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Fossil-Lagerstätten Nr. 6*:

On the deposition of the Solnhofen lithographic limestone (Lower Tithonian, Bavaria, Germany)

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With plates 1—4, 2 figures and 1 table in the text

Abstract: In the prolonged debate on the depositional mode of the Lower Tithonian Solnhofen lithographic limestone the author pleaded for sedimentation in shallow quiet marine water (BARTHEL 1964). The floor of a backreef-lagoon consists of ridges, built by Lower Kimmeridgian sponge reefs. Their concomitant basins were an ideal sedimentary environment for carbonate mud deposition. The relief in the lagoon favored part-time stagnancy within the basins. Sediment was supplied from the open sea via passages in the barrier of coral reefs.

Burial of friable animal tissue and its preservation were tested by means of experiments. A carbonate mud: salt water: animal-system was used to simulate the Solnhofen environment.

The fossils specially considered were *Limulus, Mecochirus, Penaeus,* a butterfly, the jelliyfish *Rhizostomites,* pterosaurs, and birds. Correlation of evenly and thinly stratified beds over miles, absence of evaporites and of algal growth on bedding planes, lack of tidal-channels, as well as our experiments, do not support water recess from the lagoons.

Comparable deposits of lithographic limestones (Cerin-France, Monsech-Spain, Haqel and Hejoula-Lebanon a. o.) suggest common factors (geomorphology, climate) governing their origin.

Zusammenfassung: Der Ablagerungsmodus der Solnhofer Plattenkalke ist bis in die letzten Jahre in Diskussion geblieben. Schon früher (BARTHEL 1964) hat der Autor darauf hingewiesen, daß die feingeschichteten Kalke in ruhigem Milieu und unter dauernder Wasserbedeckung abgelagert sein mußten. Das Ablagerungs-Gebiet war eine hinter dem Riff gelegene Lagune, deren Boden durch ältere Schwamm-Riffe gegliedert war. Die so entstandenen Teilbecken wiesen zeitweise stagnierende Bedingungen auf.

Anhand von Experimenten wird die Möglichkeit der Einbettung fragiler Tierreste sowie die von Spuren und ihre Erhaltung in diesem Environment erklärt. Unter den Arthropoden wird an *Limulus, Mecochirus, Penaeus* und einem Schmetterling demonstriert, wie die Verhältnisse von Karbonat-Schlamm : Salzwasser : Lebewesen in den Solnhofener Lagunen gewesen sein müssen. Auch für Quallen, Vögel und Pterosaurier läßt sich dies rekonstruieren. Die ebenschichtigen, weithin korrelierbaren Ablagerungen, das Fehlen von Evaporiten, Algenbildungen und Prielsystemen spricht ebenso wie die Ergebnisse der Experimente gegen Trockenfallen der Lagunen. Vergleiche mit anderen, ähnlichen Vorkommen (Cerin-Frankreich, Montsech-Spanien, Haquel-Hejoula-Libanon u. a.) lassen gemeinsame, geomorphologisch-klimatische Bildungsbedingungen erkennen.

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* Nr. 5 Siehe N. Jb. Geol. Paläont., Mh. 1970, 65—68.

Introduction

The Solnhofen lithographic limestone and its mode of deposition have been under discussion for some time. Various theories on its genesis have been advanced. GÜMBEL 1891, for instance, thought of a coccolith-ooze laid down in quiet bays. The proximity of reefs soon led to the idea of lagoonal origin. The crucial point, however, remained the origin of the fine sediment. Carbonate mud from the shore (NEUMAYR 1887, p. 318), fine detritic material carried over the reefs (WALTHER 1904, p. 211), windblown carbonate dust (ROTHPLETZ 1909, p. 332, ABEL 1927), chemical precipitation (div. authors), and even brackish to freshwater environment (WALTHER 1904, RODE 1933) have been considered.

Lately the lithographic limestone was the object of electron micrograph studies by FISCHER, HONJO & GARRISON 1967 and especially by FLÜGEL & FRANZ 1967. They report coccoliths, very fine cephalopod debri and few foraminifera within the limestone. Being marine fossils their presence hints at a marine origin.

The bulk of the sediment may well have been Drewite (cf. BARTHEL 1964, p. 64). But since the question of its algal origin (LOWENSTAM 1955) or chemical precipitation (CLOUD 1962) is still pending we will not pursue this matter.

In addition to the origin of the sediment the mode of its deposition has been under debate. There are mainly two opposed views today:

One view considers episodic withdrawal of the sea as essential to explain the perfect preservation of fossils (ABEL 1927, MAYR 1967). The fossils are left as the sea receded. Sediment and organic material are desiccated, then either wind covers the lagoon with carbonate dust (ABEL) or „another wave" brings fresh sediment (MAYR).

The second concept claims continuous cover by the sea. Modification of former interpretations (GÜMBEL and others) becomes necessary as the knowledge of the geologic facts increases.

In 1964 the author published a model assuming deposition of the Solnhofen lithographic limestone within an intricate system of smaller basins. Episodic stagnancy and hypersalinity depended seafloor morphology and hot climate during the Upper Jurassic (fig. 1).

This model has not remained uncontested. JANICKE 1969 has reconsidered the most controversial arguments at some length.

Outline of geological setting

During the Upper Jurassic most of the area now known as the Suabo-Bavarian high plain, was covered by the sea. Two major islands restricted this sea toward the NW, and the NE. Between them a wide passage connec-

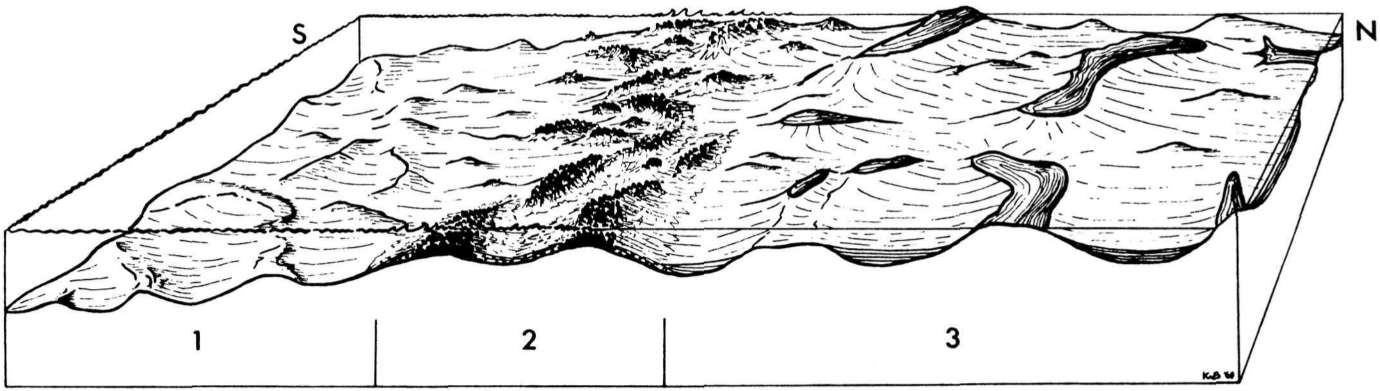

Fig. 1. Reconstruction of the sea floor during the Lowermost Tithonian in Bavaria. Uplift in the N, downward tilt in the S.

1: Open sea with relief of sponge-reefs (still actively growing in places).

2: Uplifted dead sponge-reefs with corals thriving on their tops. Coral growth approximately followed todays course of the Danube between the Ries and Regensburg.

3: Dead sponge reefs in the backreef-lagoon. Lime mud, now Solnhofen lithographic limestone, was deposited in basins fringed by these reefs. Actual coastline in the N has been truncated by erosion.

ted the Suabo-Bavarian sea with northern realms. Todays position of the former islands is marked by the Black Forest and the Bohemian Massiv.

By the end of the Lower Kimmeridgian extensive sponge and algal growth (HILLER 1964) had built up a complex relief on the sea floor. At that very time the area between the two islands started rising. Corals began to spread from the shores towards the open sea. The uplift continued during the Lower Tithonian and exposed the sponge-reefs in the N. In adjoining southern regions water-depth remained at a level favorable for coral growth. Still further S the water was deeper and sponge-reefs continued to exist. A girdle of patch reefs of corals and hydrozoans finally developed, following a line which is now the southern margin of the Franconian Alb and coincides also with the present course of the river Danube. The patch-reefs formed a string of barriers protecting the backreef lagoon in the N from agitated water of the open sea in the S. (fig. 1). The floor of the lagoon also had a strong relief of dead sponge reefs barely reaching the water surface and forming a complicated pattern (EDLINGER 1966, fig. 5). The basins episodically received fine lime mud by onshore currents. Thin-bedded limestones prevailed toward the shore (N), layers grow thicker approaching the reefs (see facies map of v. FREYBERG 1968, fig. 4, 2 nd from bottom).

According to v. FREYBERG (1968) sponge-reefs and coral-reefs present two reef generations. He also advocates the idea of the Solnhofen lithographic limestone representing a backreef-facies (1968, p. 22/23 see also HILLER 1964, p. 167). However v. FREYBERG is somewhat noncommital because all traces of the northern shore have been removed by erosion. Our present knowledge of the paleogeography during and after deposition of the lithographic limestone leaves no doubt about their backreef nature. Further uplift in the N forced the reefs gradually southward. During the early Upper Tithonian the coastline was close to the Danube and the outer margin of the recifal-facies had reached a line S of Munich (BARTHEL 1969b).

The regional distribution of the lithographic limestone ranges irregularly from the Ries to the Bohemian Massiv (see fig. 2).

A study of the eastern area (Kelheim region) by SCHAIRER & LUPU 1969 reports frequent graded beds and coarse detrital material in the lower part of basinal sections. Toward the top signs of slumping grow less significant and similarity with lithographic limestone becomes striking. The change is either caused by a slow southward shift of the reefs and hence less turbid waters, or by rather steep basin slopes which are susceptible to slumping. In the second case the steepness of slope will diminsh as sedimentation goes on, and consequently the frequency of slumps decreases.

In the W (Solnhofen region; compare v. FREYBERG 1968, p. 15) sedimentation of lithographic limestone (Lower Solnhofen member) starts with very thin limestone laminae alternating with marly portions, a type of rock that is not worth quarrying. Deposition of industrially exploited lithographic lime-

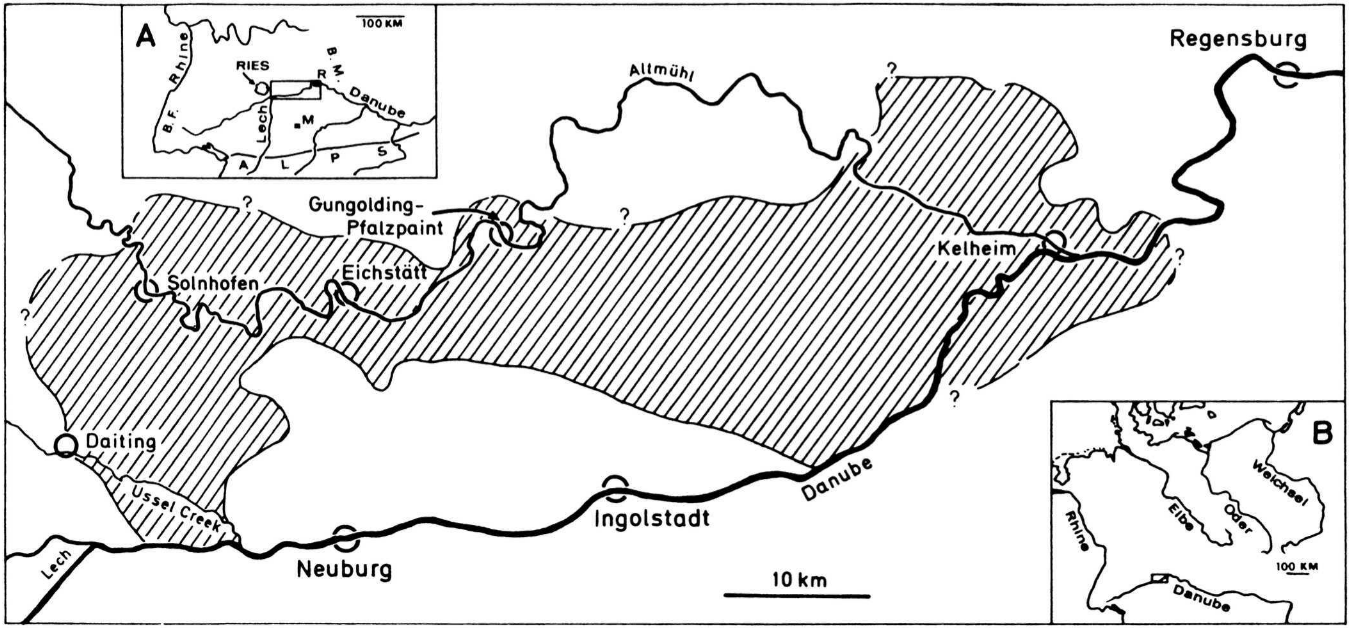

Fig. 2. Distribution of lithographic limestone in Franconia (crosshatched). Grossly simplified after v. FREYBERG 1968. Crosshatched area also includes some reefs especially so between Kelheim and Eichstätt. Southwestern region (Daiting) exposes more recent lithographic limestones.

Inset A: Southern Germany. Area of interest marked by square. M = Munich; R = Regensburg; B.F. = Black Forest; B.M. = Bohemian Massiv.

Inset B: Central Europe. Square as in inset A.

stone (Upper Solnhofen member) begins above a widely distributed subaquatic slump. The Upper Solnhofen member, in turn, is overlain by another set of beds distorted by subaquatic slumping.

Graded beds were not recognized in the western region so far. However, GOLDRING & SEILACHER (oral communication) infer „microturbidites" from their observations on limulid tracks. The absence of coarsely graded beds in the western region indicates fairly undisturbed deposition behind the reef-barrier. The existence of a „Vindelician landmass" in the S has to be refuted for the Upper Jurassic (FESEFELDT 1962 and reconnaissance wells). This landmass was considered an important source by ABEL 1927 and others to derive the sediments from. Recent investigations confirm a shoreline in the N only.

Stratigraphic situation

The Upper Jurassic deposits of the Franconian Alb range from Oxfordian to Upper Tithonian. Regression and subsequent erosion toward the end of the Upper Tithonian or during the dawn of the Lower Cretaceous prevented preservation of possible later sediments (BARTHEL 1969b). Lithographic limestone is known from the Lower Tithonian only. In the Solnhofen-Eichstätt area these rocks are generally restricted to the early Lower Tithonian.

Tithonian	U.	hiatus	
Tithonian	M.	Neuburg formation	Oberhausen member Unterhausen member
Tithonian	Lower	Rennertshofen formation	not subdivided
Tithonian	Lower	Usseltal formation	Usseltal lithogr. ls. member Gansheim member Spindeltal lithogr. ls. member Tagmersheim member
Tithonian	Lower	Solnhofen formation	Mörnsheim member Upper Solnhofen lithogr. ls. } members Lower Solnhofen lithogr. ls. } members Rögling member
Lower Kimmeridgian			
Oxfordian			(not exposed in the area under discussion)

This outline accounts for the stratigraphy of the area between Solnhofen-Eichstätt and the Danube. It is based on the investigations of FESEFELDT 1962 and others for the Lower Tithonian and the author's work on the Middle and Upper Tithonian (see BARTHEL 1969b). In the Kelheim district the facies is differentiated but correlation is not too difficult (v. FREYBERG 1968). Facies very similar to the lithographic limestones, of Mörnsheim and Usseltal age, developed near Daiting. At Daiting many an important „Solnhofen“ fossil was recovered.

Experiments and observations

In BARTHEL 1964 and 1966 the author re-interpreted some evidence in the light of his model of entirely subaquatic origin. This evidence had been used to „prove“ episodic water recess from the lagoon (MAYR 1967). In 1964 only theoretical interpretations were possible for some of the crucial features. Now, these interpretations will be supported by experiments and further observations.

Arthropods are among the most frequent fossils found in the Solnhofen lithographic limestone. WALTHER (1904) listed more than 70 species belonging to about 25 genera. Since the rock has preserved even the slightest marks on the bedding planes numerous tracks of these animals might also be expected. This, however, is not the case. There are only two genera which occasionally left more or less conspicuous tracks (BARTHEL 1964, p. 57). The decapod *Mecochirus* rarely made trails of any length. It is the horseshoe crab *Limulus* only that produced tracks over some distance.

What caused this discrepancy between a considerable number of fossils and the scantiness of their trails? It was because ecologic conditions were lethal. The arthropods were not able to live on the floor of the Solnhofen backreef-lagoons. This is also confirmed by the absence of botton- and sediment-dwellers. Only very resistant forms were able to exist there for a limited time. *Mecochirus* and *Limulus* were just such animals. The living *Limulus* is known to survive impressive changes in salinity, temperature and oxygen content.

At Solnhofen *Limulus* tracks have been considered to be vestiges of land animals until CASTER 1940 identified them properly.

The depth of *Limulus* - tracks in the mud grows neither successively shallower nor deeper while the animal was crawling. Increasing stickyness of the sediment, therefore, may be ruled out. The animals's exertion and eventual death must have had another reason. Spiral or irregular paths with *Limulus* in the center or at the end are well known. They offer some help. Spiralling of the animal is a sign of disorientation. And disorientation in want of oxygen, according to our Solnhofen model, seems to be a resonable cause of death.

Cohesiveness of the mud, high water content of freshly deposited sediment and aging by subaquatic dehydration certainly played an important role in preserving differing sets of *Limulus* - tracks (see also MALZ 1964, p. 95).

Limulus carcasses of more than 15 cm in width are not frequently found in the quarries. Larger individuals are scarce and represented by trails only (estimated width of living animals up to 35 cm). This means that mainly younger *Limulus* were diverted to the lagoons, a fact consistent with FÖRSTER's (1966, p. 156) publication on erymid decapods from Solnhofen.

SCHÄFER (1964, p. 102) reasons along these lines though he adheres to the water recess hypothesis.

According to this hypothesis the retreating sea left many animals behind. Trying to reach the low-waterline stranded animals must have created quite a random pattern of tracks and trails. Even swimming crustaceans like shrimps should have done so. Observing living shrimps at the aquarium of the Marine Fisheries Institute (Mandapam Camp, India), it was found that largely their telson forms a wide but shallow furrow as the shrimp drags it over the ground. A different pattern originates once the water has been removed. This became obvious during an experiment run on Ramrod Key (Fla.). The shrimps were active to escape from a cloggy surface of carbonate mud. They jack-knifed their abdomina forward and below the cephalothorax. The crustaceans then propelled themselves backward as they snapped the abdomina to normal position. Each time the animals hit the ground either the entire bodies or the abdomina effected elongated impressions. The result of continued jackknifing was an irregular pattern or a sequence of zig-zag track (pl. 1 fig. 3). The fossil Solnhofen shrimp *Antrimpos* („*Penaeus*") has never been reported to have left similar signs of action. This holds true even if a high percentage of the fossils were exuviae.

Thus, almost complete absence of animal vestiges, combined with a special sedimentary environment, provides a criterium in favour of continuous persistence of the sea in the Solnhofen lagoons.

In 1964 (pp. 57/58) the author noted some facts on drowned insects and subsequent descent of their remains to the bottom of a tank. The insects, at that time, were mostly flies and other dipterids with wingspans up to 2,5 cm.

An additional experiment was conducted to find out whether an insect with larger and fragile wings would sink without much decay after drowning. A butterfly with a wingspread of about 5 cm was placed into a vessel containing carbonate mud and saltwater. Five hours after insertion the wings were fairly wet. Next day the insect's body was almost below the water surface but still afloat. The entire experimental system then underwent a car transport from Ramrod Key (Fla.) to Princeton (N. J.). The experiment seemed a failure since the butterfly had disappeared from the surface. But once more it came up close to the water level, after the turbid mud had settled. Some days later it finally reached the bottom (pl. 1, fig. 4). The dead animal had been floating for a total of 9 days. Excepting the car-ride the temperatures, outdoors in Florida as well as indoors in Princeton, were above 20° C. The carcass did not show any obvious signs of decay during the experiment.

In nature descent from the water surface to the bottom might have taken longer if the salinity was high and the water remained quiet. It is safe to assume such conditions in the Solnhofen backreef-lagoons. In any case the experiment supports the idea that the Solnhofen insects, including the giant moth *Kalligramma* with a wing span of more than 21 cm, died on the waters of the lagoons and finally settled on the bottom.

As our 1964 observations revealed, this happened in the position of death and according to body-shape i. e., butterflies and dragonflies mostly reach the bottom with wings spread. Flies and grasshoppers, with wings folded, roll over sidewise once touching the ground.

If such experiments are performed in fresh water strongly contaminated with algal spores, floating insects will soon be covered with algal filaments. As a result an indistinct organic mass will reach the bottom. In sea-water the salt content, however, will preserve the carcasses.

The well known Solnhofen jellyfish pose special problems. Two types of preservation are known, one occurs within the fine-bedded limestones of the northern facies belt and commonly is found in an advanced state of decay. These fossils are included in the genus *Leptobrachites.*

The second type is more frequent and is familiar to paleontologists under the name of *Rhizostomites. Rhizostomites* is usually recovered from the southern, rather thick-bedded facies. In the Pfalzpaint-Gungolding quarry district where *Rhizostomites* mostly are found, different sedimentary conditions are recognized. The sediment is micrite. Erosional ripples, current ripples, and scour-marks indicate temporally increased water agitation. Within the beds there are also laminated portions in which the jellyfish are commonly found. All sedimentary structures within a bed range in mm and cm dimensions (Janicke 1967, pp. 21—24 and 1969). The jellyfish also occur on planes separating the beds.

Perfect preservation of the jellyfish was thought to be due to water recess. Janicke 1967, 1969 pleads in favor of very shallow water whereas Mayr 1967, p. 22 prefers the view that *Rhizostomites* had sunken in deeper water.

Hertweck 1966 published experiments on the possibilities of underwater fossilisation of jellyfish. His findings that jellyfish are preserved rather well in foul water and on fine mud bottom are consistent with our ideas (Barthel 1964). However, on carbonate mud, as shown by Hertweck's figures 5 and 6, recognizable imprints or clear remains of the specimens are not be seen.

Our own experiments were conducted in 35 ‰ salt water with a bottom of Florida carbonate mud. A dead *Aurelia* slowly went down to the bottom and settled on the soft ooze (pl. 3, fig. 7).

Very slight current is able to move the dead jellyfish over the mud surface. To lift it off the ground we added highly saline water (total increase in tank to 50 ‰). Adaptation of the animal tissues to the new salinity conditions made the jellyfish sink again, after some hours of floating at the interface of lighter and heavier brine. While floating the appendages remained in contact with the ground and thus left marks (cf. pl. 2, figs. 5, 6 and JANICKE 1967, pl. 2 and 1969, pl. 1). The underwater marks were clear-cut, and quiet waters prevailing, another carbonate layer will preserve them easily.

JANICKES *Rhizostomites sections* (1967, fig. 36), on the other hand, suggest that there was mud within the gastric-cavity of at least some jellyfish. We must therefore, reckon with the burial of substantial *Rhizostomites* individuals.

In any case we do have to consider both, imprints and casts of actual body-remains, in the *Rhizostomites* type of jellyfish preservation.

There is no doubt that permeabilitty of animal tissues played an important role in jellyfish largely because less concentratded fluids are being extracted from the body. The residue is readily preserved and entombed. Again, this has been verified by *Aurelia* experiments. After three days in highly saline water the animal's body had lost much of its original water content, many wrinkles became visible on its dorsal surface. This is another feature recognized in many a *Rhizostomites* of the Upper Jurassic (pl. 3, fig. 8). Almost any specimen shows at least a wrinkled marginal ring.

On covering an *Aurelia* with mud layers we received a sedimentary surface closely resembling those over Solnhofen *Rhizostomites,* coming from within a carbonate bed. Since there is no change of structure in the sediment above buried *Aurelia* or *Rhizostomites,* dehydration must occur before or during precipitation of sediment.

We have no evidence on the decay-rate of our jellyfish because our specimens were mailed from Helgoland in 4 % formaldehyde/seawater — solution. Though washed in seawater before insertion into the water of the experimental tank, the remainder of the formaldehyde plus the increased salt content may have counteracted decay. Excepting some loss of water, the jellyfish-carcass showed but little change after more than four weeks in the brine. Further loss of body fluid became evident at the end of the second month.

At any rate, our experiments permit to state that jellyfish preservation must not necessarely depend on extremely shallow water (JANICKE 1967, p. 88, 1969 p. 166) nor on water recess.

The badly preserved *Leptobrachites* type is the result of continued decay or even of stranding and retrieval by lagoonal water (cf. SCHWARZ 1932, p. 286). JANICKE (1967, p. 86 and 1969, p. 166) assumes entirely subaquatic burial conditions for these specimens while MAYR (1967, p. 22) would rather have them stranded. Fossilisation conditions of *Leptobrachites* are, naturally, just inverse as with birds and pterosaurs (see p. 11) and so fit with the entire setting.

Birds and pterosaurs deserve particular attention in our interpretation of the Solnhofen depositional environment. W. SCHÄFER (1962 pp. 55—58) gave an instuctive description of post-mortem incidents that may happen to a bird's carcass prior to burial on the sea-floor. Sinking of the cadaver is reported to have occured after a floating stage of several weeks. SCHÄFER's text implies that preservation on the sea-floor is more favorable in quiet waters and anaerobic environment.

His observations in the coastal area of the North Sea indicate a considerable number of dead birds at the shore-line and on sandbars. Here the drying process mummifies the cadavers and effects the curious backward twist of head and neck. A slight rise of the water level coupled with a seaward wind may easily drift some mummies off-shore and they may finally sink there. The only remains of birds from Solnhofen, *Archaeopteryx,* have been found in just such an awkward mummy-like condition. There are, however, differences in preservation of the known specimes. The rather well preserved Berlin specimen was recovered from the near-shore facies. This means the cadaver had not been drifting in the lagoon as long as the first and the third specimens. These remains were found in the off-shore region of the lagoon. They must have been considerably longer adrift for their remains show progressive stages of decay. WELLNHOFER (oral communication) finds this consistent with the distribution of preservational stages in pterodactyls.

Compared to recent birds, anatomic features made an *Archaeopteryx* cadaver much less subject to polonged drift. The bones of *Archaeopteryx* lack pneumaticity, an acquisition distinctive of modern birds. The skeleton was heavier because of its long reptile-like tail (see HELLER 1959 p. 22). So the feathers only, and what other mummified parts remained, could have retarded sinking.

In this light any train of thoughts to declare *Archaeopteryx* a paramount proof of water-withdrawal from the lagoons is misleading. Thus the double imprints of *Archaeopteryx* feathers (RAU 1969, p. 7) are not due to the mummification process but to slightly agitated water preceeding complete entombment.

The following observations are concerned with rather sedimentological and general aspects.

1. Underwater drag-marks of ammonite shells (figured in fossil state: ROTHPLETZ 1909, pl. 2, fig. 3 and BARTHEL 1964 pl. 8, fig. 1) were simulated by gently pulling an ammonite steinkern over carbonate mud. For ammonite rollmarks see SEILACHER 1963 and BARTHEL 1964.

A narrow and deep furrow was engraved into the ooze by means of a pin (pl. 4, fig. 9). Feather-marks at the rims tell the direction of drag (see BARTHEL 1964 pl. 8 fig. 1 in fossil state).

Both marks held clearly in the soft mud until the ooze was stirred up after several weeks. It is important to note this because it has been doubted that soupy mud would keep any marks under water. Comparable marks in the lithographic limestone, therefore, have been assumed to be imprints on drying mud (MAYR 1967, p. 23).

2. Buff carbonate mud from Florida had been kept in a tank for approximately three months. Below the surface it had turned into a badly smelling bluish-gray to black ooze. During this time the covering salt water had neither been removed nor had any water been replaced. Sediment dwellers, if ever present, did not leave any signs of action at the sediment/water interface.

Temporary stagnancy in the Solnhofen basins must have brought about similar results. Today the limestone has a light gray to buff color. Dark and bluish-gray rock is exposed in just a few deep quarries.

Leaching of the original rock is due to prolonged exposure to karstic waters, as the beds came to rest above sea level for at least 130 M. Y.

3. FESEFELDT 1962 and v. EDLINGER 1964, 1966 supplied facts corroborating deposition of the Solnhofen lithographic limestone in basins („Wannen") framed by dead reefs (see p. 3). The bottom of the basin center, in most cases, was deeper than the channels to adjoining basins. Hence complete drainage, as propagated by some authors, was virtually impossible.

Evaporation of the residual water should precipitate gypsum, anhydrite, and salt. Except for occasional indefinite pseudomorphoses on bedding planes, traces of evaporites are unknown.

Drying mud, observed during the butterfly experiment (p. 8) contained numerous tiny salt crystals at its surface. Since the climate was hot and rather dry at that time, the lithographic limestone should be rich in evaporites if the basins had fallen dry.

4. The sediment itself provides a valuable feature, suggesting permanent-inundation during and after deposition. v. EDLINGER reports (1964, p. 57) single beds to hold out for more than 8 km, regardless of basin morphology. To v. EDLINGER this means very uniform sedimentation in quiet water. Recent carbonate deposition in close proximity to the shore-line is strikingly different from the above pattern. Reworking and deep incisions in the mud-flats by tidal channels are common in these realms. Tidal channels are missing completely in the Solnhofen area. The assumption of an intertidal or supratidal environmental origin for the lithographic limestone, therefore, has to be rejected.

5. There is little doubt that a thin algal cover will form on any mud-flat exposed for some time. As desiccation of the sediment goes on the algal mat will warp and shrink. At the appearance of mud-cracks the mat tears up to form algal „chips". These chips often begin to roll up at their margins. Continued sedimentation will protect such sedimentary structures from destruction, at least in some places.

The Solnhofen lithographic limestone, however, are devoid of comparable algal features.

6. Let us assume for a moment that the lagoons fell dry. The carbonate mud was rather soupy then. Animals trapped would be sloppy with mud in

the effort to free themselves and whatever vestiges would be smeared. The instant the mud-surface hand developed a surface film there must have been the possibility for insects to walk on. Still later it should have carried lighter, and, eventually, heavier land animals. Their tracks could hardly be missed.

Further exposure to the atmosphere had certainly caused mud-cracks. Formation of Loferites (A. G. FISCHER 1964) and related structures were to be expected.

None of these features have ever been reported from the Solnhofen lithographic limestone. Structures supposed to be mud-cracks, according to JANICKE 1967, 1969, result from subaquatic shrinkage due to syneresis.

7. The Solnhofen lithographic limestone is a rather pure carbonate. This fact has been known for long and it is confirmed by our samples below.

Two microsections were taken. One, picked near Eichstätt, measures 16,2 cm, and thickness of beds ranges between less than 1 mm and 9 mm, with 45 beds discernible. The second, recovered at Langenaltheim near Solnhofen, covered 11 cm with 14 beds ranging between 2 mm and 33 mm. The samples for analysis were distributed rather equidistantly over the sections (Eichstätt: 13; Langenaltheim: 8).

Mrs. G. CAMMANN (Petrographisches Institut, Munich University) kindly analyzed these samples. She reports $CaCO_3$ values between 95,85 % and 98,51 %, a $MgCO_3$ average of 1,12 %, and a residue percentage of 0,56 to 2,72.

SEIBOLD (1952, 345) pointed out that in his paper the entire residue, remaining after dissolution in HCl of the samples, is referred to as ‚clay'. Our Solnhofen samples provide but traces of Al_2O_3. Their residues actually consist of SiO_2 and Fe. Samples with high residue contents (2,62; 2,72) nevertheless are very ‚marly' in appearance. High residue content apparently made these rock-portions more accessible to weathering. Further chemical studies are highly desirable because the mode of sedimentation may be comparable to such as SEIBOLD suggests for parts of his Oxfordian section (1952, 355—362).

Carbonate as well as non-carbonate were supplied by water influx from the open sea. Rocks of the low northern hinterland must have provided the particles dispersed in the sea.

Summarizing experiments and criteria presented in this paper, we find that the Solnhofen lithographic limestone has been formed in permanently submerged lagoons. The results further corroborate our 1964 model.

Model for the depositional environment of the Solnhofen lithographic limestone

The following model has been developed by the author in his 1964 paper. Some modifications are added here.

1. Sea bottom relief of sponge-algal reefs.

2. Uplift in the N, downward tilt in southern direction. Exstinction of sponge-reefs in the N.

3. Development of a coral-hydrozoan reef-barrier at optimal water depth for these animals, on dead sponge reefs. Sufficient sediment-supply into backreef-lagoon via reef-belt and its channels. Predominance of marine faunal elements.

4. Dead sponge reefs form ridges and basins within the backreef-lagoon. For 1.—4. see fig. 1 and pp. 2—6.

5. Hot climate (reptiles, corals, plants, carbonate sediments) suggests strong evaporation.

6. Heavier salt brine sinks to the lagoonal floor. Stagnancy on basin bottoms (compare SCHMALZ 1969, p. 804, initial stages). Epi- and infauna absent.

7. Low inter-basinal and inter-recifal bars permit episodic brine flow-off (see also SCHMALZ 1969, p. 804, fig. 5). No precipitation of evaporites.

8. Depths of water may be estimated from sponge-reef relief (30—60 m). Minimum depth to warrant density stratification (according to SCHMALZ 1969, p. 799) is 20 m.

9. As sedimentation proceeds, the basinal relief alsmost disappears and, finally, different types of sediment take over.

Occasional freshwater influence in the near-shore region cannot be excluded. Episodic rains may have spread a sheet of freshwater over parts of the lagoon as evidenced by insects and small reptiles. Remains of larger land vertebrates are unknown. Freshwater influence, however, was supposedly stronger in the N, in areas now truncated by erosion.

Comparisons

There remains the question whether the Solnhofen lithographic limestone is a unique sediment. The answer is negative. This type of sediment occurs since Precambrian times.

Then, if it is not time-bound, does this rock have to be allocated to certain geological and climatic conditions? This seems true as far as the author can judge from Mesozoic localities. A Middle Triassic type at Montreal (Spain) is presently under investigation by G. MÖLLER Tübingen (oral communication).

The author has visited the Upper Jurassic beds of Nusplingen (Württemberg, Germany), Cerin (France) and the Cenomanian fishbeds of Lebanon. The Monsech occurrence (Spain) is receiving a sedimentological survey by G. SCHAIRER & V. JANICKE 1970, Munich.

Deposition in more or less restricted depressions is common to all of the Mesozoic beds named. Excellent bedding and many other features indicate sedimentation in undisturbed waters. Bottom dwellers are largely absent. Preservation of fossils is generally excellent. Four deposits of six are associated with reefs or reef-like structures (Montreal, Cerin, Nusplingen, Solnhofen).

Whether this was also the case with the Monsech limestone (Tithonian/Berriasian, KRUSAT 1966 (up to Barremian); SCHAIRER & JANICKE 1970, in print) is difficult to say since lateral correlation is problematic. Fauna, flora and type of sedimantation render the assumption of a coastal lagoon acceptable. The Lebanon fish deposits are considered as being laid down in local syn-sedimentary tectonic depressions on the neritic shelf. Detailed paleoenvironmental and stratigraphic studies of the Haquel and Hejoula localities are being completed (U. HÜCKEL, in preparation for this series, and personal observation of the author).

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Explanation of plates

Plate 1

Fig. 3. Subaerial activity of a *Penaeus* on moist carbonate mud (Big Pine Key, Florida). Length of animal about 10 cm. — Solnhofen ‚Penaeus' have never been found in association with such tracks.

Fig. 4. Simulation of subquatic insect preservation. It took nine days to sink the butterfly presented in the picture. As in other experiments the bottom of the vessel is covered with carbonate mud. ca. 0,66 ×.

Plate 2

Fig. 5, 6. Two stages of experiment to produce subaquatic imprints of jellyfish. Substrate carbonate mud (Big Pine Key, Florida). Diameter of jellyfish *Aurelia* about 9 cm. Note dehydration wrinkles on dorsal side of jellyfish which is covered with a film of mud. — Similar impressions have been recovered from the Solnhofen lithographic limestone.

Plate 3

Fig. 7. Complete setting of jellyfish experiment (see figs. 6, 7). Maximum length of tank 25 cm. Salinity of water 50 ‰.

Fig. 8. *Rhizostomites,* fossil jellyfish from the Lower Tithonian lithographic limestone found at Gungolding-Pfalzpaint (Eichstätt-Solnhofen area at large). Dehydration wrinkles are marked by arrows. Depository of specimen: Bayer. Staatssamml. Paläontologie etc., Munich, 1955 I 262. × 2/3.

Plate 4

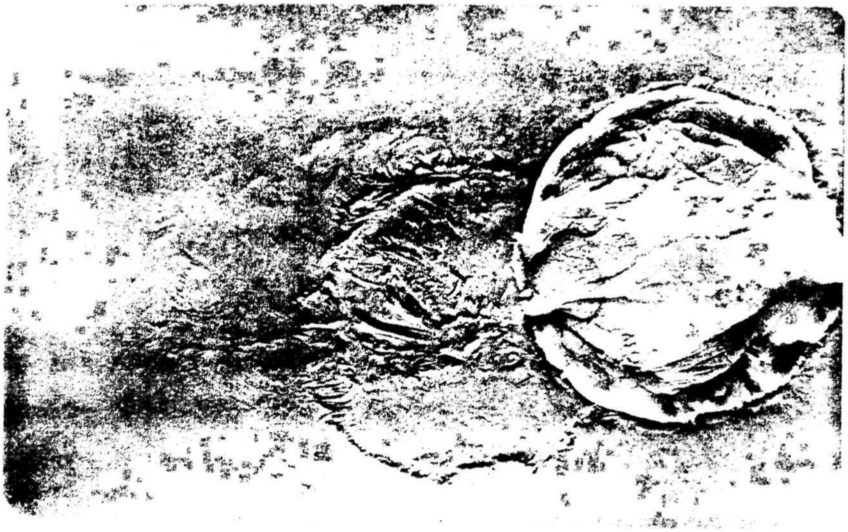
Fig. 9. Subaquatic mark in carbonate mud. A pin point was used to show stability of even the slightest impressions. These marks proved restistant to moderate oscillatory water movements. About nat. size.

Fig. 10. Microsection of thinbedded lithographic limestone in situ. Harthof near Eichstätt. Left: weathered; Right: unweathered; bedding is indicated by manganese dendrites. Diameter of lens cap: 5,5 cm. Beds or sets of these beds have been traced uninterruptedly over kilometers.

3

4

K. W. Barthel: On the deposition of the Solnhofen Lithographic Limestone.



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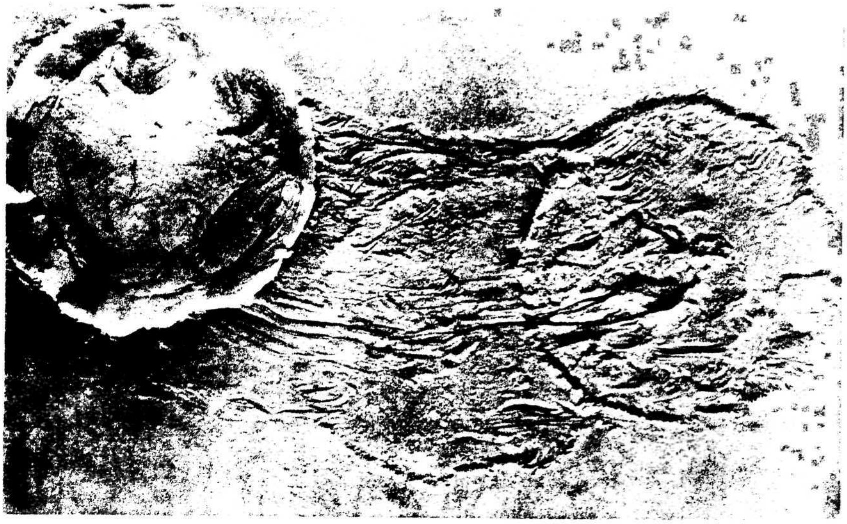

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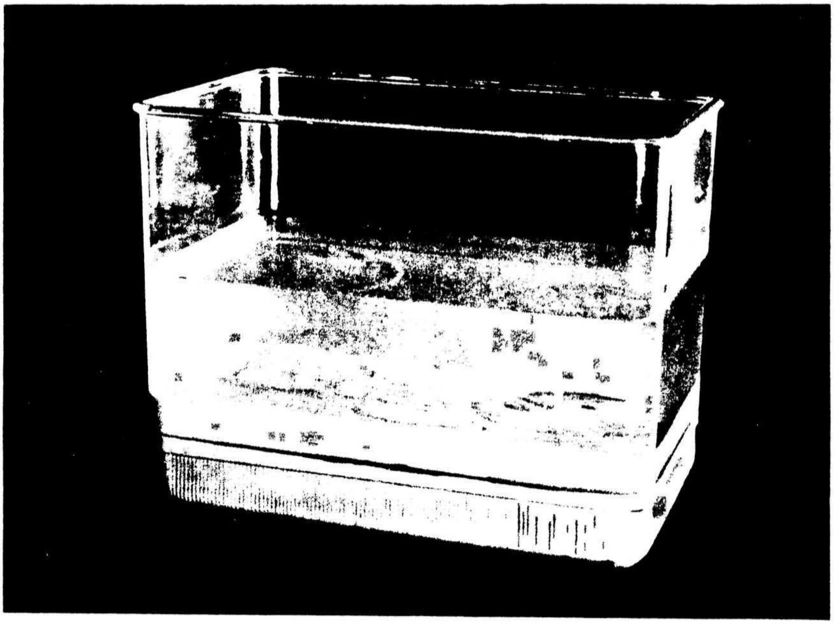
K. W. Barthel: On the deposition of the Solnhofen Lithographic Limestone.



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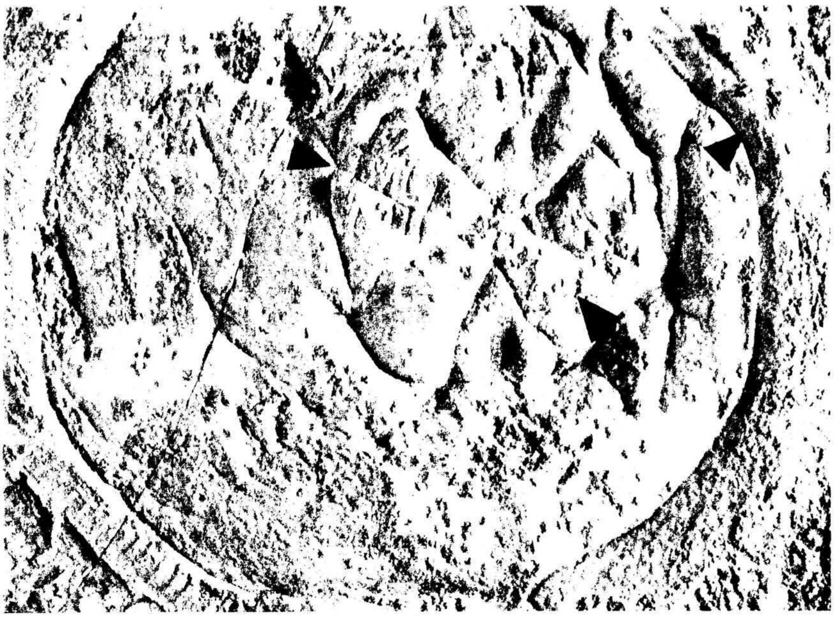

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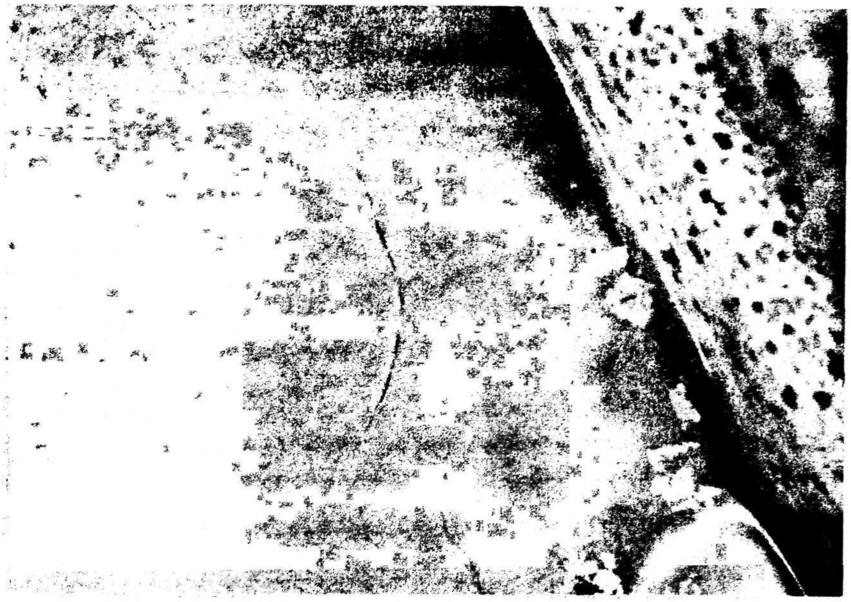
K. W. B a r t h e l : On the deposition of the Solnhofen Lithographic Limestone.



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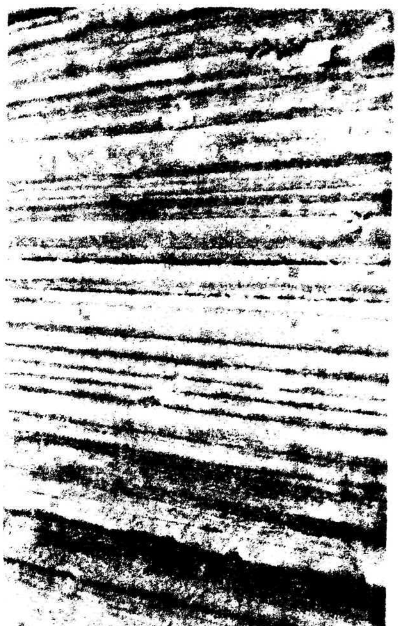

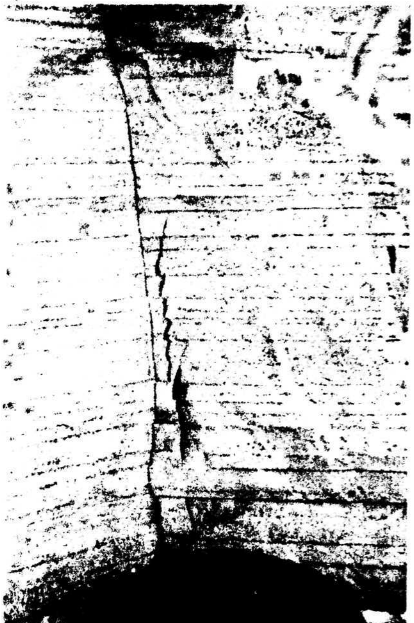

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K. W. Barthel: On the deposition of the Solnhofen Lithographic Limestone.