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Hidden hiatuses and related phenomena

Some lithological problems

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The lithological variations in a marine series of strata have arisen as a consequence of changing conditions of deposition and of supply of allochthonous material. Particularly common and pronounced are variations in series formed in shallow water, where changes in the movement of the water, the strength and direction of currents, are immediately registered. An increase or decrease in the depth of the water can give rise to radical, prolonged changes. Momentary surges and eddy currents, subaquatic sliding, earthquakes, etc. have had a spontaneous effect and left more or less noticeable traces in the series of strata. Some of the lithological irregularities will be illustrated below and their origin discussed. In the first place problems concerning submarine denudation and corrosion will be dealt with, examples being taken from limestone series. Closely connected with these problems is the question of the origin of hidden hiatuses. Their formation will be discussed. Some observations and reflections on a certain form of graded bedding are adduced in conjunction with what has previously been stated.

Submarine denudation

Examples of submarine denudation can be found in most series of strata. The hiatus formed by the denudation is sometimes easy to establish stratigraphically and paleontologically; in other and the majority of cases it is only noticeable lithologically. However, in the latter case it may be very pronounced, e. g. in a nonconformity or in an intraformational conglomerate. Less far-reaching and shorter-lived denudation is, however,

Fig. 1. Bedding surface with coarse fossils accumulated by submarine denudation. — Sphaerocodium limestone. Silurian. Bjersjölagård, Skåne. Nat. size. Photo. 1802.

much more common. It only forms small, often indistinct or wholly hidden hiatuses. How deep a denudation has gone may be difficult to determine, unless remains of the denuded strata have been preserved or a stratigraphical examination makes possible an estimation of the size of the hiatus.

A submarine denudation first of all attacks the uppermost, most recent, and still unconsolidated layers. If these are entirely or partly washed away from a certain part of the sedimentation area, the latter may be deprived of deposits from a considerable space of time without our being able to demonstrate that this has been the case. If some fossils resist the denudation, they become accumulated and play the same part as an intraformational conglomerate: they show that a denudation has taken place (fig. 1). At best they also give an indication of the extent of the denudation.

Unconsolidated mud-layers which have not contained skeletal remains of organisms or coarse grains show an indistinct or wholly hidden hiatus following a temporary denudation. An entirely similar hiatus would have been formed through a temporary cessation of sedimentation. Non-deposition is probably in fact the most common cause of the origin of small hiatuses. In these cases the hiatus either is not at all evident lithologically or appears as a more or less distinct bedding-plane. It may be impossible to decide whether denudation together with non-deposition has formed the hiatus, unless there are denudation remains.

Submarine denudation in coarse limestones (coquina, fragment limestones, etc.) has often been sharply delimited in space and time. If the denudation occurred during increased movement in normally active water, it has left no trace in the form of fine-grained beds. The denudation surface and any denudation remains are overlaid by material similar to the denuded material. Marked bedding-planes and fully visible hiatuses are seldom formed by this type of denudation. The occurrence of conglomerates, with pebbles of fossils or limestone, may indicate that a denudation has taken place, but other conditions, too, can have given rise to entirely similar primarily deposited coarse calcareous sediments (cf. HADDING 1956).

The reason for a normally proceeding deposition's being interrupted and perhaps followed by denudation will be further discussed in dealing with hidden hiatuses. Another phenomenon, corrosion, is closely related to denudation and will be examined below, insofar as corrosion is noticeable in limestones.

Submarine corrosion of calcareous sediments

Limestone beds here and there exhibit chemically decayed surfaces, corrosion-surfaces. As a rule they have been formed in connection with non-deposition and denudation. Corrosion, like denudation, has reduced the thickness of earlier deposited sediments. At the same time it has formed peculiar structural forms.

A corrosion-surface, which is also a bedding-plane, is quite different according to whether it has been formed in a dense limestone or in a coarse-grained fragment limestone. A bed rich in calcareous mud exhibits corrosion-surfaces with irregular cavities and elevations. Forms of this kind of corrosion-surface come out particularly well in vertical sections of a limestone bed. Very often the corrosion-surface is covered with a thin crust of glauconite. Glauconite also occurs as impregnation beneath the corrosion-surface. If the corrosion has taken place after a denudation which has formed a conglomerate, the glauconite has been deposited as a crust or an impregnation on limestone pebbles, too (cf. HADDING 1927, and 1932).

Inside a bed of dense limestone several corrosion-surfaces may be found (fig. 2). The connection between the material above and below a corrosion-surface is not eradicated or diminished in spite of the fact that the surface

Fig. 2. Vertical section of a limestone bed with three corrosion-surfaces. Sharply protruding parts contain fossil fragments. Colour banding: olive-green, brown, grey. — Limbata limestone. Lower Ordovician. Borghamn, Östergötland. — Nat. size. Photo. 1803.

has been formed because of not inconsiderable breaks and changes in the sedimentation.

Bands of different colours may occur below the corrosion-surface. Particularly common and pronounced are the colour-bands in the Lower Ordovician limestones of Sweden. As an example may be mentioned the Planilimbata limestone of Öland. Immediately below the covering green crust or impregnation of glauconite there is often a yellow band, which below grades over into a red, followed by a grey. The grey band is separated by a sharp boundary from a lower corrosion-surface and its possible glauconite crust.

Colour-banding, corrosion, and deposition of glauconite help us to see the changes which have taken place in the environment of formation of the limestone exemplified. The course of events has been as follows:

1) Fine calcareous mud rich in small organic fragments was deposited, together with a small quantity of argillaceous matter, in a neutral or at times weakly reducing environment. A slight quantity of glauconite and iron sulphide has been added to the mud. Formation took place in shallow,

slightly moving water. (In consolidated beds we find this sediment as a grey or slightly greyish-green band, here and there with scattered small crystals of pyrite and allochthonous green grains of glauconite.)

2) The deposition of mud continues without the content of fragments or $CaCO_3$ changing. The colour, however, grades successively from grey to greyish-red and deep brownish-red.[1] The temperature of the water goes up, and its pH-value is increased. The sedimentary environment becomes more and more markedly oxidising. Red ferric hydroxide is precipitated. There is no pyrite or authigenous glauconite in this band.

3) The calcareous mud is subjected to corrosion, probably preceded by denudation. The water becomes more active, the temperature falls, the pH-value is reduced. The CO_2-content is increased, the carbonate is dissolved, and released argillaceous matter is washed away. Irregular, occasionally winding and deep cavities are formed,[2] partly with the aid of organisms.[3] In the immediate vicinity of the corrosion-surface the red ferric hyroxide grades over into yellow. The corrosion-surface and the cavities in it are entirely free from argillaceous detritus.

4) The temperature falls still further. No deposition of calcareous or argillaceous mud takes place in the still fairly agitated water. The environment becomes neutral or slightly reducing. Dissolution of the carbonate (corrosion) comes to a halt. Glauconite is precipitated on the corrosion-surface. The walls of the corrosion cavities also receive a glauconite coating.

5) The movement of the water becomes progressively less strong. The temperature rises, the $CaCO_3$-concentration is increased, calcareous and argillacaeous mud is deposited together with small fossil fragments and odd grains of glauconite. The environment is at times neutral, and a small quantity of glauconite is precipitated. A new, grey band, similar to band 1, begins to be formed.

The sculpture of the corrosion-surface shows that the calcareous mud must have had a certain adhesiveness (toughness or hardness) when the corrosion took place. The cavities, which are deep in relation to their width, would not have been preserved in totally unconsolidated mud. The same is true of the protuding sharp tops and ridges which are to be seen on the surface. They have been formed about parts difficult to dissolve, usually fossil fragments (see fig. 2 and HADDING 1958, fig. 17 and 121).

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[1] The author will deal with the origin of different colours of limestone in a forthcoming paper.

[2] There are no mud cracks, trails or other traces of subaereal origin.

[3] For the limestone-dissolving effect of plants (algae) see K. O. EMERY 1946, p. 209.

Fig. 3. Vertical section of limestone bed with strongly disturbed colour bands grey, green, yellow, and red). The sediment was unconsolidated when the submarine sliding took place. — Planilimbata limestone. Lower Ordovician. Borghamn, Östergötland. — Nat. size. Photo. 1808.

We may ask whether corrosion takes place in unconsolidated as well as in firm layers. Dissolution of the carbonate occurs when the water is not saturated with $CaCO_3$ and particularly if there is a surplus of CO_2, which may occur also when unconsolidated calcareous mud covers the seafloor. In fact the soft mud should be more readily dissolved than the firm beds. A direct proof of corrosion's occurring in unconsolidated layers is found here and there in strongly disturbed, distinctly slid mud layers, with colour-banded corrosion zones (fig. 3).

The more or less rhythmical appearance of the corrosion-surfaces in certain beds recalls the equally rhythmical occurrence of thin marly layers lying in and between the limestone beds (fig. 4). The principal difference is that during formation of the mudfree corrosion-surfaces the current has been sufficiently strong to wash away entirely the argillaceous matter released when the calcium carbonate was dissolved. The argillaceous layers between the limestone beds are wholly or partly a calm-water

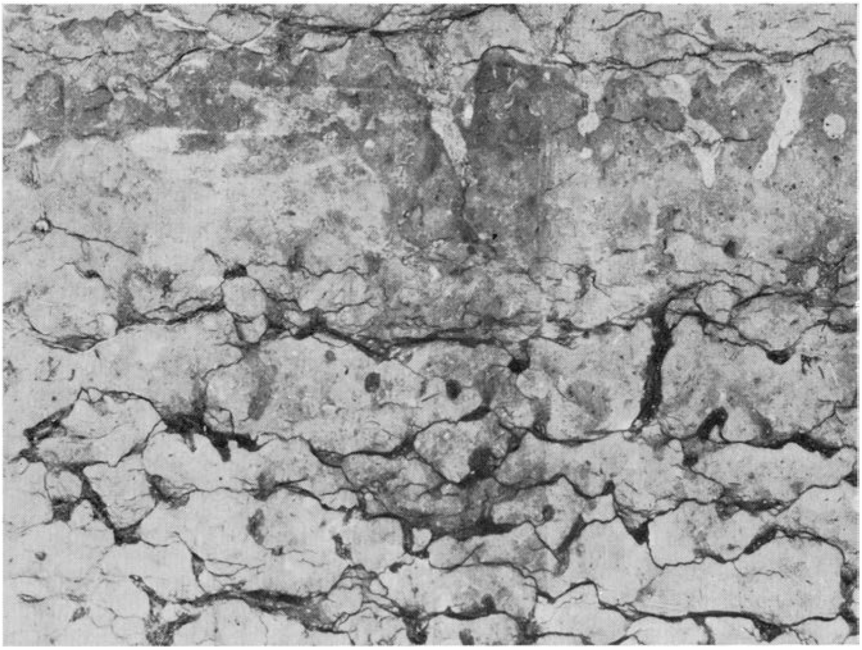

Fig. 4. Vertical section of limestone bed with corrosion-surfaces covered by residual, argillaceous matter. – Limbata limestone. Lower Ordovician. Yxhult, Närke. – Nat. size. Photo. 1508.

residuum of the calcareous sediment.[4] Nothing serves to indicate that changes of the sea-level have caused formation of the bedding or corrosion-surfaces.

The corrosion discussed in the foregoing has concerned dense or fine-grained (microcoquina) limestones of the type predominant in the Lower Ordovician of Sweden. The coarse-clastic fragment limestones with relatively mud-free accumulations of fossil fragments have differently developed corrosion-surfaces. The decay appears in a rough, granular ("gravelly") surface with protruding sharp fossil debris (fig. 5).[5] In the cases observed the corrosion-surface has no glauconite coating. Colour-banding does not occur either. Whilst corrosion was going on, no new material was deposited. Terrigenous detritus (argillaceous substance), released through the dissolution of $CaCO_3$, was washed away. The corrosion has taken place

[4] Cfr K. Andrée 1908, p. 415. A similar interpretation of conditions in the Ordovician Galena-Trenton series is given by Frederick W. Sardeson 1914, p. 265.

[5] Fully analogous dissolution can be observed in dense, Ordovician limestones containing cephalopods or cystoids (see Hadding 1958, fig. 112).

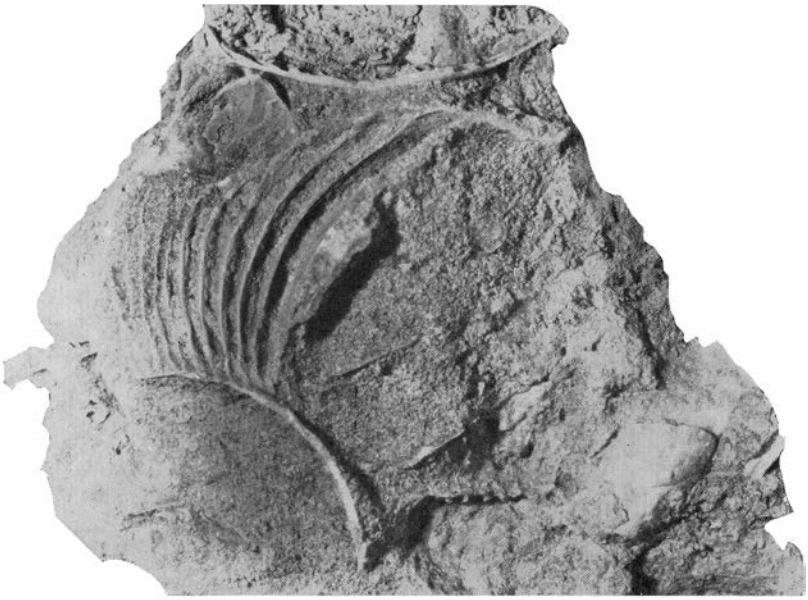

Fig. 5. Grainy corrosion-surface on coquina limestone with cephalopod fragments. — Slite group, Silurian. Klinthagen, Gotland. — Nat. size. Photo. 1804.

in moving water. It has been caused by a lowering of the temperature, reduction of the pH-value, and probably an increase in the CO_2-content of the water. Corrosion has gone on for a considerable time, during which the corrosion-surface has lain clean-washed. During this time or in connection with a reversal to earlier environmental conditions, the corrosion-surface was invaded by benthogenic organisms, including disciform corals (fig. 6). Afterwards the surface was covered with new material, as a rule of the same nature as in the corroded bed.

Hidden hiatuses

Breaks are found in most series of strata, especially those deposited in shallow waters. Above, the occurrence of hiatuses in connection with denudation, corrosion, and non-deposition has been mentioned. Certain hiatuses are so large that they can be established stratigraphically. Many are very pronounced lithologically. The vast majority, however, are smaller, less pronounced, more or less hidden. It is above all these hiatuses which will be discussed below. They occur in apparently conformable beds or as a stratigraphically undemonstrable disconformity.

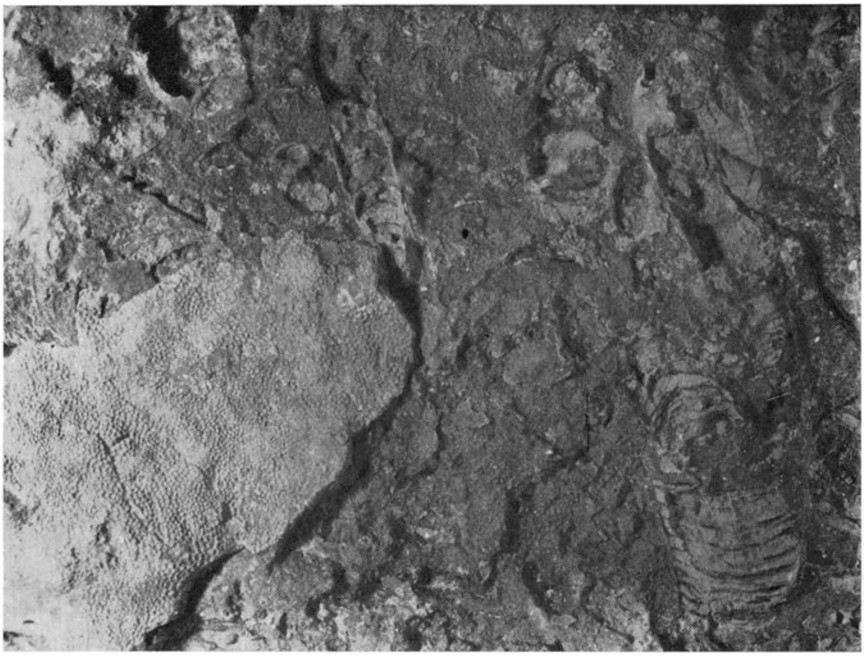

Fig. 6. Compound, massive, tabulate coral (*Favosites*) grown on the corrosion-surface of a fragment limestone. — Slite group. Silurian. Klinthagen, Gotland. — Nat. size. Photo. 1800.

A strictly continuous deposition of sedimentary material can possibly take place for a lengthy period of time in deep sea, never in the shelf area. In the shallow-water areas, where the sedimentation can be directly affected by currents and waves, continual disturbances occur in deposition. These disturbances (mostly in the form of temporary interruptions in deposition, possibly also stirring-up of already sedimented material) may be regarded as a normal phenomenon of sedimentation. Only when the interruptions have comprised a long period of time or when for other reasons they have had more noticeable effects, have we reason to suppose that a hiatus has arisen. With reference to the disturbances in sedimentation discussed above (non-deposition, denudation, and corrosion) we can summarise the occurrence and origin of more or less hidden hiatuses as follows:

1) Non-deposition gaps. A marine sedimentation is interrupted if the production or supply of autochthonous or allochthonous material comes to a halt. Continued production of autochthonous material (e. g. autochthonous calcareous mud) is dependent on unchanged favourable

conditions of formation. A deterioration in these, e. g. through a change in the temperature of the water, pH-value, etc., may diminish or completely prevent the formation of autochthonous material. If, meanwhile, allochthonous material is not supplied, a gap occurs in the series of strata. If the interruption is of relatively short duration and normal deposition follows, the gap is very difficult to establish. It is often represented by a bedding-plane (e. g. in lithographic limestone).

A deposition of allochthonous material may be interrupted if the movement and carrying-capacity of the water undergo a change. A slight increase in the movement may prevent the deposition of argillaceous matter. A weakening of the current may cause transportation and deposition of sand or fossil fragments to come to a halt. The pre-requisite for a gap to arise, however, is that only material of a certain nature (uniform grain-size etc.) is available for transportation. In thick series of shales with no coarse-grained material and in marine siltstones and fragment limestones (calcarenites), with few or no argillaceous layers, there are more or less hidden hiatuses, which have originated in the way sketched out above. One might expect that if transportation and deposition of arenaceous matter come to a halt, the deposition of argillaceous matter would create mud layers. This is the case. That these layers are missing or play a remarkably subordinate role in many series of strata, is due partly to the fact that the interruption in question has been of short duration and the content of argillaceous matter small. In part and perhaps primarily the absence of argillaceous layers is due to the fact that sedimented mud has been washed away when the movement of the water became stronger and transportation of arenaceous matter was renewed. In the latter case, however, deposition and denudation have taken place, but the effect, the occurrence of the break, is the same as if only a non-deposition had occurred.

2) Denudation gaps. An increase in the movement of the water in a marine sedimentation area may, under the conditions mentioned, prevent deposition of the transported material and give rise to a gap in the series of strata. If the movement becomes somewhat stronger, earlier deposited, but still unconsolidated material will be washed away. The gap is widened, but it can still be difficult to establish, particularly in shales and dense limestones. However, bedding-planes may have been formed, possibly with accumulated fossil fragments. If the unconsolidated material has been stirred up by the increased movement of the water without at the same time being carried away by currents, it is resedimented in the area without a gap arising. If the sediment contains fragments of different kinds redeposition occurs with sorting of the material (see further p. 170).

Unconsolidated coarser sediments, silt, sand, coquina, etc. contain as a rule varying quantities of more fine-grained fragments. An increase in the movement of the water in the sedimentation area can involve either deposition of coarse material or removal of earlier deposited material. If the latter is stirred up, the fine-grained fragments will be removed first of all, the coarser ones being thereby accumulated (fig. 1). If whole layers of unconsolidated material are washed away, a break arises which is difficult to discover. Often, however, some part of the coarsest material is left. In limestones with large fossil fragments these may be found much worn and accumulated into fossil conglomerates. Similar conglomerates may be formed by supply of fresh material, so that it is difficult to determine whether a hiatus exists or not (cf. HADDING 1956).

Gaps arising through denudation so deep that even fully consolidated beds (limestone beds) have been broken up, are in general entirely distinct. They are so extensive that in many cases they can be established stratigraphically, and the conglomerates formed contain pebbles of the denuded rock. The gap is, however, bigger than the pebbles indicate. It also comprises washed-away layers of unconsolidated material.

3) Corrosion breaks. Submarine, chemical dissolution of calcareous sediments will result in the formation of a break, if all the material is dissolved. As this is seldom the case, a part will be left undissolved. This part, usually argillaceous matter, may remain on the original deposition site and appear in the series of strata as argillaceous layers in and between limestone beds (cf. p. 164 and fig. 4). If the movement of the water has been strong enough to remove the undissolved material released by dissolution of $CaCO_3$, corrosion can proceed deeper and more rapidly, and a real break may be formed. If the corrosion leaves distinct traces, in the manner cited above (p. 162), the break can easily be observed; if there are no marks of corrosion, it may remain hidden.

Corrosion also occurs in coarse-grained sediments, e. g. coquina, fragment limestones. Broken and worn shells, often with a coating of glauconite, bear witness to this corrosion. Whether it has formed important breaks has not, however, been apparent from the observations made by the author.

4) Gaps occurring because of sliding of sediments. How the parts which have been subjected to removal by sliding appear in their new situation is well known from a large number of observations. We are not so well informed of what stratal sequences look like which have been deprived of material by sliding. There is a gap there, but it may be entirely concealed.

Graded bedding[6]

Certain authors have connected graded bedding with submarine slumping, turbidity flow, and earthquakes (see PETTIJOHN 1957, pp. 176–178 and the works quoted there). All agree that graded bedding is a "product of settling through comparatively still bottom water" and that "each graded unit records a single short-lived episode". The author shares this opinion,[7] but he does not consider that the formation of graded bedding always is bound up with earthquakes, turbidity flow, or submarine slump. Fossil fragments arranged according to size and weight can also be found in thin-bedded uniformly thick extensive limestone beds, e. g. in the Lower Ordovician of Öland. The fossiliferous mud forming the beds must have been stirred up and resedimented without any part of it being carried away. The primary deposition in such cases has occurred in flat, marine basins, so shallow that occasional strong surges or eddy movements have been able to affect (stir up) the loose bottom mud. It is to be pointed out, however, that in these series only odd beds show distinct sorting of material; usually the stirring-up has been accompanied by further transportation and denudation, so that more or less noticeable hiatuses have arisen.

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[6] No account is taken here of the graded bedding occurring in glacial (late glacial) stratified clays, where sorting according to grain-size takes place principally in running water with periodically changing carrying-capacity.

[7] We have an excellent example of graded bedding in the Loftarstone of Jämtland, a Middle Ordovician calcareous rock, deposited in connexion with tectonic disturbance and submarine slump (cfr. HADDINC 1927, and 1929).

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