On the Origin and Diagenesis of the Bituminous Posidonia Shale (Toarcian) of Southern Germany

by

KLAUS BANDEL, Hamburg & HARRY KNITTER, Freiburg*)
With 27 Figures

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Abstract

From sections studied in Unterstürmig and Hetzles, north of Erlangen in Franconia, the depositional history of the Toarcian oil shale is reconstructed. Posidonia Shale originally consisted of a soft fecal pellet mud with abundant remains of planktonic organisms and indistinct bedding. This sediment was usually deposited under aerobic conditions and only rarely bottom water was free of oxygen. Within the deposits, concretions formed at different times sealing and preserving subsequent stages of compaction and particle dissolution. The course of diagenesis can be unraveled and revealed a compaction from 40 to 1, thus of 100 m of mud into 2.5 m of shale, now with laminar, distinct bedding.

Base and top of the oil shales consist of shallow-water deposits that are the result of erosion during regression and biological activity following transgression. The fauna now found in different beds of the Posidonia Shale is as much the result of planktonic and benthic communities living in the Toarcian Sea as of the diagenetic history of the shales, marls and limestones. Deposition occurred on a shallow epicontinental shelf flooded by nutrient-rich, upwelling water for less than 1 million years.

*) Addresses of the authors: Prof. Dr. K. BANDEL, Geologisch-Paläontologisches Institut und Museum, Universität Hamburg, Bundesstr. 55, D-2000 Hamburg 13; Dr. H. KNITTER, Geologisches Institut, Universität Freiburg, Albertstraße 23b, D-7800 Freiburg i. Br. Federal Republic of Germany.

Zusammenfassung

Die Analyse der Posidonienschiefer-Profile von Unterstürmig und Hetzles (Nordostfranken) ermöglicht eine Rekonstruktion der Ablagerungsbedingungen dieses Ölschiefers des Toarciums (Unterer Jura). Ursprünglich bestand das Sediment aus einem weichen Kotpillen-Schlamm mit zahlreichen Gehäuseresten planktonischer Organismen. Der Schlamm setzte sich vornehmlich im aeroben Milieu ab, nur selten herrschte über dem Boden Sauerstofffreiheit, im Boden allerdings war Sauerstoff schon direkt unterhalb der Oberfläche aufgezehrt. Innerhalb der Ablagerungen bildeten sich zu verschiedenen Zeiten Konkretionen, die den jeweiligen Zustand des Sedimentes fixierten.

Es erweist sich, daß Kompaktion und Lösung zu einer Volumenverringerung von 40 zu 1 führten, so daß für die heute vorliegenden 2.5 m Ölschiefer 100 m Schlamm abgelagert werden mußten und zudem eine undeutliche bankige Schichtung sich in feine, scharfe Lamellenschichtung wandelte.

Die Ölschiefer werden von Flachwassersedimenten unter- und überlagert, die während der Abtragung von Sedimenten bei der Regression und der biologischen Aktivität von Organismen nach erneuter Transgression entstanden. Die in verschiedenen Lagen des Posidonienschiefers auftretende Fauna ist sowohl das Ergebnis planktonischer und benthischer Lebensgemeinschaften im Toarc-Meer als auch der Diagenesegeschichte der Posidonienschiefer. Die Ölschiefer lagerten sich in einem etwa 50 m tiefen Schelfmeer während eines relativ kurzen Zeitraumes (weniger als 1 Million Jahre) ab, zu dem der Tethys Ozean im Süden mit dem arktischen Meer im Norden in Verbindung trat und nährstoffreiches Auftriebswasser für hohe Planktonproduktion sorgte.
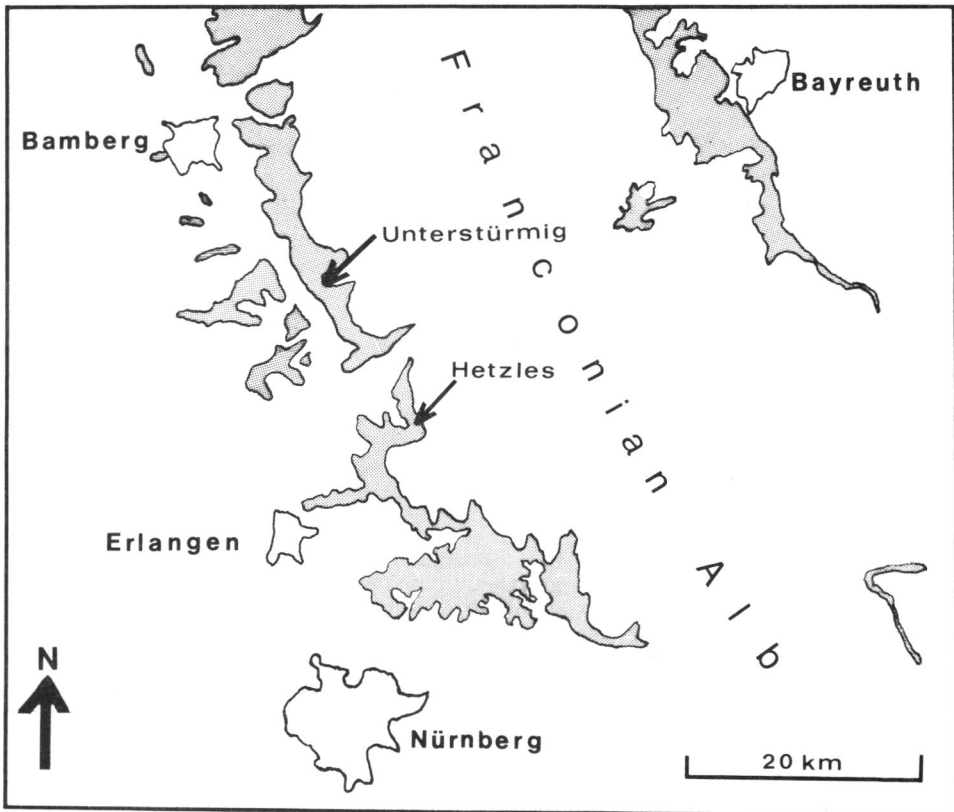
Fig. 1: Map with localities of studied sections indicated.

1. Introduction

The Lower Toarcian Posidonia Shale has been studied many times, especially regarding problems of its sedimentology or faunal content. The tradition of scientific investigations of these oilshales goes back into the last century (e. g.QUENSTEDT, 1858). Several more recent works deal with sedimentological and palaeontological problems (e. g. BIRZER, 1936; MÜLLER & BLASCHKE, 1969; BRENNER & SEILACHER, 1978; URLICHS et al., 1979; KAUFFMAN, 1981; KEUPP, 1981; BANDEL & KNITTER, 1983; RIEGRAF et al., 1984, RIEGRAF 1985; JENKYNS, 1985). KNITTER (1983) treated the problem of Posidonia Shale facies of the Lower Toarcian in its widespread occurrence all over Europe as well as other regions. The models of the origin of the Posidonia Shales suggested in literature reach from a totally anaerobic sea, like the modern Black Sea, to a well oxygenated sea with anaerobic conditions only within the sediment.

The good exposure of Posidonia Shale in a Northern Bavarian section near the small village of Unterstürmig about 30 km north of Nuremberg/Bavaria (Fig. 1) provided the opportunity to study many sedimentary and diagenetic features within this one outcrop and correlate them with sections of Posidonia Shale in Southern Germany and also in other regions. In another outcrop at Hetzles just about 18 km to the SSE, the topmost layers are better developed and can be included with this description (Fig. 3).

2. Description of the Unterstürmig Profile

The base of the Posidonia Shale is well exposed in the claypit of Unterstürmig (Fig. 2). It consists of a conglomerate overlying fossiliferous grey marls of Upper Pliensbachian age. This conglomerate, the „Bollernkalk" (BANDEL & KNITTER, 1983), consists of nodules of micritic limestone with a diameter of up to 20 cm. These nodules („Bollern") lie within a matrix of coarse arenaceous limestone. Other components (besides the „Bollern") are calcareous intraclasts and rostra of belemnites. Pyrite may impregnate components and matrix. The thickness of the Bollernkalk-member can be up to 25 cm and locally shows a great variability. Nodules as well as other components have been bored by different organisms. The faunal contents of the surrounding sand of the matrix consist of foraminifera, ostracods, bivalves, gastropods, cephalopods, rare brachiopods and echinoderms. Bivalves clearly lived between the nodules as well as attached to them by cementation (e. g. oysters) or by byssus (e. g. pectinids). Other thick-shelled bivalves occur, too, some arcids, e. g. pectinids, oysters and, some heterodont species, and large archeogastropods, such as pleurotomariids. The sand fraction of the matrix is composed mainly of echinoderm debris and microfossils.

The nodules are reworked geodes from Upper Pliensbachian marls. Evidence of this consists in the occurrence of Upper Pliensbachian ammonites within them. Three types of borings can be distinguished in the nodules and in the bioclasts. The first type consists of 3 to 6 mm wide, non-branching tubes that have a micritic calcareous layer at their walls. Their apertures to the surface are narrower than the actual tubes, and the inner ends are rounded. This could have been brought about by endolithic bivalves (Fig. 4).

The second type of borings consists of 2 to 3 mm wide chambers which are connected with each other by narrow tubes. Thus, a network of tubes and chambers perforates the entire nodule and it may make it look like structures known from modern boring sponges like *Cliona* (Fig. 5).

The third type of borings has a diameter of up to 1 mm and shows irregular and branching tracks. It also occurs in bivalve shells and belemnite rostra and in
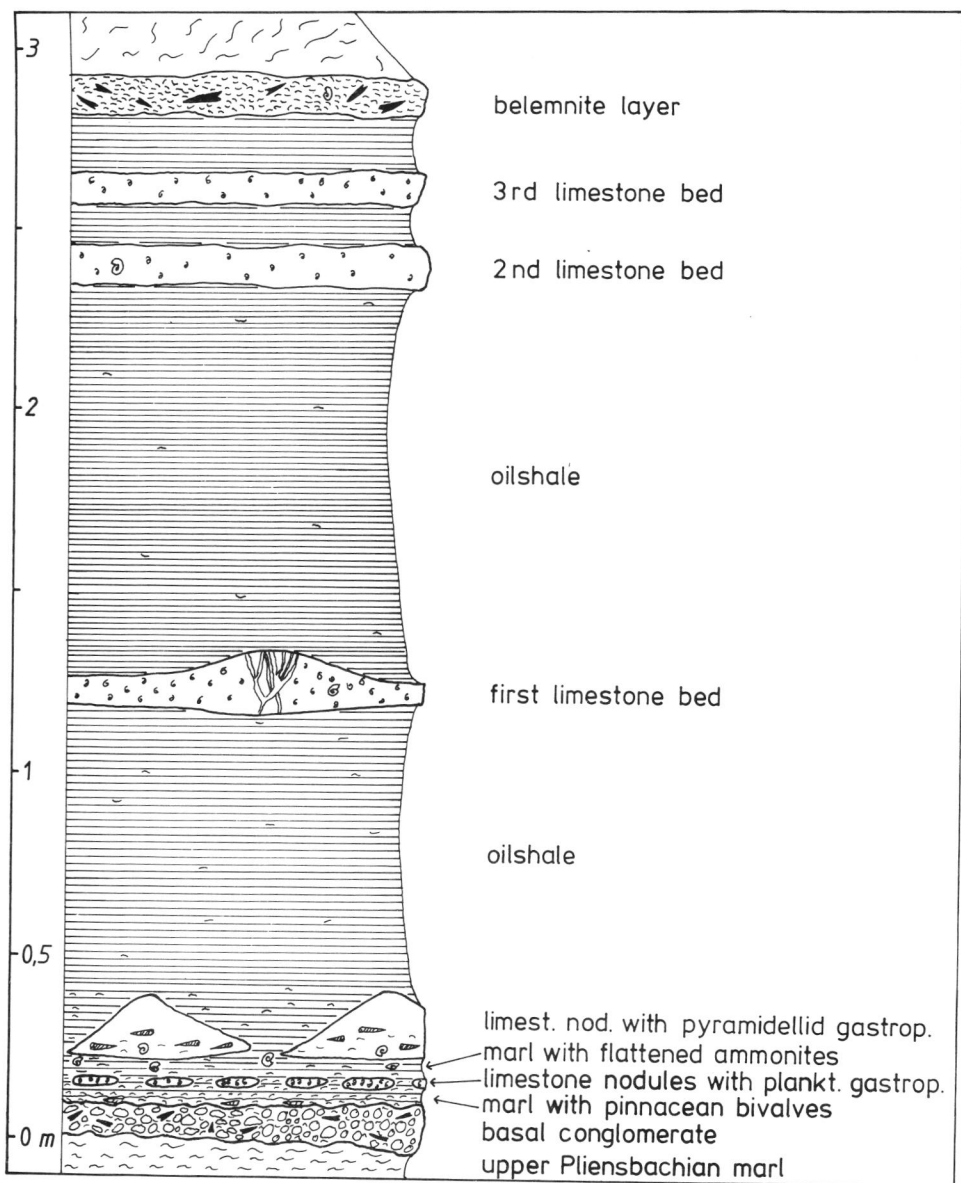
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Fig. 2: Profile at Unterstürmig

other remains of organism. The tracks resemble borings like those produced by endolithic algae or fungi (Fig. 6).

The Bollernkalk-member is a horizon of reworked material from the Upper Pliensbachian strata below, probably representing the *Dactylioceras tenuicostatum*-zone, the lowest ammonite zone of the Toarcian. Other sediments of this zone which occurs in several South German sections, cannot be identified by ammonites in Franconia. Reworking occurred within the sea by agitated water, so that objects could be bored at all surfaces, and sediment became strongly bioturbated. Burrows of bottom living organisms, probably crustaceans, even reach into the top of the marls below producing tubes that filled up with the

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characteristic sand of the Bollernkalk-member above. The amount of bituminous components in the matrix is low at the base of the Bollernkalk, but it increases towards its top. Preserved burrowing structures show that the bituminous material was mixed in as a result of the activity of vagile endobenthic organisms when they entered the conglomerate from above.

Above the Bollernkalk-member bituminous shale follows with a sharp transition. The irregular surface of the conglomerate cannot entirely be equated with this lithologic unit, which is only 3 cm thick. The characteristic fossil within this layer is a pinnacean bivalve about 20 cm long. Its valves lie flat within this highly compacted sediment. Other fossils are ammonites of different sizes and shells of *Inoceramus*-type bivalves. The orientation of the ammonites shows that they originally were embedded vertically, obliquely, or horizontally, and now lie flattened in the bedding plane like the bivalves. Other fossils or their fragments include aptychi, attached worm tubes and inarticulate brachiopods, bones and teeth of vertebrates and logs. Many of the larger ammonites have been embedded as fractured shells and pieces of wood became strongly flattened.

In thin sections this layer shows laminae of about 0.2 to 0.5 mm thickness. They have a wavy surface and extend over a distance of only about 5 cm. All fossils are compacted. Flattened molluscan shells may lie obliquely, crossing several laminae, thus indicating that they were embedded in vertical or inclined position to the laminae, but not parallel to them.

The uppermost part of the preceding member may be substituted by flat round limestone lenses up to 25 cm in diameter and 5 cm high. They contain numerous small gastropods and have a strong odor of bitumen. Because of these features this member was called "Schneckenstinkstein" (i. e. stinking stone with snails) by QUENSTEDT (1858). Within this limestone the topmost pinnacean bivalves are present. Top and base of these nodules often consist of a big ammonite or a driftwood log. Stratification is always weakly developed within the limestone and cannot be traced laterally into the marly shales. Compaction is absent even in very thin-shelled organisms. Ammonites of all sizes are embedded in various directions from vertically to horizontally to the bedding plane and are not flattened, while laterally within the shale they are totally flattened and small individuals are not preserved. Also in the shales just beside it no trace of the many gastropods found inside this "Schneckenstinkstein"-layer is preserved.

In thin sections the sediment resembles a peloidal packstone with fecal pellets only slightly deformed. Spaces between the micritic pellets are filled by spar. Small spar-filled round particles are present, which might represent radiolaria, which have been also noted in other sections (RIEGRAF, 1985). Conches of gastropods of all ontogenetic stages are filled by calcite. Fine-grained pyrite is distributed throughout the limestone lenses (Fig. 7).

The following member is characterized by a very smooth and horizontal stratification, a good cleavability and of many flattened ammonites and inoceramids. Pinnacean bivalves are not found. The lower 2 cm contain many large ammonites, while ammonites in general become rarer further up and usually occur in smaller sizes.

In thin sections and cuts the sediment shows a laminaceous bedding. Fossil remains are extremely compressed and may extend through several laminae.

The highest parts of the preceding member are occasionally substituted by large limestone nodules with the thickest part (about 30 cm) in their middle. The tops of these nodules are more convex than their bottoms. The small gastropods

characteristic of the "Schneckenstinkstein" can only be found in rare thin layers together with many small ammonites. In central layer within the nodules, which is about 4 cm thick, a small trochospiral gastropod is common. This snail was first thought to be a cerithiid mesogastropod (BANDEL & KNITTER, 1983) but since has been reinterpreted to represent a pyramidellid snail. This has ecologic consequences, as will be described further below. Together with these snails ammonites, fish remains and bivalves (especially *Pseudomonotis* and *"Inoceramus")* occur (Fig. 8). Often driftwood and large ammonites are partially or totally integrated in the top of the limestone lenses.

In the central parts of the nodules remains of molluscs are not compressed, but towards the edges deformation increases, and in the lateral shales only totally flattened fossils can be found (Fig. 9). The central layers of these nodules are only indistinctly stratified. The upper parts show a fine lamination which can be traced into the lateral shales. The 4 cm thick central layer is not stratified within the nodules, but thins continuously towards the margin of the nodules and finally extends as a ca. 0.7 cm thin, finely laminated bed in the surrounding shales (Figs. 10 and 11).

Thin sections demonstrate that the original particles may be preserved undeformed within the sediment fillings of ammonites or "inoceramids" fixed to driftwood. The consist of grey, micritic and brown, bituminous fecal pellets and small fossils filled with calcite. Among them small gastropods are present. Spaces between these components are filled with calcitic cement (Fig. 12). Outside the areas sheltered by thicker shells alterations of the sediment can be observed. Shells of larger molluscs and vertebrate remains are not or only slightly deformed, but sediment around them shows fluid structures. Small circular microfossils (radiolaria?) have vanished completely or are strongly compressed, and small gastropod shells have vanished as well. The pellets have become deformed in different ways in relation to their original composition. Micritic pellets are compacted to half of their original height, whilst the brown organic ones are flattened to tiny flags (Fig. 13). In the central bioturbated layer the number of brown, organic pellets is smaller than in neighboring stratified layers. While here no stratification can be seen indistinct stratification of layers in cm-thickness occurs above and below it. At the edges of the nodules this indistinct stratification becomes narrower and can be traced into the nearby shales. Also, fossil remains become compacted so that the shells are fractured and their fillings compressed. A layer of driftwood of 4 cm thickness within the nodule thus is compacted to 3 mm thin layer at the most.

Dehydration of the central layer of the nodules resulted in open fissures in the laminated area above followed by infill of mud. Fissures cannot only be found in the limestone nodules but also in the nearby shale. Therefore they have formed prior to the nodules, i. e. before the compaction of the lateral marls.

Within the nodules small mollusc shells have been dissolved, whereas bigger ones were cracked. Primary calcitic shells, like the outer prismatic layer of *"Inoceramus",* are preserved with their original structure, whilst aragonitic parts of the shells recrystallized after deformation and fracturing (Fig. 14).

Oilshales follow above these nodules consisting of 2.10 m of finely lami- nated, evenly cleavable, bituminous marly shales. Fossils are relatively rare. Ammonites, sometimes with aptychi, coleoids, often with inksac, bivalves, vertebrates, often with bones connected to each other, and larger coprolites can be found. Thin layers may contain endobenthic bivalves as well as *Pseudomonotis.* The oilshale is intercalated by three limestone beds.

The first limestone bed occurs above an about 90 cm thick pack of oilshale and has a thickness of 12 to 25 cm. Actually, the bed consists of huge flat
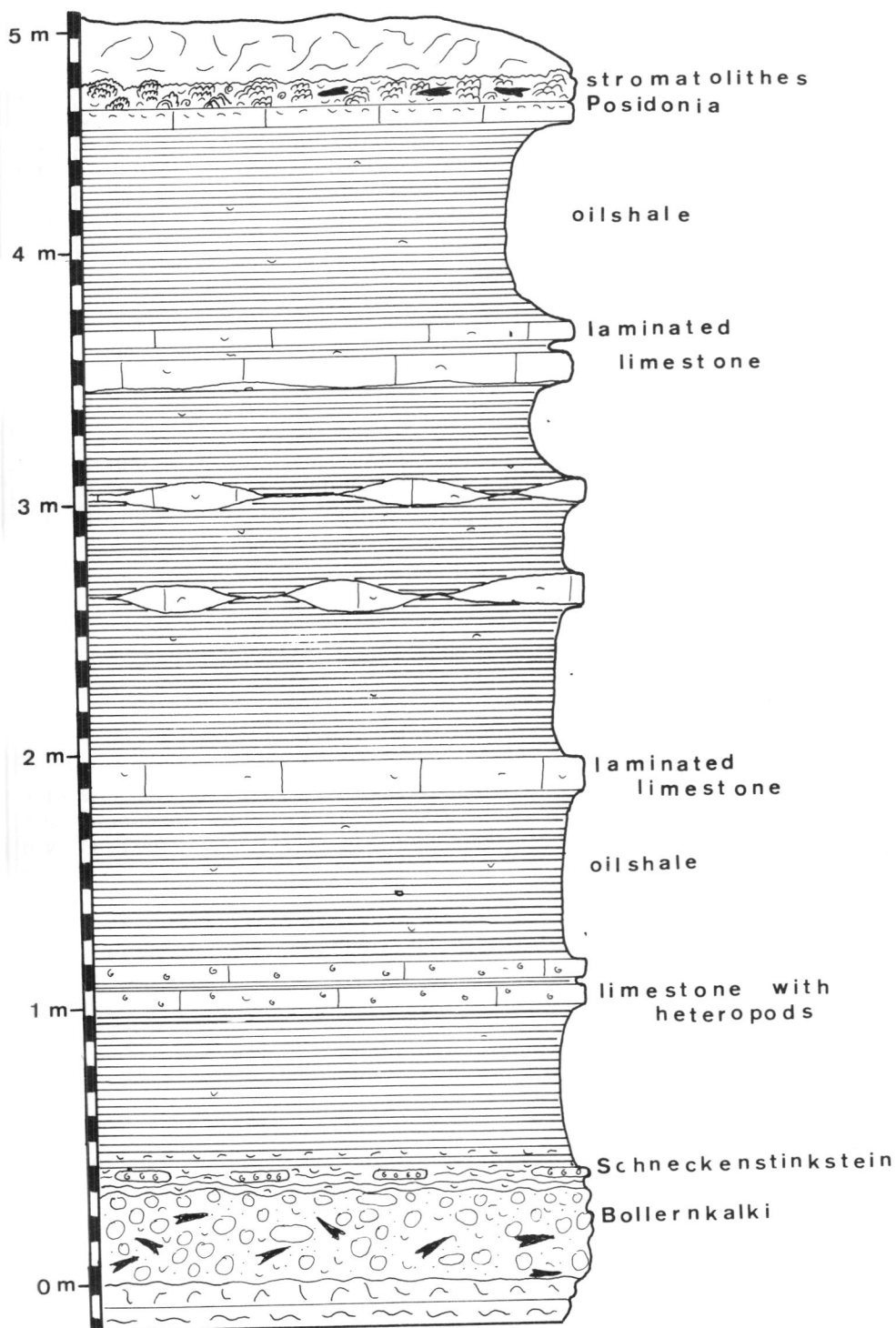
Fig. 3: Profile at Hetzles

limestone lenses of more than 2 m in diameter. Their thicknesses correspond with 1 cm of shale, and the indistinct lamination inside this limestone-lens can be traced into the shale. Weathered limestone appears like yellowish sand. In fresh fracture it is greyish and smooth with a strong odor of bitumen. Small gastropods are distributed randomly within the rock, and *Goniomya* with both valves connected occurs. In the middle part of the limestone bed ammonites are not compressed, while the less common coleoids (loligosepiids) and crustaceans are completely flattened. The limestone layer is commonly fractured by fissures, ending in small cones at the surface of the bed. Probably they are dehydration structures that formed at a time when the shells had not yet been cemented in the mud. Fissures, that come in contact with shells do not fracture them but run around them. Cracks have reopened after first filling, and several generations of cracks may cross each other. They contain cements as well as fragments of slightly consolidated sediment. The sediment components of the fissures seem to have been of a jelly like consistence, so that younger generations of fissures could easily form. They clearly represent structures formed during dehydration of the limestone bed and strata below and above (Fig. 15).

The other two limestone layers are of more regular thickness than the first one, but in their composition and faunal content they are similar. In thin sections they resemble the "Schneckenstinkstein", but pyrite is lacking and small snails are less frequent.

The top of the profile is formed by an 8 cm thick bed of arenaceous limestone containing a lot of belemnites. This belemnite layer consists mostly of broken "*Inoceramus*" shells and whole shells of *Pseudomonotis*. Sediment preserved in the alveoles of belemnites show that it consisted of loosely packed biogens and a fine-grained matrix (Fig. 16).

In Hetzles the upper limestone beds are much more laminated than the beds of a similar position in Unterstürmig. Their fossil content is similar to that of the shales. Just below the uppermost limestone bed platy marly limestone shows numerous *Posidonia* shells which had been absent below. This limestone also consists mainly of broken parts of bivalves like *Posidonia* and "*Inoceramus*" (Fig. 17). It is sharply truncated (Fig. 18) and has served as growth surface for stromatolites forming pillow-like structures of about 15 cm in diameter and a few cm in height. Growth structures of these organic buildups are well visible in polished slabs (Fig. 20) as well as in thin sections (Fig. 19) because of terrigenous stains. During growth small pinnacles and mounds have formed and grown on the limestone surface as well as on belemnites, mud intraclasts or broken ammonites. The stromatolites show desiccation cracks, which commonly are healed by laminae (Fig. 21). The micritic sediment between the stromatolite knolls contains foraminifera as well as spines of *Diadema* like seaurchins and coated grains resembling recrystallized ooids. Larger fossils like ammonites, bivalve shells and belemnites are usually strongly bored and incomplete. Heavy belemnites as well as mud intraclasts have been deposited on top and between the stromatolites and have, in part, been included into the stromatolitic structures. Small tubes, like those produced by polychaete worms, often are found integrated into the stromatolite pinnacles and have grown with them. Fissures are filled with pelloidal calcareous mud and cellular bioclasts. Small gastropods like those of the limestone beds in Unterstürmig are very rare. Some stromatolites have become bored (Fig. 22).

3. Sedimenation and Diagenesis of the Posidonia Shale

From sediment composition and structure of the different rock types between the basal conglomerate and the marls containing pinnaceans on the one

hand, and the belemnite layer and the stromatolitic top bed on the other, seven steps of sedimentary and diagenetic processes could be deciphered.

(1) The original sediment consisted of limy mud, organic material and clay. The clay can be derived from more or less distant land. Driftwoods came from the same source. These terrestrial components are mixed with organic and calcareous matter produced in the sea. The resulting sediment is a calcareous mud with high contents of organic matter. The fine-grained calcareous matter consists entirely of calcareous nannoplankton (coccoliths, *Schizosphaerella* and others). Zooplankton and -nekton consist of gastropods, larvae of bivalves, cephalopods, vertebrates and so on. In addition, huge amounts of shells of pseudoplanktonic bivalves (like *"Inoceramus"*), fixed to driftwood, and less frequently oysters cemented to ammonite shells contribute to the sediment.

(2) The sea bed normally is so soft that bigger organisms may sink into it completely or partially. In this way ammonites can be embedded vertically or obliquely. The colonies of byssate bivalves attached to drifting wood also sink into the sediment, when the wood saturated with water becomes too heavy, and grounds. Fishes, reptiles and coleoids become embedded totally in this soft mud, too, when their corpses sink to the bottom. Incompleteness of fossils of fish and missing heads of squids (fossil *Vampyromorpha*) suggest that both had died due to attack and had partly been eaten. The sediment particles are fecal pellets, derived from planktonic organisms in the water column.

(3) The soft water-saturated sea bed is settled by a specialized fauna of soft-bodied endobionts, bioturbating the sediment from its surface to about 10 cm depth. The organisms are of small size, so that only small sediment particles are effected by their activity. The softness of the sediment is not or only slightly altered during this process, but primary lamination, if present, becomes destroyed. In this mud only those animals can live who can gather their breathing water from the water column above the sediment. The pore water is completely anaerobic just below the sediment surface, due to its high contents of organic matter.

(4) In case of decreasing sedimentation rate, the sea bed becomes more consolidated. It becomes dehydrated and more strongly bioturbated, and, therefore, life conditions improve. Now, together with the worm-shaped specialists, a fauna of siphonate bivalves (e. g. *Goniomya* and *Solemya)* can settle. The small gastropod mentioned above has been proven to be a pyramidellid opistobranch by the morphology of its embryonic and larval shell. Pyramidellid gastropods now commonly live as ectoparasites or commensals with a variety of worms and molluscs a fact supporting the existence of the postulated, yet not fossilized bioturbators. Small byssate bivalves are fixed to organisms reaching above the surface of the sediment. During the time of deposition of the Posidonia Shale s. str. life conditions improved for short times as much as to permit foraminifera and ostracods to live. This process can be observed three times in various parts of Southern Germany (W. RIEGRAF, Münster, personal communication; RIEGRAF, 1985).

(5) When sedimentation rate increases again, the softness of the sea bed is re-established and the small benthic fauna of molluscs or even foraminifera and ostracods become extinct and embedded in-situ. The sediment deeper under the surface becomes altered, by dehydration. Embedded coleoids, whose soft tissues are sometimes preserved (loligosepiids), crustacean remains, and smaller vertebrates become compressed during this process of sediment compaction. The volume of the sediment decreases to one half. These conditions are preserved in the "Schneckenstinkstein" and in the three (Unterstürmig) and two lower limestone beds (Hetzles) within the oilshale. The rest of the interparticle

porosity is closed by spar during cementation. The calcium carbonate is derived from the surrounding sediment.

(6) **Deeper beneath the surface as yet uncemented sediment becomes** altered during the next stage of diagenesis. Two processes can be distinguished. First, the small aragonitic shells of the planktonic gastropods become dissolved completely. Second, the roundish fecal pellets become flattened and may even flow into each other. During these processes the sediment thickness decreases by, at least, another half. The result is a compaction to a minimum of one fourth of the original thickness. The rock cemented after this diagenetic stage is preserved in the central parts of the nodules from the second nodule layer at the bottom of the oilshale proper.

(7) In the next diagenetic stage also bigger aragonitic shells become dissolved. Thereby the rather thick-shelled pyramidellids of about 1.5 cm in size can disappear completely, due to their cross-lamellar shell structure, which contains only little organic matter. After decalcification only the thin periostracum is left. The motions of sediment particles during compaction, however, disrupt this thin organic lattice and destroy it, so that no trace of it remains to be seen. The same happens to smaller ammonite shells. Bigger ammonites are preserved. The shells of the ammonites are nacreous and contain much organic matter, which is preserved after decalcification. Now shells of which only organic matter has been left become totally flattened, either filled with sediment, like the living chamber, or empty, like the phragmocone. Calcitic shells of the bivalves "Inoceramus", Pseudomonotis, Pinna or aptychi are preserved. The bigger valves become broken and therefore flattened, while smaller ones, like those of young "Inoceramus", of Pseudomonotis, and aptychi retain their shape, and the sediment flows around them during diagenesis. During this process the sediment thickness decreases again to one tenth of its former one.

In summary one may say: During the diagenetic alteration of a soupy mud to the oilshale realistically a total compaction of at least 40 to 1 has to be considered. A 2.5 m thick pack of oilshale required at least 100 m of soft water-rich mud. The processes of diagenesis and compaction already began during sedimentation.

The conglomerate at the base of the Toarcian and the belemnite layer on its top are erosional horizons. They contain components of the compacted sediments below. The lower conglomerate formed from the Upper Pliensbachian marls by erosion, transport of the fine-grained material and accumulation of the geodes and biogens. During this process currents have been so strong that the nodules have been turned over as is indicated by borings and growth of sessile organisms all around their surfaces. The belemnite layer consists of the biogens of the oilshale. Smaller shells are preserved as a whole and bigger ones occur only as fragments, showing that they are derived from sediment that was already compacted. In the profile near Hetzles, such a shell coquina bed formed a hardground that became settled by stromatolites of up to 15 cm in diameter. They grew in shallow, probably intertidal depth with periodic strong currents. The base and the top of the Posidonia Shale, therefore, must have been formed in very shallow water, at least above the wave base or, in the case of the stromatolite layer, even in an inter- to supratidal environment. According to this hypothesis also the Posidonia Shale proper cannot have been deposited in a much greater water depth, say about 50 m or less.

4. Discussion

The Upper Pliensbachian microfauna as well as the ammonite containing geodes derived from the same strata show that the basal layer is an erosional

horizon, formed in a high energy environment. The limestone nodules are bored from all sides and are partly so destroyed that irregular fragments are their only remains. This shows that a rich filter-feeding fauna has lived here over an extended period of time. Bivalves and occasionally brachiopods living on hard substrates and in coarse sediments are also part of this fauna as well as gastropods and sea urchins. All these organisms do occur neither in the Upper Pliensbachian marls nor in the pellet sediment of the Posidonia Shale proper. The basal conglomerate has been mentioned in several papers (KRUMBECK, 1932; KUHN, 1953; KOLB, 1964; ZEISS & SCHIRMER, 1965; SCHRÖDER, 1968). Most of these authors place this layer into the Upper Pliensbachian because of its content of ammonites of the species *Pleuroceras spinatum*. Only a few authors interpret it as a basal conglomerate (KÜHN, 1953) or as erosion horizon (KOLB, 1964). Part of the fossil contents must have been derived from the Upper Pliensbachian marls and cannot be used for age determination because of redeposition. The difference between the Upper Pliensbachian fauna and the autochthonous fauna of this layer shows that a long hiatus of sedimentation must have occurred. It lasted until Lowest Toarcian time, because in the Franconian region the lowest ammonite zone *(Dactylioceras tenuicostatum-*zone) is not present. In the Swabian region the same time is represented by marly and calcareous sediments (EINSELE & MOSEBACH, 1955).

Where erosion did not uncover calcareous sand and concretions, as e. g. near Altdorf (own observation), the Bollernkalk is not present.

The following member, a marl containing pinnacean bivalve, is only a few centimeters thick and consists of fecal pellets, as can be seen in equivalent limestone nodules. The autochthonous benthic fauna consists mostly of pinnacean bivalves, often in life position. They could live in the soupy pellet sediment as long as their upper edges reached over the substrate. The nature of a very soft bottom is postulated from the vertical position of ammonite shells up to 10 cm in diameter. After deposition many ammonites broke up and worm tubes, inarticulate brachiopods and oysters detached from them.

The fossils of the Posidonia Shale provide the most useful tool in the reconstruction of the conditions during sedimentation and during diagenesis. BROCKAMP (1944) could not prove any planktonic microorganisms in the Posidonia Shale, but postulated their existence and their destruction during diagenesis. MÜLLER & BLASCHKE (1969) found an alternation of dark layers, rich in organic material, and lighter ones, consisting mostly of coccoliths. The calcareous nannoplankton (coccoliths and the problematic *Schizosphaerella)* are responsible for the content of calcium carbonate of this sediment (KEUPP, 1981). Planktonic bivalves and gastropods are mentioned by JEFFRIES & MINTON (1965). They interpret *Steinmannia* (the former *Posidonia)* as a planktonic bivalve. This was denied by KAUFFMAN (1981). In Unterstürmig *Steinmannia* was not found, whereas it is present just below the topmost layer in Hetzles and in a similar position near the Castle of Bantz (N of Bamberg). The gastropod "*Coelodiscus*" represents a planktonic species as was assumed by JEFFRIES & MINTON (1965) and proven by BANDEL & KNITTER (1983). It does not represent a scavenging gastropod as postulated by QUENSTEDT (1858), EINSELE & MOSEBACH (1955), URLICHS, WILD & ZIEGLER (1979) and KAUFFMAN (1981). "*Coelodiscus*" is a planktonic heteropod and a composite of the recent genus *Pterotrachea* and the fossil genus *Coelodissus* as redefined by BANDEL & HEMLEBEN (1986). These gastropods are free swimming predators.

The carnivorous gastropods are only part of the zooplankton. Planktonic crustaceans might have also contributed to the production of the numerous fecal pellets. Fishes and reptiles, whose teeth and other remains have been

found, might have lived from plankton. Omnipresent onychites representing the arm hooks of belemnite-like squids and common gladii of vampyromorph squids (BANDEL & LEICH, 1985) show that also coleoid cephalopods must have been common in this sea. Pseudoplanktonic bivalves (like "Inoceramids") attached to driftwood or others, such as oysters, that attached to drifting ammonite shells lived from filtering small plankton. KAUFFMAN (1981) assumed that these bivalves have settled their substrate, when this was lying on the sea bed and not during the drift phase. He argued that recent driftwood has, too, a short driftphase to allow growth of adult colonies of bivalves. The fact is, that in the Posidonia Shale driftwood and ammonites are settled on every side and not only from above, as should be expected when settlement could occur only if the substratum is permanently fixed to the ground. The colonies might have continued to grow even on the ground, but only as long as they reached above the soft soupy sediment. The recent short driftphase of wood is caused by the boring activities of teredinids. Members of this family of wood-boring bivalves first appeared in large numbers in Cretaceous time. In the Toarcian sea long before the evolution of wood-boring bivalves wood, therefore, could have drifted much longer. The opinion of SEILACHER & WESTPHAL (1971) and SEILACHER (1982) that "Inoceramus" and Ostrea have been pseudoplanktonic in the Posidonia Shale sea is supported by our data.

The rare occurrence of benthic organisms in the middle part of the Posidonia Shale section, the actual oilshale, was explained by the presence of a very soft sediment by BIRZER (1936) and BANDEL & KNITTER (1983). The partially preserved fish Pachycormus from a geode from Altdorf, described by KEUPP (1981), supports this opinion. The fish may have sunk some tens of centimeters into a muddy substrate, because of its state of conservation. KAUFFMAN (1981) postulated a stable substrate and not a mud. In his opinion the good preservation of fossil remains was caused by an algal mat covering the sea bed. Under this algal mat the condition was anaerobic. Such a cover of photosynthesizing organisms should have carried reasonable amounts of benthic organisms, such as foraminifera or ostracoda, which could be found only in few layers (RIEGRAF, 1985). KAUFFMAN (1981) also mentioned that vertically or obliquely embedded ammonites were very rare in the Swabian Posidonia Shale. EINSELE & MOSEBACH (1955) found obliquely embedded ammonites sometimes in limestone beds but not in the real oilshale. But this is quite normal when compaction rates of ground 40 to 1 are considered. In the limestone nodules and beds those ammonites are conserved in their original position, after they have reached the sea bed, because there is no or only little compaction. The original oblique position in the shale can be proven by the fact that flattened ammonites often extend through several laminae of the shale, even when at first sight they seem to be embedded in horizontal position.

In the lower bed of limestone nodules (the "Schneckenstinkstein") and in the limestone beds stratification is very indistinct. The large number of planktonic gastropods and other fossil remains are scattered throughout the sediment and are not arranged horizontally. Bioturbation has destratified the sediment. The frequent occurrence of siphonate bivalves (Goniomya and Solemya), preserved with both valves, proves that they have lived in the vicinity, and are not derived from neighboring biotope as postulated by RIEGRAF (1977). In addition, they are too common to represent members of an episodic fauna, as is assumed by BRENNER & SEILACHER (1978). These bivalves have gathered their breathing water from the water column above the sediment, which could not have been anaerobic. Bioturbating worm-shaped organisms also required oxygenated water from above the sediment-water interface. In the second layer of nodules the pyramidellid gastropods probably lived as parasites or commensals with

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larger worm-like benthic animals. Together with these gastropods the byssate bivalve *Pseudomonotis* occurs. It must have been fixed to an unknown substrate, probably sessile organisms which extended above the sea bed but did not become fossilized. *Pseudomonotis* also is embedded in situ, because all ontogenetic stages have been found. A transport by currents, as postulated by BIRZER (1936), can be excluded, at least for the actual oilshale.

The fossil remains can give us some useful hints to the diagenesis of the sediment. The shells of the planktonic gastropods were entirely aragonitic and very thin. In the marls and in the oilshale they cannot be found at all. Their shells have been preserved only in the central parts of the big geodes of the second nodule layer within especially protected zones, such as the living chambers of ammonites, the alveoles of belemnites or within two-valved bivalves. In the limestone outside these protected zones they have vanished completely. This gives a hint to the relative date of their dissolution. The finely laminated geodes have not been cemented any earlier than the not stratified ones, as postulated by EINSELE & MOSEBACH (1955), but vice versa. At first those areas have been cemented which now show bioturbation and indistinct stratification. The dissolution of the aragonitic shells in the stratified areas shows, that diagenesis continued when in the other regions lithification had reached almost the present status. Where compaction continued, fecal pellets were deformed which enhanced lamination. The aragonitic gastropods vanished, due to carbonate dissolution. Many other microfossils, such as foraminifera or ostracods, would not have been dissolved, if present, because their potential of fossilization is much greater, due to their calcitic shells. Probably, they only existed periodically in this biota (RIEGRAF, 1985).

The nodules of the second layer allow to reconstruct the compaction rate from 4 to 1 in the limestone to the amount of 40 to 1 in the shale. Here ammonites with sediment-filled living chambers have been compacted in the same way as the empty phragmocones. Already EINSELE & MOSEBACH (1955) postulated compaction rates from 40 to 1, if ammonites would be flattened in this way, but they could not imagine that also the living chambers contained sediment.

A diagenetic selection of faunal remains occurred during the process of lithification. Several discrete fossil assemblages led KAUFFMAN (1981) to assume oxygen reversals, which in some cases resulted in ammonite mass mortality. He applied this interpretation to ammonite thanatocoenoses, that contain all sizes of shells and terminated cathastrophically. In contrast other associations contained only bigger specimens indicative of normal life and death cycles. Such associations, however, may form only as a result of carbonate dissolution. Smaller ammonites, whose shells are aragonitic, are less resistant to dissolution and sediment flow than bigger ones, whose carbonate has become calcitic due to growth of cements. Thus, mass mortality of ammonites due to oxygen reversal cannot be proven for Posidonia Shale sedimentation.

SEILACHER (1982) reconstructed the depositional environment of the Posidonia Shale as one of oxygen-depleted water in a stagnant basin. The lamination of the shales documents, in his opinion, basically anoxic conditions as the background situation with episodic development of a monospecific epibenthic community when oxygen became available. He considers laminae as the product of sedimentation in very quiet water, that would only be preserved in the complete absence of macroscopic bioturbation. This model does not take into account that lamination may have developed by compaction rate of 40 to 1, as is shown above, and that the macroorganisms like *Goniomya* are fairly common in the shales, at least in Franconia.

The belemnite layer on top of the Unterstürmig section can be correlated with the famous "*Dactylioceras*-Bank", which is found in several localities of Franconia and the "Kloake" and the "Schlacken" in Swabia, these all are condensation beds. The occurrence of stromatolites on top of condensation bed proves the deposition in very shallow epicontinental sea. Whereas many of the condensation beds are of Lower Toarcian age, the stromatolitic layer is of middle Upper Toarcian age (*Grammoceras thouarsense*-zone) (according to B. ROSCHER/Karlsruhe, written communication, 1983). A widespread regression must have happened at the end of the Posidonia Shale deposition, which lasted until the middle Upper Toarcian, when bioturbated marls are found that are rich in belemnites. Also, the lack of lower Upper Toarcian ammonites and microfossils (KNITTER, 1983) in Franconia shows that a large hiatus follows the Posidonia Shale sedimentation.

5. Summarized Sedimentological Conclusions

(1) The base and the top of most sections of Posidonia Shale are formed by redeposited material. They have formed in a high energy environment, and mainly represent reworked particles of sediments that have been deposited before.

(2) The substrate at the bottom of the Posidonia Shale sea consisted of fecal pellets, and was bioturbated by a specialized fauna.

(3) The sediment was produced by an association of planktonic organisms and was strongly altered during diagenesis.

(4) The molluscan benthos consisted of endobenthic siphonate bivalves, a pyramydellid gastropod and some small byssate bivalves. Pinnacean bivalves could live only at the beginning of Posidonia Shale sedimentation.

(5) The molluscan plankton consisted of heteropod mesogastropods and larvae of gastropods and bivalves. Pseudoplanktonic oysters and "inoceramids" were present.

(6) Nektonts are ammonites, loligosepiids, belemnoteuthids, crustaceans and vertebrates. Belemnites are rather rare, exept in beds with redeposited material.

(7) Different stages of diagenesis can be recognized. In limestone nodules and limestone beds they have been preserved by cementation.

(8) The oilshale itself is the result of strong compaction of the original sediment. Compaction enhanced lamination. A decrease of thickness from at least 40 to 1 must be considered.

(9) Limestone beds of the middle Lower Toarcian cannot always be correlated over greater distances. In different localities they occur in different positions.

(10) The lower and the upper parts of the Lower Toarcian in Southern Germany differ in lithology. The middle part is very uniform.

(11) The sea during deposition of the Posidonia Shale was not deeper than about 50 m. It formed during a phase of transgression in the middle Lower Toarcian and ended with a regression.

(12) In upper Lower Toarcian and lower Upper Toarcian times the area of the Posidonia Shale lay just above sea level, and deposition occurred at intratidal to supratidal conditions. Erosion set in.

6. General Considerations About the Lower Toarcian Posidonia Shale

The widespread occurrence of the Lower Toarcian Posidonia Shale, especially in central Europe but also in other regions, raises the question, what caused the special lithology of these sediments. The regional distribution in and around the former Tethys may give a hint to the solution of this problem. Earlier authors (e. g. BROCKAMP, 1944) thought that the nutrients for the production of the organic matter and parts of the organic matter itself came from the nearby land areas. Except for a big estuary in Poland, however, no major sources for such an input are known. Other areas of Posidonia Shale facies would not have direct connection to this estuary (e. g. Greece, Southern Russia, the Tethys itself etc.). BRENNER & SEILACHER (1978) thought that a mayor change in the current pattern within the German Basin should have caused the anoxic conditions of the Posidonia Shale sea. According to their measurements of belemnite rostra, the main current direction has changed from south to north at the boundary of the lowest Toarcian to the middle Lower Toarcian and again from north to south at the boundary of the middle Lower Toarcian to the upper Lower Toarcian. In addition to the fact that these current changes alone cannot solve the problem of widespread Posidonia Shale occurrence, our sedimentological model for the deposition of the actual Posidonia Shale (see above) makes it unlikely that adjustment of belemnite rostra might have happened at all during the middle Lower Posidonia Shale. Thus, the measurements of directions of belemnite rostra in the Posidonia Shale should be reevaluated. A change of current patterns may be an artefact because of misinterpretation of palaeocurrent reconstruction (see also KNITTER, 1983). Other reasons must explain the occurrence of Posidonia Shale. The following model tries to avoid some contradictions with observations which occur in earlier models.

The carbonate content of the Posidonia Shale is mostly derived from calcareous nannoplankton. Similarly, most of the organic matter comes from this source. Thus, the nutrients for the phytoplankton might also be of marine origin.

The timing of the occurrence of Posidonia Shale facies is restricted to a very short period. The oilshale proper mostly occurs in the *Harpoceras falciferum-*zone of the Lower Toarcian. The lithology of the lowest zone of the Lower Toarcian, the *Dactylioceras tenuicostatum*-zone, as well as the highest, the *Hildoceras bifrons*-zone, differs strongly from one locality to another. Together with the regional distribution the short interval of the Posidonia Shale has to be considered in the regional palaeogeographic framework of the Toarcian.

In Upper Pliensbachian times the Tethys Ocean had no connection with the northern epicontinental seas of central and eastern Europe. At the beginning of the Lower Toarcian connections can be proven by the migration of the dactylioceratid ammonites from the Tethys to the north (DONOVAN, 1967). This means that an early Toarcian transgression caused drowning of the sill between the Tethys and the northern epicontinental seas (ARKELL, 1956; HALLAM, 1978). The transgression coincides with the beginning of deposition of Posidonia Shale facies in Europe. The diverse facies patterns of the lowest Lower Toarcian show that the transgression was not a uniform anoxic event. Only in the middle Lower Toarcian conditions became stable enough to produce oilshales in various palaeogeographic situations. As shown above the Lowest Toarcian sediments may be represented by conglomerates. They might be the result of a transgression after an Upper Pliensbachian regression phase. The different palaeogeographic settings, therefore, had to be equalized during the *Dactylioceras*

tenuicostatum-zone. This may be the reason why actual oilshales are rare in deposits of this time and restricted to a few localities.

Similar features characterize the end of Posidonia Shale sedimentation. In some localities Posidonia Shale facies continues into the *bifrons*-zone of the Lower Toarcian as well as even into the lowest zones of the Upper Toarcian, while in other places the regression ends this kind of sedimentation and inter- to supratidal sediments came to deposition as shown in the Hetzles profile.

Black shale facies has often been described often in connection with transgression. It is not clear at all, however, why transgression can produce such sediments. In the special case of the Posidonia Shale the opening of the Tethyan ocean might be responsible.

In Upper Liassic time the Tethys was a wedge-shaped small oceanic basin connected in the east to the open ocean. Main currents ran from east to west (BERGGREN & HOLLISTER, 1977; KRISTAN-TOLLMANN & TOLLMANN, 1981). The southern shelf seas of this oceanic basin were wide and differentiated. Here sediments of the Northern Limestone Alps and the Southern Alps were deposited. The northern shelf in contrast was narrow, the Helvetic Basin was of minor importance in this time. A high, the so-called Vindelician Land, reached from the Bohemian Massif in the east to the Massif Central in the west and separated the Tethys from the northern epicontinental sea of central Europe. At the beginning of the Toarcian the Vindelician Land was drowned partially so that Tethyan water masses could enter this northern basin, bringing with them a major change in the fauna and flora.

Waters from the Tethys were forced to flow up the shelves by the geometry of the oceanic basin, and upwelling conditions may probably have become established. Nutrient-rich water initiated increased phytoplankton production in the adjacent seas (KNITTER, 1983; JENKYNS, 1985). In the beginning of the transgression only in the deeper parts of these seas a real Posidonia Shale facies could develop. Localities of a shallower position now show other sediments such as conglomerates or non-bituminous marls. The transgression went on and drowned even shallower areas (below the wave base). After the ammonite-zone of *Dactylioceras tenuicostatum* conditions became stabilized to develop the uniform Posidonia Shale facies surrounding the Tethyan Basin, especially in the north.

The deposition of the ubiquious Posidonia Shale Facies lasted only over one ammonite zone, the *Harpoceras falciferum*-zone. In the later Lower Toarcian, the *Hildoceras bifrons*-zone, new facies appearead, due to regression. In some profiles hiati can be found, whereas in others sedimentation continues with either bituminous or non-bituminous marls.

Therefore, the end of Posidonia Shale deposition seems to be determined by this regression. However, regression alone does not explain the end of this facies. Additional characters are observed. The regression during the *Hildoceras bifrons*-zone effected only some localities, while in others sedimentation continued without any visible effect. The end of Posidonia Shale deposition also coincides, more or less, with the first opening of the Central Atlantic at about 180 million years ago (DEWEY et al., 1973; BERNOULLI & JENKYNS, 1974). In the Central Atlantic this date is also recorded by the rapid transition from shallow water sediments to deep water sediments with a large stratigraphic gap after Upper Pliensbachian time (e.g. in Leg 79 off Morocco, RIEGRAF & LUTER-BACHER, 1984). If the date of the opening of the Central Atlantic is correct, the connection of the Tethys with the Central Atlantic would have caused major changes in hydrographic conditions. Open to the west waters of the Tethys were

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no longer forced to well up the shelves, thus reducing the nutrient supply to the epicontinental sea including the area of Posidonia Shale sedimentation.

HALLAM (1978) related Posidonia Shale deposition with eustatic megacycles, stating that oilshale sedimentation occurred during a transgressive maximum. Also KAUFFMAN (1981) did the same when he recorded a symmetric cyclothem beginning with a transgression in Lower Toarcian time, its maximum in middle Lower Toarcian time and a regression in the Aalenian. However, this cyclothem ended already in upper lower Toarcian time with a regression, as recorded from our sedimentological data. The models of HALLAM (1978) and KAUFFMAN (1981) only connected transgression and regression with the beginning and with the end of Posidonia Shale sedimentation, respectively, but did not give any reasonable hint why these eustatic changes should have caused such a widespread result. The coincidence of the geometry of the Tethyan ocean, the opening of the Central Atlantic and eustatic sea level changes, however, may have resulted in the widespread deposition of blackshale facies around the Tethys as described in our model.

According to CURRAY (1980) opening oceanic basins often are related to blackshale facies, as can be seen in earth history. Perhaps the proposed model for Posidonia Shale deposition can help to solve questions concerned with this general problem.

Acknowledgements

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Figures 4–27

Fig. 4: Reworked concretion of the base of Posidonia Shale bored by bivalves. The borings are coated. × 2

Fig. 5: Reworked concretion of the base of Posidonia Shale bored by sponges. Borings are connected with each other. × 1

Fig. 6: Borings produced by algae or fungi in an eroded belemnite rostrum from the base of Posidonia Shale. × 30

Fig. 7: Thin-sectioned "Schneckenstinkstein" with gastropods, pellets and radiolaria. × 30

Fig. 8: Pyramidellid gastropod and *Pseudomonotis* on limestone bed. × 2.2

Fig. 9: Cut concretion of limestone bed with *Inoceramus* shells more and more compacted and fractured from right to left. × 0.8
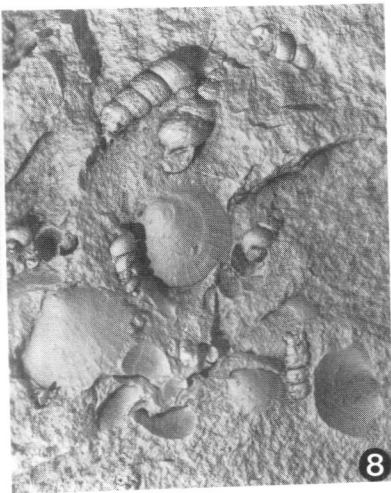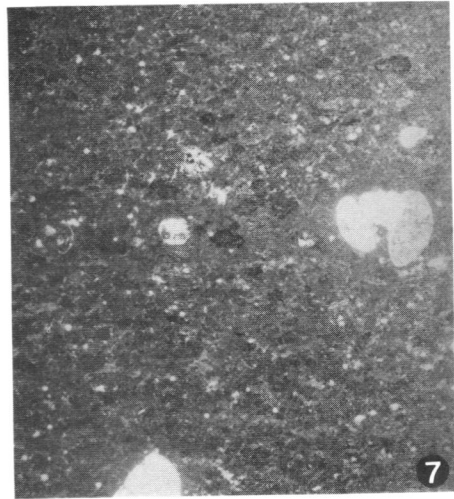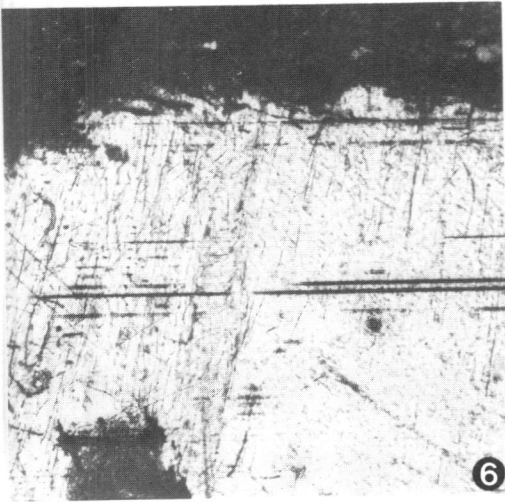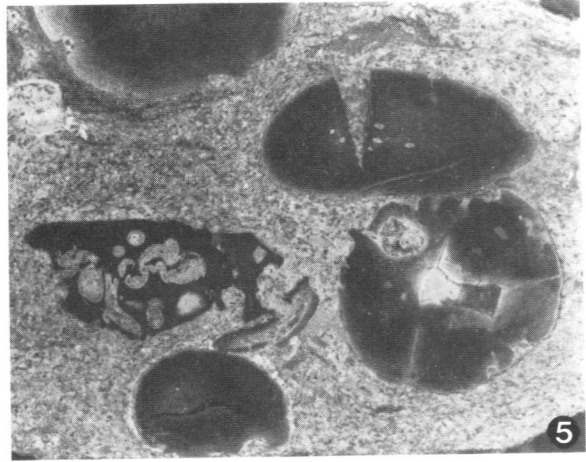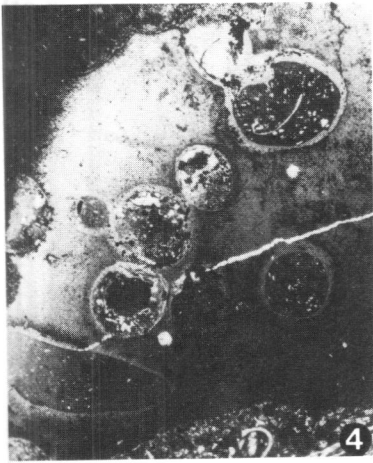
Fig. 10: Compacted and stratified concretion with mud crack. × 2

Fig. 11: Compacted and stratified oil shale with mud crack, more compressed and deformed than in Figure 10. × 2

Fig. 12: The original pellet structure of the sediment is preserved within a bivalved *Inoceramus*, while it is destroyed outside of its shelter due to compaction. × 3

Fig. 13: Compacted mud becomes laminar. × 30

Fig. 14: *Inoceramus* shells are not dissolved during compaction but become cracked into small pieces. × 5

Fig. 15: The first limestone beds of the Unterstürmig section is cut by fissures which have been closed and reopened. Fillings consist of jelly-like aggregates of calcium carbonate. × 4

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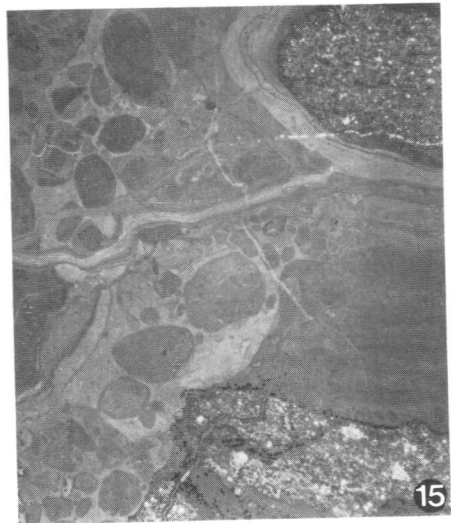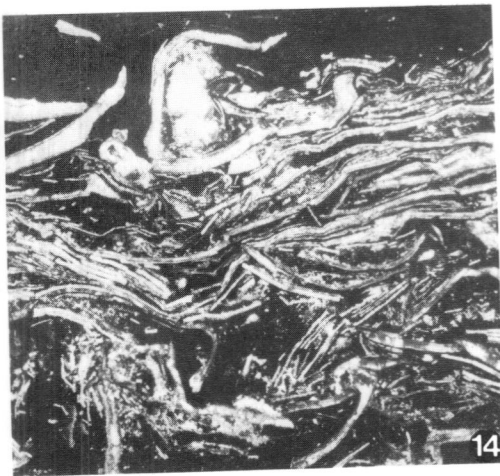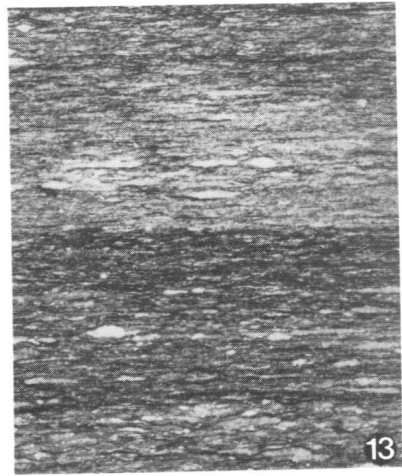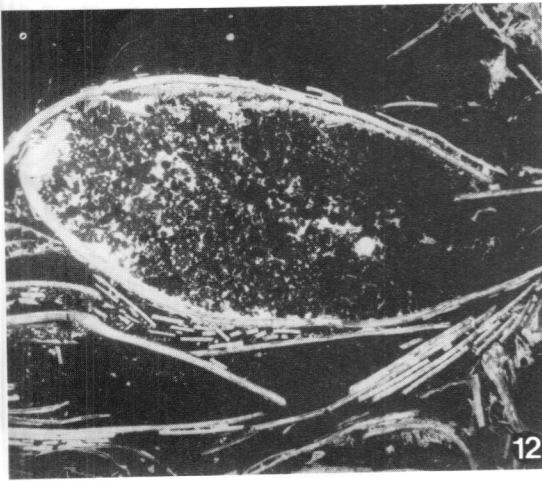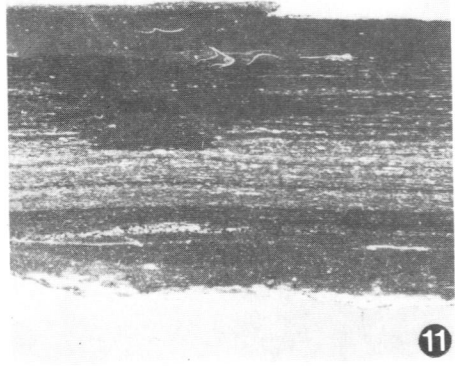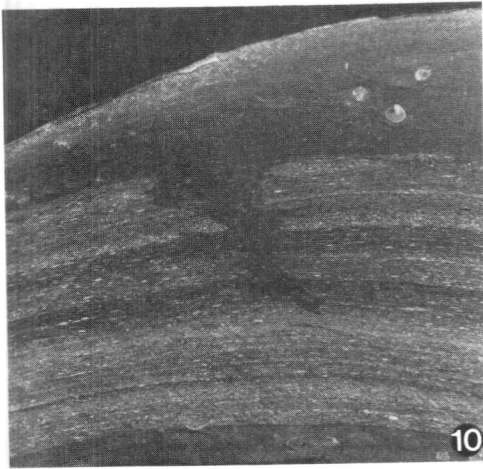
Fig. 16: The belemnite layer of the Unterstürmig profile ends with a coquina of reworked *Pseudomonotis* shells. × 5

Fig. 17: Stromatolites at the Hetzles profile are underlain by a coquina of *Posidonia* and *Inoceramus* shells reworked from eroded shale. × 5

Fig. 18: Uppermost limestone bed of the Posidonia Shale at Hetzles had been uncovered and eroded truncating a desiccation crack. This surface served as base for stromatolite growth. × 5

Fig. 19: Stromatolitic growth on shell fragment. × 4

Fig. 20: Oval stromatolite cut vertically and polished. × 0.8

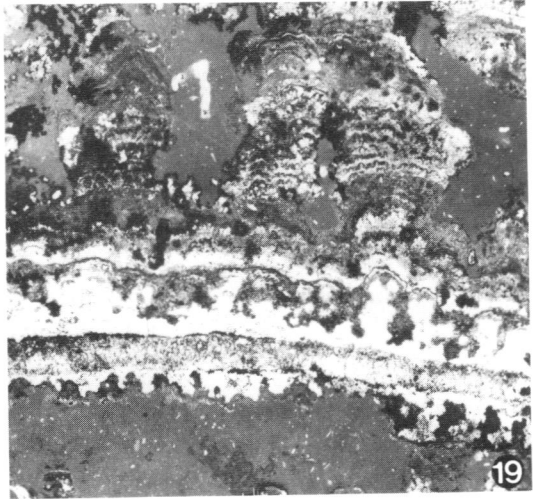Fig. 21: Stromatolitic crust cracked and fissure filled with sediment and covered by new stromatolitic layer. × 4
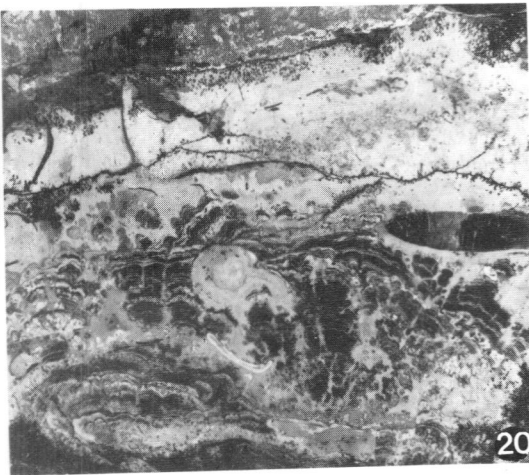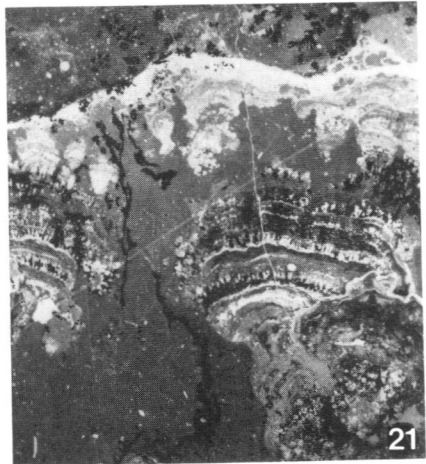
174
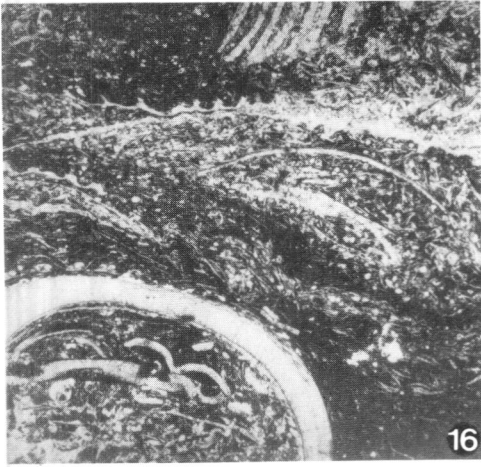
Fig. 22: Sponge borings in stromatolitic crust. × 16

Fig. 23: Pectinid bivalve from Posidonia Shale, laminated limestone. × 1.5

Fig. 24: "*Inoceramus*" and *Goniomya* from the limestone with pyramidellid gastropods (Fig. 2). × 1.8

Fig. 25: Posterior part of a small fish preserved with bones articulate and remains of the soft body. × 1.8

Fig. :26 Aptychi are well preserved in the oil shale due to their composition of organic material and calcite. × 2

Fig. 27: Oysters that have grown on floating ammonite shells are preserved much better than the ammonites, since they have been calcitic. × 4