storm wave base. Today, most experts agree that they formed in small basins, which received most sediment from surrounding reefs or carbonate platforms in the form of turbidity currents (Einsele and Seilacher 1991). Toxic bottom waters explain the unusual preservation of carcasses as well as the absence of autochthonous benthos, including scavengers. Fossils either sank down from the habitable upper part of the water column, or alternatively, they became washed-in (sometimes still alive) by turbidity currents. In addition, microbial mats enhanced fossil preservation, protected surfaces against erosion during subsequent events, and allowed the rock to be quarried for tiles. Details have been published in a vast literature (see Frickhinger 1999 and references therein).

Difficulties arise only when one tries to classify platy limestones in a genetic sense. On the one hand, there is no sharp boundary to bituminous shales formed under similar conditions, but in larger basins with less carbonate (Seilacher 1982). The other difficulty arises from

occurrences that share the same lithology, but formed under different environmental conditions. One of these non-fitting examples are the platy limestones of the Benkovac Stone in the Eocene of Croatia.

In the present context, the critical question is, whether the platy limestones of the Benkovac Stone were deposited above or below storm wave base, i.e., whether its event beds are tempestites or turbidites.

### Geologic setting

While Solnhofen-type platy limestones formed in small basins, the platy limestones of the Benkovac Stone crops out in the synorogenic foredeep of the Dinarid Mountain chain over an area more than 80 km along strike and up to 20 km wide (Fig. 1). It is part of a 2,000 m thick carbonate sequence (the Promina Formation) straddling the late Middle Eocene to Early Oligocene. Overall, this sequence is regressive, passing from a deep-water “Flysch” Formation to alluvial deposits formed by braided rivers. As their deltas were prograding to the SW, facies belts may be partly diachronic (Mrinjek et al. 2005, fig. 29).

Within the Promina Formation, one can distinguish: (1) the Korlat Unit (600 m) with classical turbidites and olistoliths; (2) the Debelo Brodo Unit (50 m) with thin interlayers of very fine-grained calcareous sand (turbiditic/geostrophic); (3) the Benkovac Stone Member (120 m); (4) the Otavac Member (>100 m) with lens-shaped limestone conglomerates and coarsening-upward cyclothems; (5) an alluvial part (Mrinjek et al. 2005).

### Sedimentology of the Benkovac Stone

Any geologist visiting the area of Benkovac near the Croatian coast is reminded of Solnhofen: old houses with large-angle gables still covered with the natural tiles; the landscape dotted with small quarries and adjacent piles of refused white rocks; pallets loaded with tiles ready for customers (Fig. 2).

While all sediments of the Benkovac Stone are calcareous, closer inspection contradicts the Solnhofen model in almost every respect. Except for occasional undeterminable plant remains and *Benkovacina* (see below), the Benkovac Stone contains no body fossils. Still, diverse trace fossils attest to a rich and autochthonous benthic fauna: large traces of brittle stars (*Asteriacites lumbricalis*; Fig. 3a) on upper, and small, backstuffed burrows (*Curvolithus*, presumably made by flatworms; Fig. 3b) on sole surfaces are still reminiscent of the shallow marine *Cruziana* ichnofacies (Seilacher 2007). The majority of the burrows, however, represent the *Nereites* ichnofacies otherwise

known only from siliciclastic deep-sea turbidites. One can also distinguish a pre-turbidite association, in which shallow burrow systems (mainly graphoglyptids) became excavated in the erosive stage of a turbidity current and cast in its depositional phase (Fig. 4). In contrast, post-turbidite burrows (*Nereites*, *Polykampton*, small *Thalassinoides*) colonized the sediment after the event and are preserved in full relief (Fig. 5). A phenomenon never observed in siliclastic turbidites is the occurrence of the graphoglyptid *Paleodictyon* on top surfaces (Fig. 6), and not only on the soles of event beds (Fig. 4a).

More unique features are epi- or hyporeliefs that, at first glance, might be mistaken for impressions of “flat clams” such as *Posidonia* and *Bositra*. Closer inspection, however (see Sect. 5), suggests that they are probably a kind of xenophyophores. These giant rhizopods lived in (or on) shallow marine biomats in Ediacaran times and survived as “living fossils” on modern deep-sea bottoms (see Fig. 9).

### Systematic palaeontology

Kingdom	Protista HAECKEL 1866
Phylum	Foraminifera D'ORBIGNY 1826
Class	Xenophyophoria SCHULZE 1904

*Benkovacina* n. gen.

2005 *Zoophycos*—Mrinjek et al.; fig. 26B

*Type species*—*Benkovacina concentrica* n. sp.

*Holotype*—GPIT 1917/6 (Fig. 8b)

*Paratypes*—GPIT 1917/5, 7,9,10 (Fig. 8a, c, d), YPM 227029-032. Large cast in the travelling exhibit “Fossil Art” of the GPIT.

*Occurrence*—Benkovac Stone Member, Promina Formation

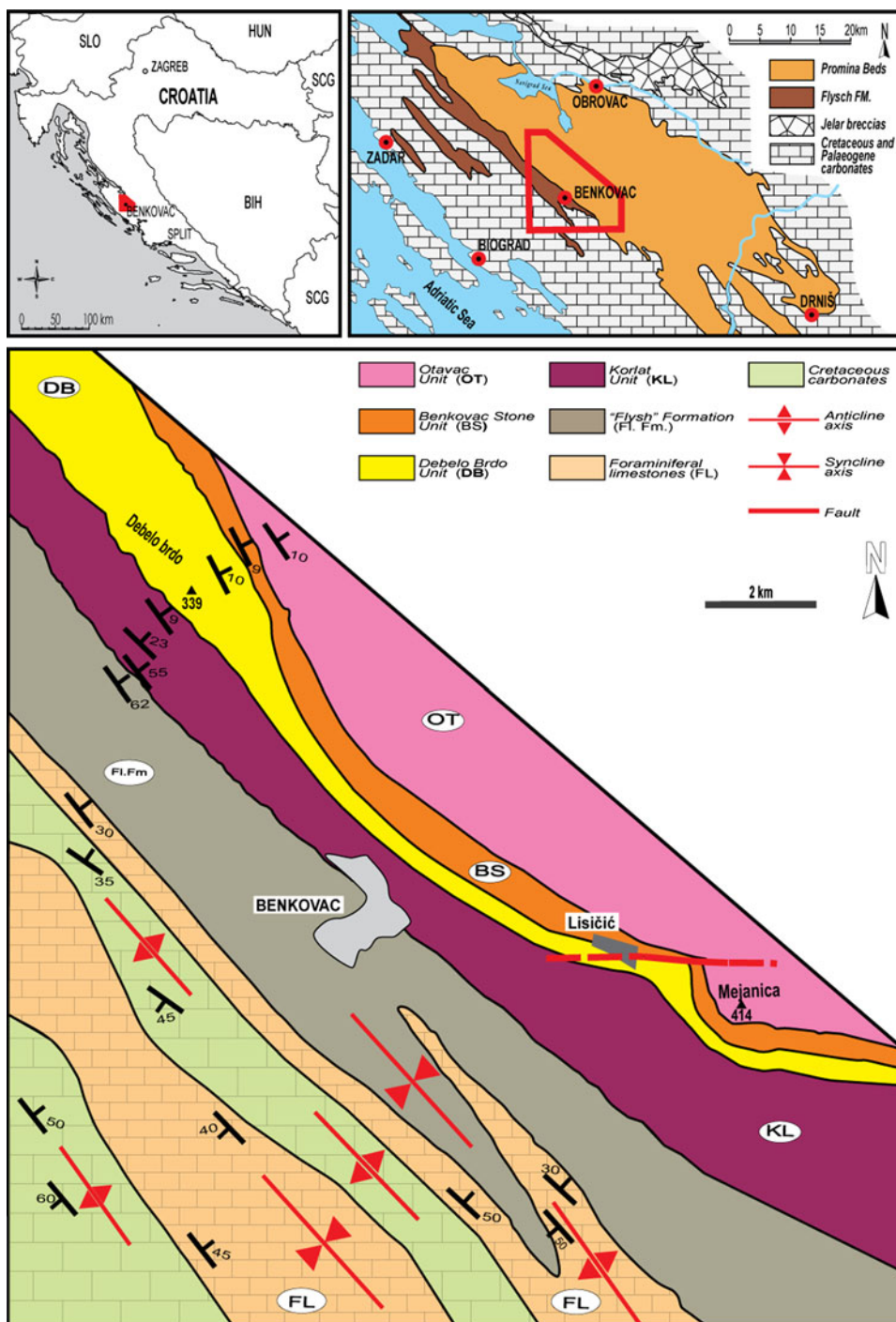
*Age*—Eocene

*Type region*—Benkovac, Croatia

*Description*—Supposed xenophyophore that was flatly attached to, or embedded in, former biomats. The narrow chambers are concentric, like growth lines of the bivalve *Posidonia*, but filled with sediment (stercomare) resembling the micritic matrix (Figs. 7, 8). After having reached the size of a coin, individuals developed either long lobes, or rows of new concentric arrays. Preserved on top as well as on sole faces of thin, calcareous, muddy turbidites.

*Remarks*—SEM studies by H. Schulz (Tübingen) revealed neither the characteristic baryte granules in the fill, nor agglutinated planktonic foraminifera in the wall. The preservation is probably due to the stercomare, which consisted of sediment taken up with the food and filled about 50% of the chamber volume. Therefore surfaces are

**Fig. 1** Geographical and geological setting of Benkovac and the Benkovac Stone in the synorogenic foredeep of the Dinarid Mountain chain. Modified from Mrinjek et al. (2005)



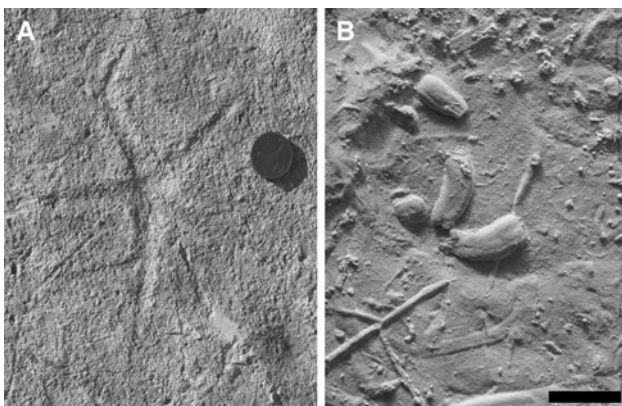
smoother, and contours sharper, than in associated trace fossils. Also, a backfill structure as in the trace fossil *Zoophycos* (Mrinjek et al. 2005) would have split in the middle plane.

Most present day xenophyophores are restricted to the deep sea (Tendal 1972). There is, however, a rich fossil record in siliciclastic laminites of Ediacaran times that were deposited in marine basins above storm wave base (Fig. 9). Unfortunately, phanerozoic examples are, so far, very rare.

Among them is a large specimen from laminated Devonian silts in Brazil (Fig. 9). It can still be affiliated with *Palaeopascichnus*, but for lack of field data, its paleobathymetric context is unknown. The next representative comes from Upper Cretaceous flysch deposits in Italy, the deep-sea origin of which is undisputed (Fig. 9d). In the latter case, the agglutinated chambers are subglobular and alternatingly arranged in a double row. As they contain a finer-grained and darker fill skeleton (stercomare), these fossils were



**Fig. 2** Pile with slabs of platy limestones of the Benovac Stone, and in the background an old house roofed by the same rock. Benkovac, Croatia



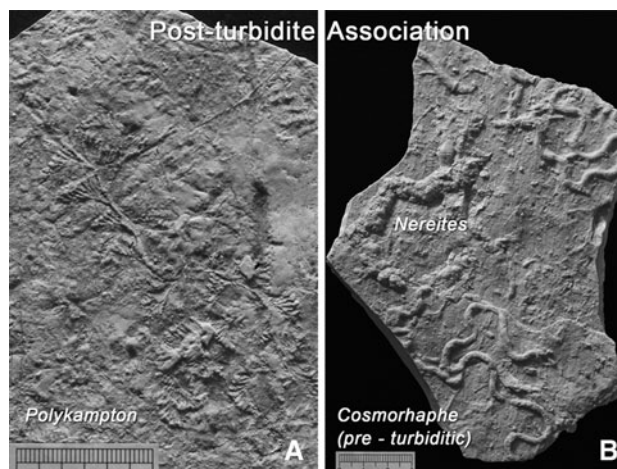
**Fig. 3** Trace fossils occurring in the *Cruziana* as well as the *Nereites* ichnofacies. **a** Epichnial resting trace of brittle star (*Asteriacites lumbricalis*) with branching arm impressions. Coin for scale. **b** Hypichnial backfill phantoms (*Curvolithus*) possibly made by a flatworm after the event. Scale bar 1 cm. Both photos taken in the field

formerly interpreted as plants or as burrows of sediment feeders. *Halysium* (Häntzschel 1975, p. W151) may be another xenophyophore.

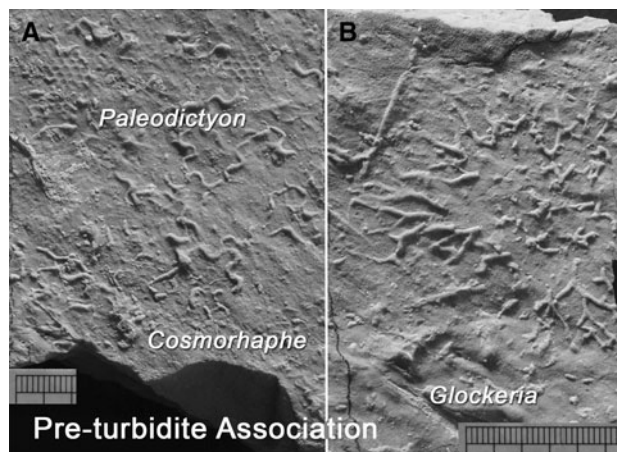
In this context, the well-preserved and abundant body fossil *Benkovacina* becomes an important link between Recent and Precambrian xenophyophores. When exactly these protists invaded deep-sea bottoms and became extinct in shallower environments (“onshore/offshore trend” of Bottjer et al. 2000), just as graphoglyptid trace fossils, is unknown. This shift probably took place in Early Paleozoic times.

### Discussion: is Benkovac a deep-sea lithographic limestone?

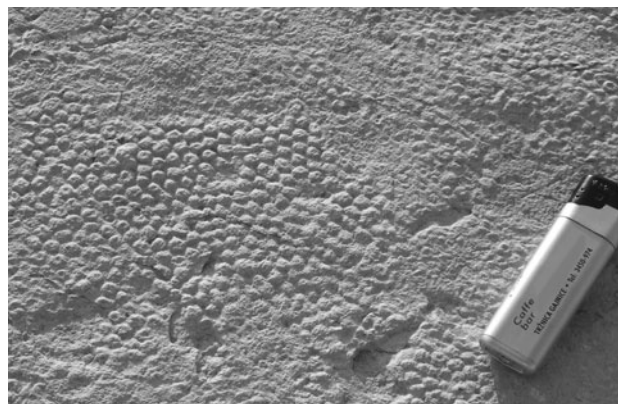
So far, the Benkovac Stone has been interpreted as part of a shallow-marine carbonate platform on the basis of



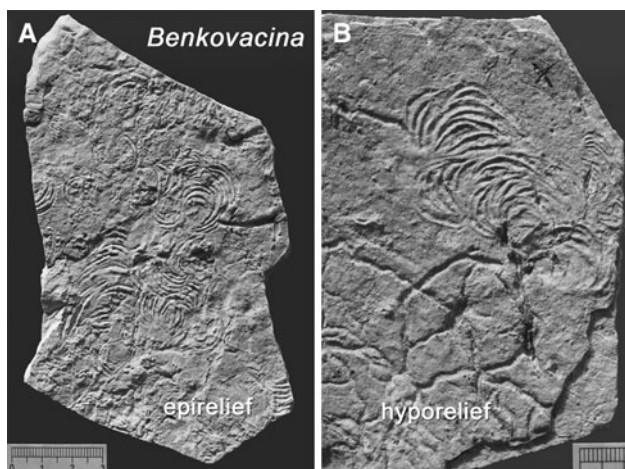
**Fig. 4** Burrows of the post-turbidite association, Benkovac Stone, Benkovac, Croatia. **a** *Polykampton* (top face). Scale bar in cm. **b** *Nereites* (sole face) associated with pre-turbiditic *Cosmorhaphe*. GPIT 1917/1-2. Scale bar in cm



**Fig. 5** Washed-out pre-turbidite graphoglyptid burrows on sole faces, Benkovac Stone, Benkovac, Croatia. **a** *Cosmorhaphe* and *Paleodictyon*, GPIT 1917/3. Scale bar in cm. **b** *Glockeria*, GPIT 1917/4. Scale bar in cm



**Fig. 6** Negative epireliefs of post-turbidite *Paleodictyon* on top faces, Benkovac Stone, Benkovac, Croatia. Photo taken in the field, lighter for scale



**Fig. 7** *Benkovacina concentrica* n. gen., n. sp., Benkovac Stone, Benkovac, Croatia. **a** On top face (epirelief) GPIT 1917/5. Scale bar in cm. **b** Holotype on sole face (hyporelief), GPIT 1917/6. Scale bar in cm

sedimentary structures speaking for direct storm influence such as: (1) rare surfaces with oscillation ripples; (2) hummocky cross stratification; and (3) conglomeratic layers (Mrinjek et al. 2005). However, the ichnological evidence contradicts traditional views. How can this dilemma be resolved?

On the one hand, oscillation ripples and hummocky cross stratification may not be as infallible criteria of wave action as is commonly thought. Seismic shock waves, for

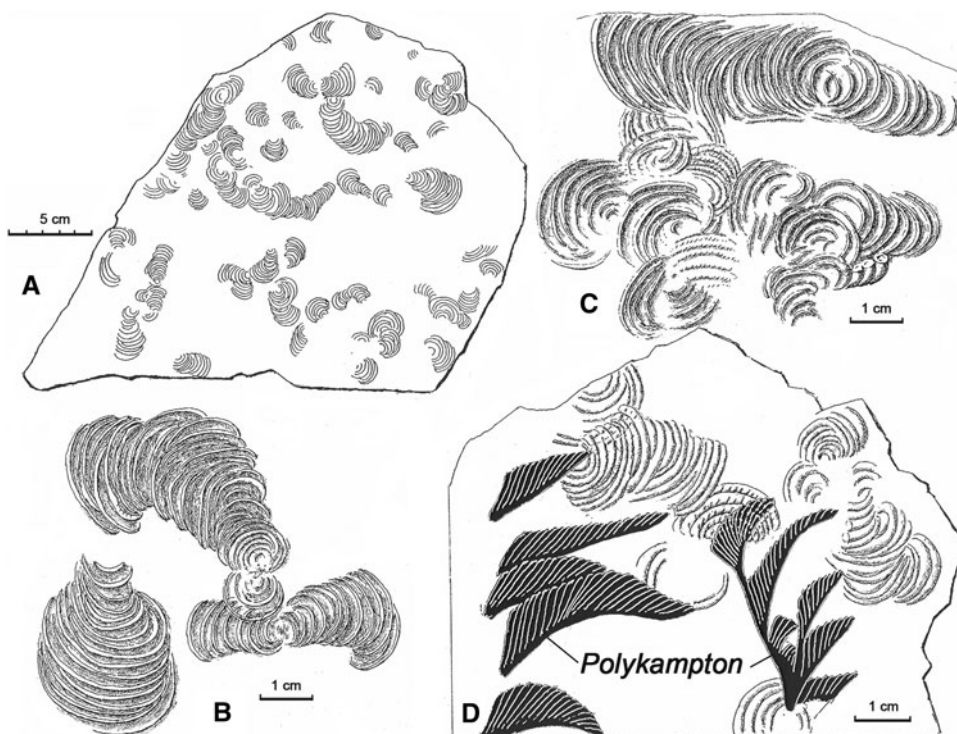
instance, might produce oscillation ripples at any depth. Also, the subspherical carbonate pebbles in the “conglomerates” might as well be early concretions reworked from carbonate muds by turbidity currents.

Neither are trace fossils infallible depth indicators. Ichnofacies reflects a combination of ecological and preservational conditions rather than water pressure (Seilacher 2007). It is not impossible that these conditions may exceptionally be met at depths of hundreds rather than thousands of meters. So the Benkovac area would be an ideal place to test the validity of both the sedimentological as well as the ichnological palaeobathymetric tools. The absence of shelly body fossils (including larger foraminifera and the calcitic oysters), which were common on shallow Eocene soft bottoms, sets another limit. For the time being, the most parsimonious interpretation would be that the Benkovac Stone is part of a shallowing-up Eocene sequence, which starts with a flysch unit and ends with shallow-marine carbonates (Mrinjek et al. 2005). Palaeobathymetrically, it probably ranged somewhere between the two end members, but was certainly deposited in a deeper basin than lithographic limestones of the Solnhofen type.

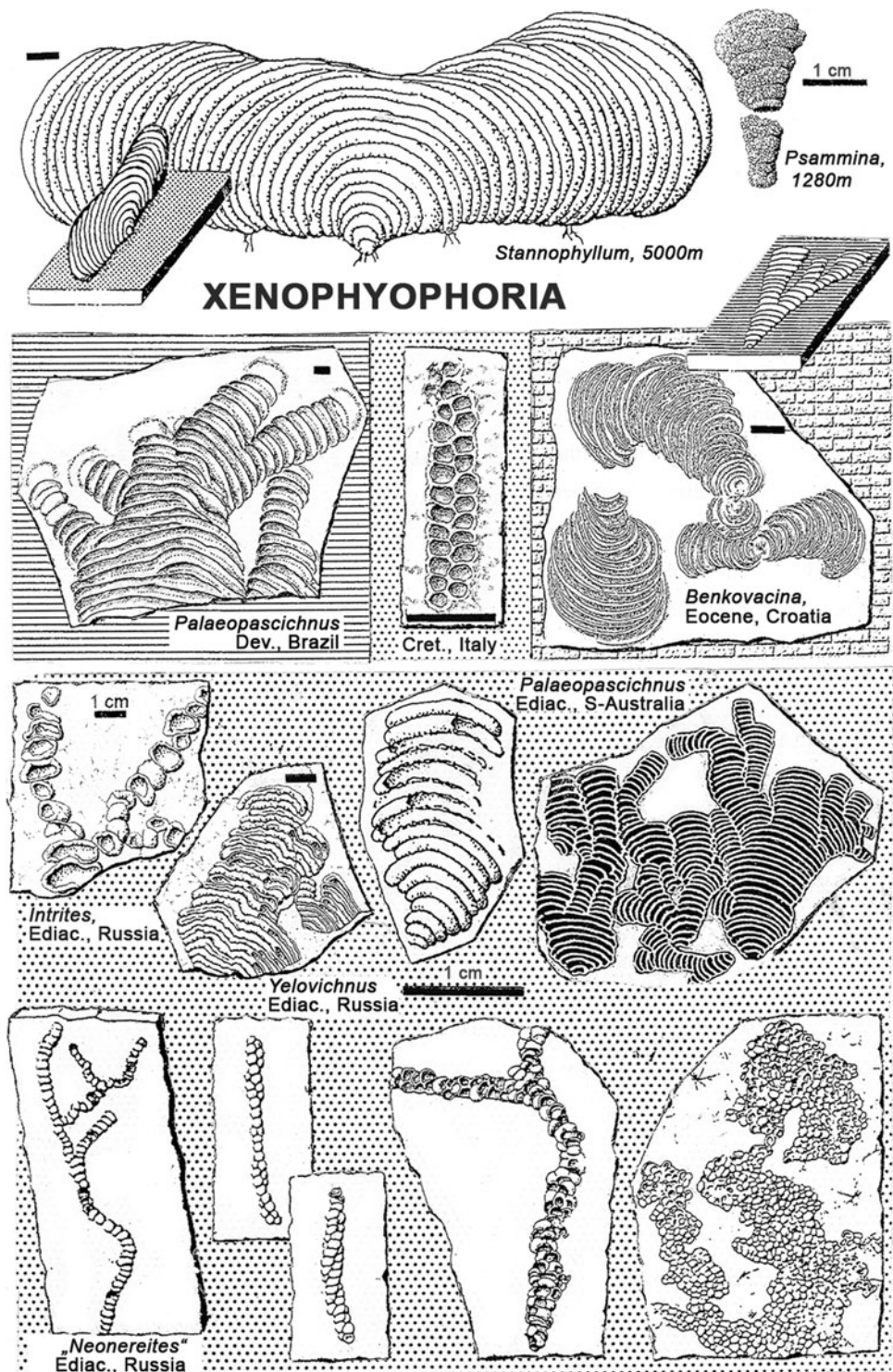
#### The role of microbial mats

Microbial mats, presumably cyanobacterial, were ubiquitous on shallow Precambrian sea bottoms (Bottjer et al.,

**Fig. 8** Drawings of *Benkovacina concentrica* n.gen., n.sp., Benkovac Stone, Benkovac, Croatia. **a** GPIT 1917/7. **b** GPIT 1917/8. **c** GPIT 1917/9. **d** GPIT 1917/10 intercut by *Polykampton* burrows



**Fig. 9** Large xenophyophorian rhizopods appear to have lived on shallow-marine bottoms in Ediacaran times (*lowermost block*). During the phanerozoic (*middle block*) they retreated into the deep sea, where several genera survive today (*uppermost block*). The lack of overcrossings in all fossil forms (including *Benkovacina* n.gen.) suggests that they were flatly attached to, or embedded into, microbial mats (*right block diagram*). In contrast, modern *Stannophyllum* is rooted in an upright position (*left block diagram*). All scale bars are 1 cm. In the Ediacaran group, the scale bar in the centre applies to all drawings except *Intrites* and *Yelovichnus*. Modified from Seilacher et al. (2003), *Intrites* and *Yelovichnus* drawings by Anton Legouta



2000). In Ediacaran times, they became so tough, that large organisms (Vendobionta) got attached to them by basal disks (Seilacher 1999). In the form of thin films, bacteria also formed "death masks" of soft-bodied carcasses; a kind of preservation that became extinct after the Cambrian Substrate Revolution (Gehling 1999; Bottjer et al. 2000). This global event, caused by increased

bioturbation in response to the onset of macropredation ("Verdun Syndrome" of Dzik 2004), restricted the development of consistent biofilms and biomats to environments hostile for benthic animals. On anoxic basin and lake bottoms, as well as in short-lived pools and some inter- or supertidal environments, microbial mats may develop at the present day.

In Solnhofen, the original presence of microbial mats is documented by geopetal rip-ups and elephant-skin structures. Sticky mats are also responsible for the preservation of soft parts (such as *Archaeopteryx* feathers) and of the undertracks of animals washed-in alive by turbidity currents, with the trace makers themselves having become buried a few millimetres higher within the turbidite layer (mortichnia, Seilacher 2007).

A more fundamental effect of the mats in carbonates, however, is often forgotten: They probably served as a separating agent between laminae that otherwise would have become welded during diagenesis. Without the mats, platy and lithographic limestones could not be as easily quarried. In this respect, the Benkovac Stone has an intermediate position. Tiles of adequate thickness can still be quarried; but in cross-section they may show additional event laminae that did become diagenetically welded. This situation can be interpreted in two ways: (1) sedimentational events (muddy turbidity currents) were so frequent that separating mats could develop only during longer quiet intervals, and (2) microbial mats developed only during anoxic events in an otherwise aerobic or dysaerobic environment. Such events would have been responsible for the preservation of trace fossils made during more oxygenated periods, and for the development of the mat-related xenophyophore *Benkovacina*. This model, however, does not explain the absence of phosphatic vertebrate remains, of aragonitic and calcitic shells, and of the calcitic ossicles of ophiuran echinoderms, whose presence is documented by trace fossils (Fig. 3a). Neither can it be applied to sole faces with graphoglyptid burrows. They had to be uncovered by erosion before becoming cast in the depositional phase of the same turbidity current (Seilacher 2007). So splitting at the base of a turbidite cannot be due to the development of a microbial mat.

A critical question concerns the *bathymetric* significance of microbial mats. In shallow water, their main constituents are Cyanobacteria and their extracellular mucus and as photosynthesizers they are restricted to the photic zone. Microbial mats, however, may contain a variety of organisms. So it should be no surprise that well-oxygenated deep-sea muds near the mid-Atlantic Rift are covered with a thin crust, which peeled off as minute tablets when modern *Paleodictyon nodosum* and other graphoglyptic burrow systems were experimentally eroded (Rona et al. 2009). This means that mats and low-grade bioturbation can coexist in well-balanced ecological systems.

## Conclusions

In practical terms, lithographic limestones and Plattenkalk share the possibility to quarry them as tiles. This quality is

probably due to the original presence of microbial mats. They inhibited the diagenetic welding of event layers, which would otherwise have taken place. As microbial mats and laminated rocks can form in different environments (shallow sea; deep sea; lakes), and in different lithologies (carbonates and bituminous shales), it is very difficult to consistently classify lithographic and platy limestones in a genetic sense.

The Benkovac Stone differs from other platy limestones by: (1) the absence of body fossils (except for the probable xenophyophore *Benkovacina concentrica* and occasional plant debris); and (2) abundant trace fossils reflecting a diverse bottom life at least during oxygenated periods. As the traces belong to the *Nereites* ichnofacies, a deep-sea origin is an alternative hypothesis to the shallow-marine interpretation based on the sedimentary structures.

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