GEOLOGIE EN MIJNBOUW VOLUME 50 (1), p. 3-8 1971

ORIGIN OF SOLNHOFEN LIMESTONE

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AGE AND FACIES

Until recently the "Plattenkalk" of Solnhofen has been regarded by most geologists as a littoral formation. This was in a large part due to the authority of O. Abel, who in his book "Lebensbilder aus der Tierwelt der Vorzeit" devoted a chapter to the fauna and environment of deposition of the limestone, entitled "Am Strande von Solnhofen in Bayern in der Oberjurazeit". Abel supposed that the Plattenkalke had been formed on coastal mud flats which were periodically flooded by the sea, and lay emerged in the intervening times.

In the last few years this interpretation has been contested, a.o. by Barthel (1964). Already before the appearance of Barthel's paper the present author had started a sedimentological study of the Solnhofen limestone, which led him likewise to reject the idea of a littoral genesis (van Straaten, 1971).

With regard to these different views it should be stressed that what in the literature commonly has been called Solnhofen limestone comprises deposits of varying age (Malm ζ 2a, ζ 2b, ζ 3 and younger, see Fesefeldt, 1962) and of varying facies. The most characteristic Solnhofen-type facies is found in the ζ 2b of the area of Langenaltheim – Solnhofen – Mühlheim – Eichstätt and near Zandt.

The deposits near Daiting, which formerly were included in the Solnhofen formation belong to the ζ 3, and differ from the typical facies by their high contents of calcitized radiolarian skeletons. Some layers are true (calcitic) radiolarites. The so-called Solnhofen limestone in the area of Jackenhausen and Hennhüll has a quite different character, with features like cross-bedding, wash-outs and layers of coarse organo-clastic material. It is clearly a border facies.

In this paper only the ζ 2b limestones of the area between Langenaltheim and Eichstätt are considered. Detailed field work (Fesefeldt, 1962; von Edlinger, 1964, 1966 and many others) has shown that they were deposited in basins, up to some 3 km wide, lying between elevations of an older reef rock formation, see fig. 1. They consist mainly of layers of very pure limestone (96–98% $CaCO_3$, 97–99% $CaCO_3$ + $MgCO_3$), of micritic texture (elements mostly finer than 5 μ): the "Flinzen", with thicknesses of about 1 mm to 30 cm. At irregularly spaced intervals layers of more marly limestone are intercalated: the "Fäulen" (s.l.).

The bedding planes of the Flinzen and Fäulen are always flat, except in the "Krumme Lagen" (fig. 1), which have been contorted by subaqueous sliding. They are quite smooth (most Fäulen, some Flinzen) or have (most Flinzen) a minor relief due to load casts, fossils, stylolites and (extremely rare) micro-ripplets ($\lambda < 1$ mm). Normal wave (or current) ripples, mud cracks, cross-bedding, wash-outs and layers of coarse (organo-)clastic material are entirely absent, proving that these layers can not have been formed in intertidal environment, or above "wave base" in sublittoral environment.

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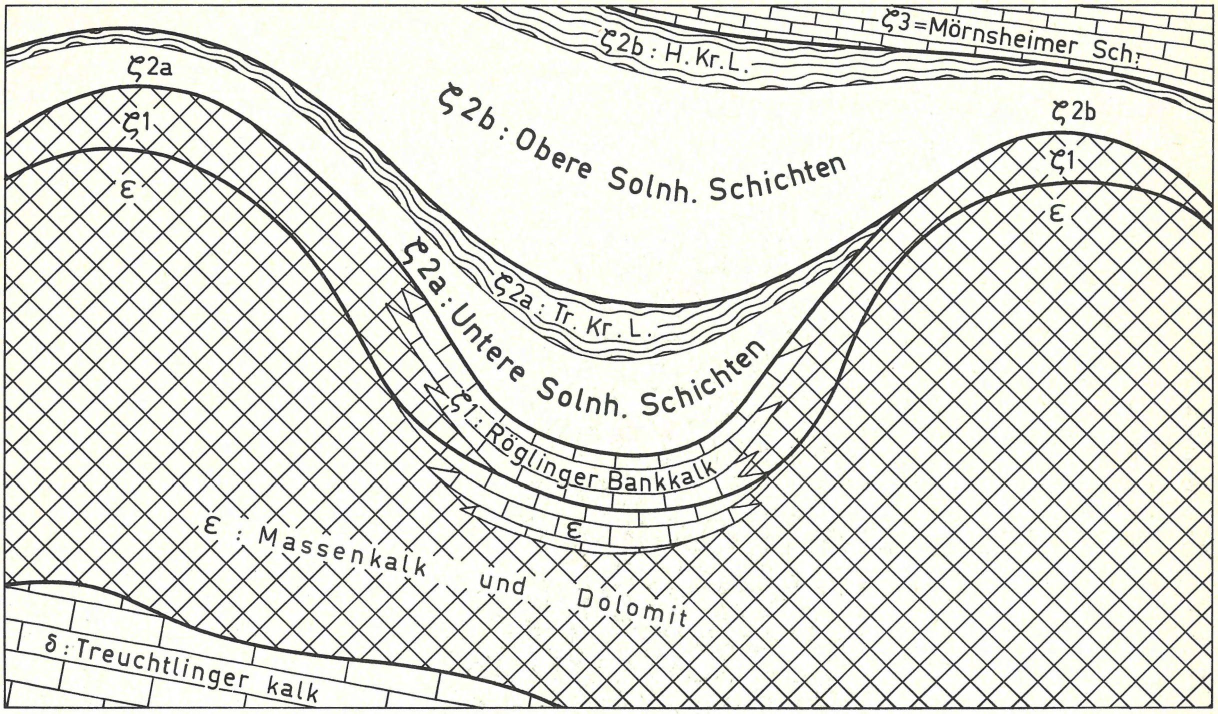

Fig. 1
Schematic diagram of Upper Jurassic in Solnhofen area, showing relief of reef rock formation (maximum difference in level circa 100 m). H.Kr.L. and Tr. Kr. L.: Hangende (upper) and Trennende (lower) "Krumme Lage".

FOSSILS

Although the Solnhofen formation, compared to most other limestones, is rather poor in fossils, the number of species that in the course of time have been found in the very numerous quarries is large. The fossils of the ζ 2b limestones in the above mentioned, limited area can be grouped as follows:

1. Marine organisms that swam or floated in the water: more than 99,99% of the total fossil content. They comprise:
   A. Macro-fossils.
      a. Pelagic crinoids; mainly *Saccocoma pectinata.* This is the only macro-fossil that is really common.
      b. Ammonites: not uncommon.
      c. Fishes, about 150 species (K u h n, 1966), yet relatively rare. The most widespread species is the small (7 cm) *Leptolepis sprattiformis.*
      d. Larger crustaceans; rare.
      e. Belemnites and squids: rare.
      f. Reptiles: very rare.
      g. Jelly-fishes: very rare and badly preserved. All well preserved fossil Scyphozoa in the Solnhofen limestone come from quarries near Pfalzpaint, east of Eichstätt, where the facies differs notably from that at Solnhofen.
   B. Micro-fossils: coccoliths (common), radiolarians and ostracods (relatively rare).
2. Bottom living animals that could also swim: some crustaceans, and (Meso-)limulus: rare.
3. Parasites: Hirudinea, rare.
4. Purely benthic marine organisms that may have drifted in, either by themselves or attached to floating objects, e.g. algae and clusters of small oyster shells: rare.
5. Purely benthic marine organisms that may have been supplied by bottom currents: Foraminifera tests, only at very few places.
6. Flying animals: insects, many species, but all very rare, reptiles, very rare and Archaeopteryx, a few specimens only.
7. Land animals: one reptile (Homoeosaurus), extremely rare.

Fossils of benthic animals or algae that could not easily be transported by drifting or bottom currents, such as calcareous algae, sponges, corals, echinoids, serpulids, bryozoans, gastropods, scaphopods, most pelecypods etc. are absent or limited to absolutely exceptional finds. On the contrary, these latter remains make up the bulk of the biogenous material in recent coastal deposits and in older sediments for which a littoral or shallow marine origin has been established beyond doubt. It must be concluded, therefore, that also the paleo-ecological properties of the Solnhofen limestone disagree completely with the interpretation given by Abel.

In a most interesting paper M a y r (1967) suggested that the insect fossils of the Solnhofen limestone point to emergence of the sea floor, because normally dead insects stay floating on the water surface by the air entrapped in their tracheae. Fossilization can take place, according to him, only when insects, fallen on wet, emerging mud stick to the bottom during subsequent flooding. However, experiments by van Straaten showed that movement of the water surface by waves soon results in the sinking down of dead insects.

Lumbricaria, which after *Saccocoma* is the most common organic feature on the bedding planes has formerly been interpreted as a fossil worm, or as the expelled intestines of holothurians, i.e. as benthic remains. In reality it is a type of faeces, consisting entirely or almost entirely of broken *Saccocoma* remains (J a n i c k e, 1970, also v a n S t r a a t e n, lectures, 1969). Hence, it must have been produced by pelagic animals (s.l.). Possibly these were (cf. K u h n, 1967) flying reptiles, which swam on the sea surface, like ducks.

In correspondence with the lack of benthos fossils, the Solnhofen limestone is devoid of burrowing structures. Accordingly, the original depositional structures are left intact, accounting, among other things, for the platy character of the limestone ("Plattenkalk"). Very exceptionally tracks have been made on the bedding planes by Limulus and crustaceans. In these cases one finds, at the end of the tracks, the fossilized animals themselves. Apparently, the few animals that landed in the bottom environment soon met with their death.

The fact that no bottom fauna could develop in the Solnhofen basins was attributed by Barthel to oxygen deficiency in the deeper water masses, caused by stagnation. Of all conceivable causes that in general can lead to absence of bottom life, oxygen deficiency seems indeed the only one which can have been responsible for it in the Solnhofen basins.

However, Barthel's arguments for stagnation are inconclusive. Among other things he mentions that at some places fossils of ammonites or squids lie immediately beside the imprints made by the dead animals, where, sinking down through the water, they first touched the bottom. It may be deduced that, in these cases at least, there were no currents of sufficient strength to displace the dead animals over the bottom, but this does not prove that such currents did not occur at other times. Moreover, even with very slow currents aeration of water can still take place.

MANNER OF DEPOSITION

Various features point to a rapid sedimentation of the separate Flinz layers: 1. the complete lack of rhythmic (seasonal) laminations within the limestone layers, indicating formation within the time of one year, 2. the abundance of load casts, pointing to sudden deposition of relatively thick beds of lime mud on top of still soft sediments, 3. the circumstance that practically all macro-fossils lie wholly or partly on the bedding planes, and hardly ever within the Flinz layers themselves.

Notably this last property renders it probable that the deposition of the successive Flinz layers took up only a very short time, perhaps not more than a few days. The bedding planes, on the other hand, may correspond to periods of moderate to great length. In this connection it is interesting to note the differences in the state of preservation of the fossil fishes, which varies from totally undecayed specimens, lying on socles, to strongly decayed remains without socles. The former evidently were covered by new mud shortly after they sank on the bottom, the socles being due to subsequent compaction (cf. fig. 2). The fishes that lay exposed to sea water for long periods underwent considerable (anaerobic) decomposition before they became embedded.

The problem arises: how could so much carbonate mud be deposited in such a short time? Many Flinz layers are several centimetres thick, the maximum being 30 cm. This problem involves the question of

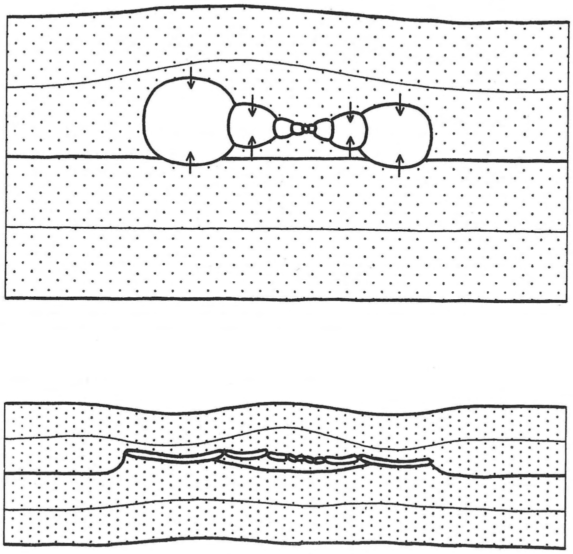

Fig. 2
Diagram, explaining formation of "socle" below ammonite fossil, due to compression of shell after covering by new sediment. Compression took place by pressure from above and from below. Similar socle formation occurred under other, originally hollow remains, and under fossils that were compressed simultaneously with intraformational decomposition of weak parts (e.g. crustaceans, fishes).

the origin of the carbonate material. Clearly, the purity of the Flinz limestone points to an origin from sea water (either by direct precipitation, or via organisms). Terrigenous sediment can never be so poor in non-carbonate admixtures. Even if the hinterland was composed exclusively of limestones, one should expect appreciable amounts of clay minerals, organic silica, clastic and authigenous quartz, and iron compounds, owing to their concentration by weathering processes.

However, the quantities that at any moment can be withdrawn from the sea water solution (directly or by organisms) are only very small. Hence, the high deposition velocities lead to the conclusion that the carbonates must have been supplied from elsewhere, from a fairly extensive source area, lying outside the Solnhofen basins themselves.

Such a supply implies current action, but, since evidence for strong currents is lacking (no wash-outs, no layers of coarse material, very few flutings[2]), only very locally some displaced benthic foraminifera tests) these currents must have been rather slow. Now, if slow currents have supplied great quantities of carbonate material, it means that this carbonate can not have been carried in solution, but that it must have been transported as suspensions (of very fine particles).

The conclusion that the carbonates of the Flinz layers have been deposited from suspensions is in agreement with the thickness distribution of these layers. The thicknesses are maximal in the deepest parts of the original basins. On the basin slopes the layers become gradually thinner, and, in part, wedge out altogether (cf. Fesefeldt, 1962). Obviously, the suspensions, after entering the basins, first collected in the deepest parts, owing to their higher density. From there they gradually filled up the basins, either partly or completely, depending among other things, on the amounts and the duration of the supply. Since the upper surface of these suspensions must have been approximately horizontal, the thicknesses of the resulting layers became related to the original bathymetry.

It is interesting that the Fäulen show, on the average, a much less pronounced relation between thickness and original water depth. Presumably, most of them were formed by normal deposition, not from suspensions flowing along the bottom, but by settling of separate particles that had been transported individually. Part of the Fäulen mud may have been supplied during periods of strong rain fall, when the density of the surface water layers was lowered and terrigenous mud from rivers was spread out relatively far over the sea.

On account of the above considerations, the author proposes the following reconstruction of the events which led to the formation of the Flinz layers. During exceptionally heavy storms wave action stirred up much carbonate mud that had been deposited on the bottom of a very shallow shelf sea, north of the belt of Solnhofen limestones. The storms may have been generated in the tropical parts of the Thetis sea, more to the south (tropical hurricanes or typhoons) and migrated in northern directions. Their average frequency may have been about once per year. Where the waves moved towards the land, water was piled up in the littoral zone, and an under-current was set in motion, directed away from the coast.

The under-current carried the finest fractions of the suspended carbonate mud towards the Solnhofen

[2]) Unlike in the Pfalzpaint facies, which is rich in such features (see van Straaten, 1971).

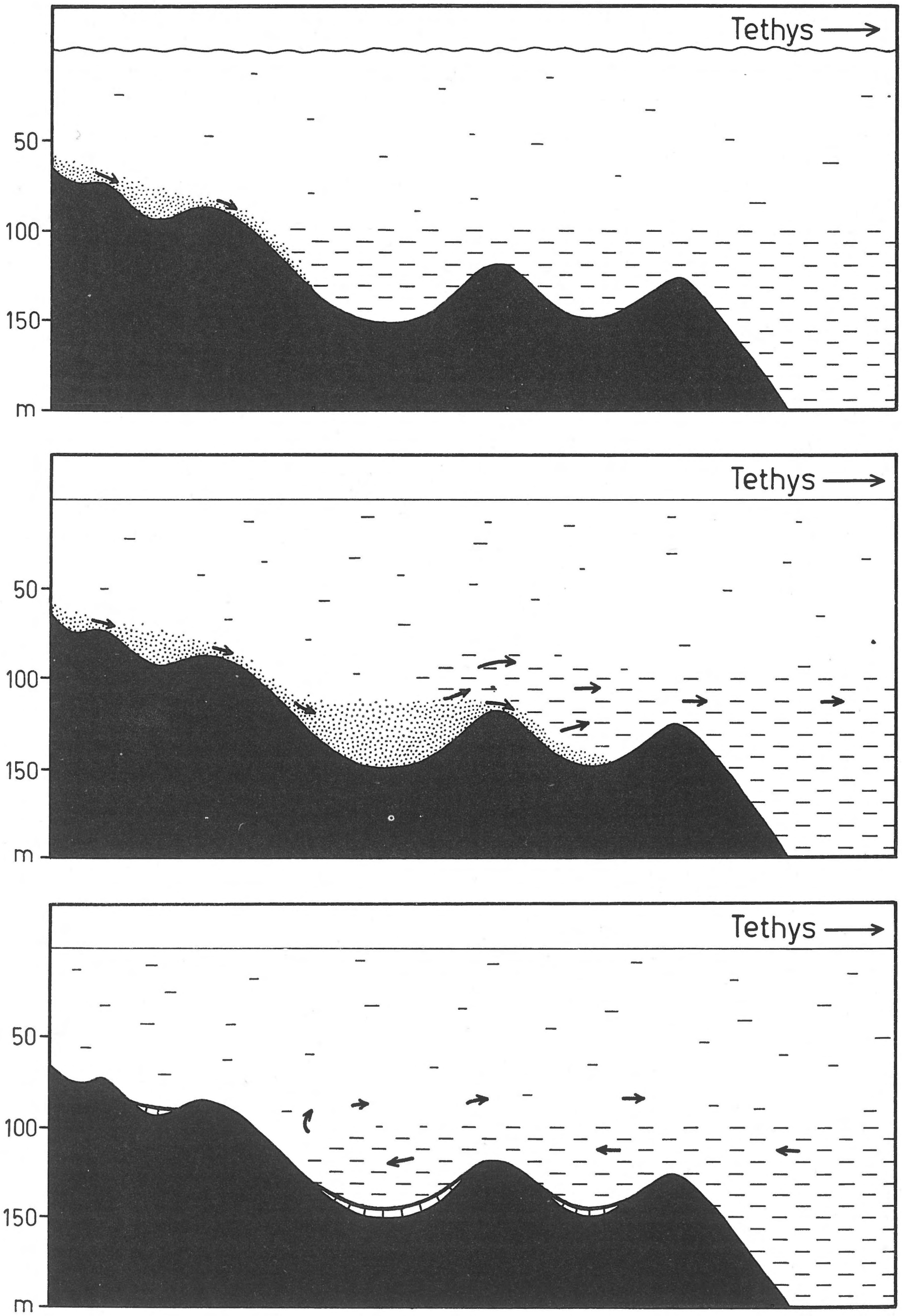

Fig. 3
Reconstruction of events leading to deposition of ζ 2b limestone in Solnhofen area. Black: older formations. Stipples: suspension of carbonate particles. Striae: oxygen-free zone.

basins. After passing over the edge of the basins the suspensions flowed down the slopes by their own weight, as turbidity currents of mostly rather low density and small velocity. The currents may have lasted for many hours, perhaps even a few days. As soon as the suspensions came to rest in the deepest parts of the basins, they started to condense, under the influence of gravity. Rare limulids and benthic crustaceans, which had let themselves be carried by these currents and landed in the condensed suspensions, must soon have died, owing to the plugging of their gills by fine carbonate particles.

Of course, the deathliness of the suspensions (for these animals at least) can not account for the lack of bottom fauna development during the intervening periods. This latter was attributed to the absence of oxygen in the deeper water masses. It may be objected that oxygen deficiency seems to be incompatible with the regular occurrence of suspension currents, because, with each inflow of suspension water from the shallow shelf sea fresh quantities of dissolved oxygen must have been introduced in the Solnhofen basins.

However, this apparent contradiction is easily solved by supposing that the oxygen deficiency was due, not to stagnation of the bottom waters, but to free communication of these waters with an oxygen-free zone in the open Thetis, south of the Solnhofen basins. Such zones without (or with only very little) oxygen are a common phenomenon in tropical and subtropical regions of the present oceans. In some areas their upper limit lies at depths of not more than 100 m.

The deeper, oxygen-free water in the basins was easily driven out by the carbonate suspensions, owing to their higher densities. But, as soon as the suspended load had settled on the bottom, the densities of the remaining waters were down again at about the values they originally had (before the storms) in the shallow shelf sea. Since these densities were lower than in the oxygen-free zone in the open sea in the south (in connection with the difference in depths), the newly arrived waters were soon driven out in their turn (fig. 3). Hence, the state of aeration each time was only of very short duration.

RELATIVE BOTTOM SUBSIDENCE

One of the shortcomings of Abel's interpretation is that it did not account for the lack of reef growth, simultaneous with the deposition of the Solnhofen limestone. During the Malm ϵ reef growth had dominated sedimentation in this area. Since then it gradually decreased. During the ζ 1 only the highest parts of the reefs were still actively growing, and in the course of the ζ 2a it came to a complete stop. If the Solnhofen limestone had indeed tormed in littoral environment, one should expect a local renewal of reef rock formation, leading to intercalations of biohermal or at least biostromal nature.

In the above given reconstruction the absence of such intercalations is no problem: it was due to the gradual deepening of the sea. During the ζ 2a the bottom was lying in the lower parts of the zone of aerated surface waters. In the ζ 2b the whole area had sunk into the oxygen-free zone.

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