ORIGIN OF LIMESTONE NODULES IN THE LOWER PALAEOZOIC OF THE OSLO REGION

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Nodular limestones occur in several stratigraphic horizons in the Lower Palaeozoic of the Oslo Region. In the Middle and Upper Cambrian and the Lower Ordovician the nodules occur isolated in the black alum shale. In the Middle and Upper Ordovician and the Silurian, nodules are more closely spaced in a grey matrix. All transitional stages between continuous limestone beds and nodular limestones can be observed. Erosional features and burrows suggest that the nodules formed prior to any deep burial. The author considers the nodules to be the remains of continuous carbonate layers that were later dissolved due to prolonged exposure to sea water unsaturated with respect to carbonate in an environment of very slow sedimentation.

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One of the most conspicuous features of the Lower Palaeozoic sedimentary rocks of the Oslo Region is the abundance of nodular limestones. The origin of these nodules has nevertheless been the subject of little discussion in the literature on these rocks. Limestone nodules occur in different shapes and sizes in several stratigraphic horizons from the Cambrian to the Silurian. The types of limestone nodules are clearly related to the rocks in which the nodules occur. In the black shale facies, most typically developed in the Cambrian and the Lower Ordovician, the nodules are generally isolated and far apart. In the grey shale facies of the Middle and Upper Ordovician and the Silurian the nodules are normally more closely spaced, and all transitions occur between nodular limestones and continuous limestone beds met with. Both in the black Cambrian shale and in the Ordovician grey shales the limestone nodules are aligned along certain horizons in the shales (Fig. 1).

Earlier work

The most detailed description of limestone nodules in the Lower Palaeozoic of the Oslo Region has been published by Brøgger. Brøgger (1882, pp. 335–336) stressed that the nodules should not be referred to as concretions since they do not differ in composition from the continuous limestone beds, and structures typical of concretions are not present. Pettijohn (1957, p. 203) states: 'Concretions are normally spherical, spheroidal or disk shaped. These structures are products of accumulations of mineral matter in the

Fig. 1. Nodular limestones from the Ampyx Limestone (4aß) at Frognerkilen, Bygdøy, Oslo. The thickness of the carbonate beds and the nodules is 5–10 cm.

pores of the sediment about a nucleus or a center.' Carbonate concretions in shales or mudstones therefore do not consist of pure carbonate, but contain a percentage of carbonate corresponding to the available pore space in the host rock (Raiswell 1969). Analyses of the carbonate content in Cambrian limestone nodules from the Oslo Region show that they may contain more than 90 % $CaCO_3$, which is similar to the continuous limestone beds.

The limestone nodules in the Oslo Region are usually devoid of any radial or concentric structure. Bedding is, however, well preserved in nodules associated with beds that have not been distorted by bioturbation. Cambrian nodules with distinct bedding are well illustrated by Brøgger (1882, p. 237), in Fig. 2 and from the Cambrian in Sweden by Hadding (1958, p. 94). On the surface of the nodules, laminae with low carbonate content protrude relatively to laminae with high carbonate content. This lamination also shows up clearly on polished sections through nodules after etching with HCl. The fact that the relief produced by etching corresponds to the surface relief of the nodules also suggests that the nodules were formed by subsolution. Brøgger points out that many of the nodules consist of finely-grained limestone which is not recrystallized. The nodules may, however, be surrounded by coarse secondary calcite (anthrachonite). Brøgger also observed coarse calcite crystals which he assumed had originally consisted of aragonite crystals that had grown in the fine calcareous matrix. He concluded that the limestone nodules originated as primary limestone of which some are recrystallized and that they are not formed by a con-

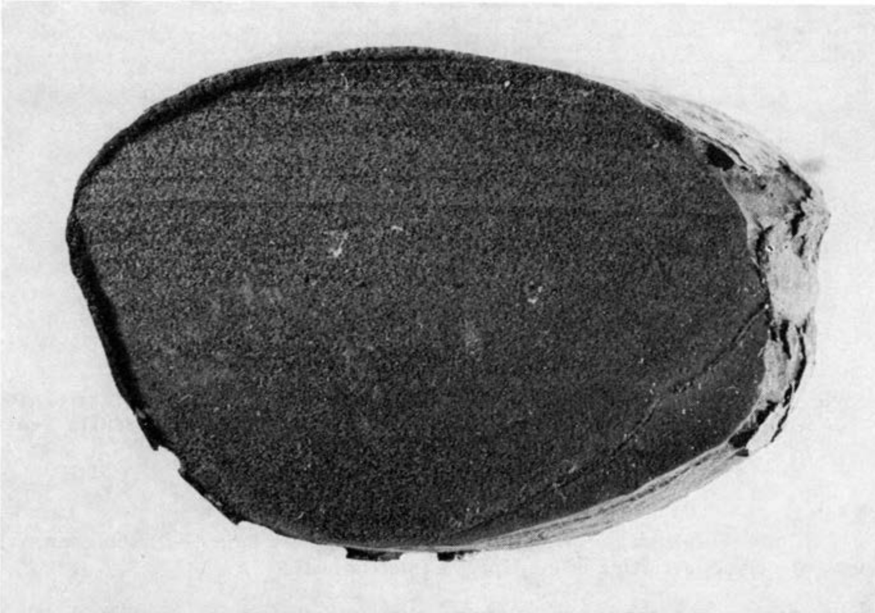

Fig. 2. Polished and etched (HCl) section of an Upper Cambrian limestone nodule. (Diameter 8 cm.) The ribbon on the surface at the nodule is parallel to bedding and corresponds to laminae with lower carbonate content on the etched surface.

cretionary process. Some of the nodules are entirely replaced by sulphides, and Brøgger's description includes excellent drawings of sulphide pseudomorphs after limestone nodules. These drawings show a fine-grained central zone surrounded by coarse sulphide pseudomorphs after aragonite.

Hansen (1945) interpreted the Cambrian limestone nodules at Bornholm to represent patches of primary carbonate in an interfingering facies of black mud and carbonate. These patches formed the nuclei of the calcareous lenses in the alum shale.

The limestone nodules of the black shale facies

Three main kinds of limestone nodules occur in the Cambrian and Lower Ordovician black shales:

Limestone nodules of unrecrystallized limestone, often containing a rich shelly fauna (trilobites).

Nodules of partially recrystallized, fossiliferous limestone, surrounded by secondary sparry calcite.

Nodules consisting only of recrystallized calcite in which no fauna is preserved.

Some of the largest limestone nodules occur in the Upper Cambrian rocks where they reach 1–2 m in diameter. Fig. 3 shows an example of such nodules in the *Peltura* Beds (2d) at Nærsnes in Asker. The central part of the nodule contains moderately recrystallized limestone with trilobites and

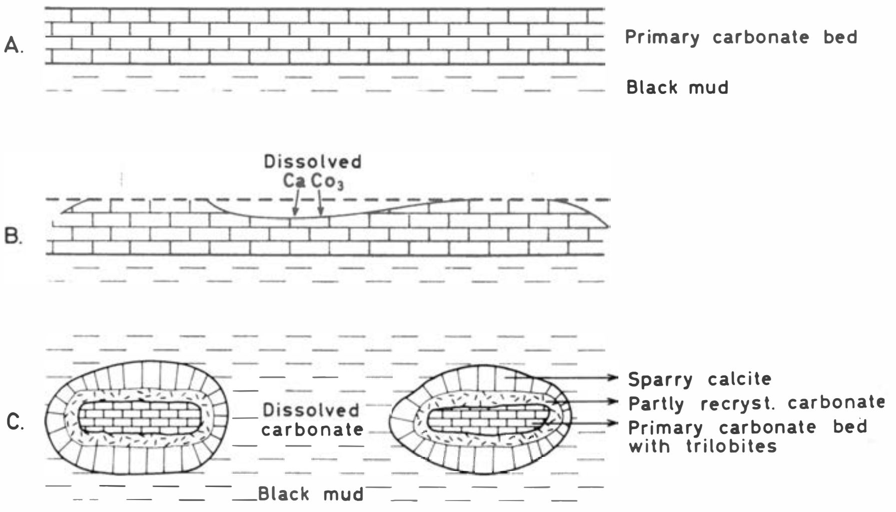

Fig. 3. A model explaining a theory for the formation of the large (1–2 m in diameter) limestone nodules occurring in the Upper Cambrian beds.

is surrounded by secondary coarse, sparry calcite (anthraconite). A transitional zone penetrated by large secondary calcite crystals, similar to those described by Brøgger, exists between the anthraconite layer and the fossiliferous limestone. The recrystallization has obliterated any trilobite shells that might have been present in this zone. The surrounding shale is gener-

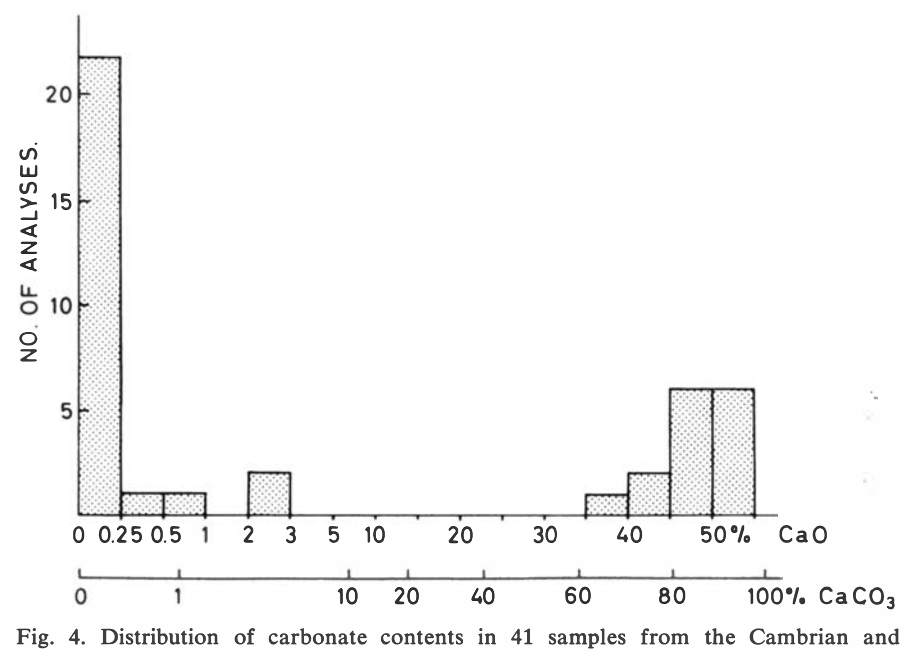

Fig. 4. Distribution of carbonate contents in 41 samples from the Cambrian and Lowermost Ordovician (Dictyonema Shale 2e) shales and limestones from the Oslo Region.

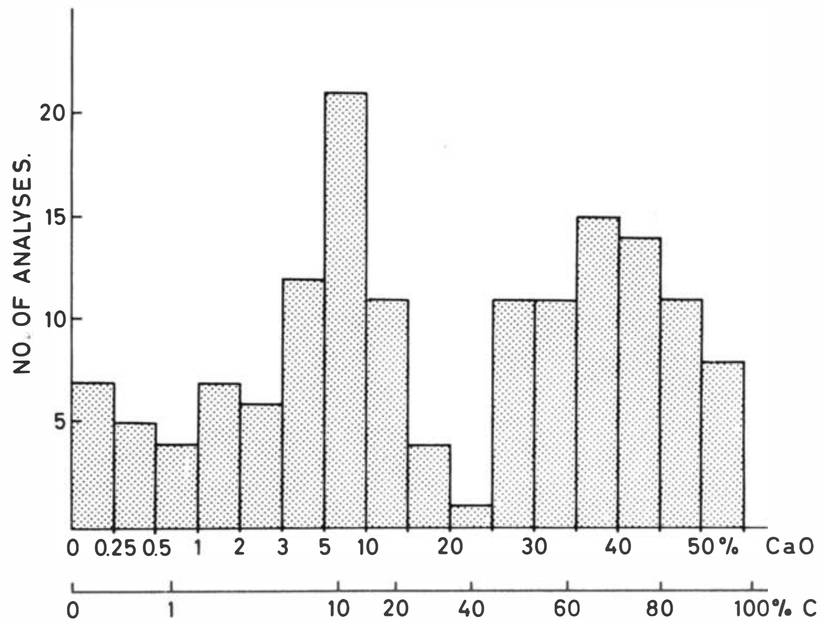

Fig. 5. Distribution of carbonate contents in 153 samples of Ordovician (from 3a) and Silurian samples from the Oslo Region.

ally devoid of shelly fauna and contains no carbonate (Figs. 4 & 5). The nodules have a very distinct bedding which is sharply truncated at the boundary to the matrix. Differential compaction of the carbonate nodules and the shale matrix may have deformed this primary contact. There is also considerable evidence that the nodules have been tectonically rotated in the matrix.

The nodules often yield an abundant shelly fauna, and the Upper Cambrian nodules in particular commonly consist of densely packed trilobite shells (Henningsmoen 1957, p. 34). The lithology of the limestone nodules is very similar to that of the continuous limestone beds (Brøgger 1882, p. 335). The associated limestone beds may also be partly recrystallized and have a secondary overgrowth of anthraconite.

In the author's opinion these facts are best explained by assuming that the nodules are essentially the remains of continuous carbonate beds. The absence of carbonate and of shelly faunas in the shale around the nodules is probably due to solution of carbonate, mostly before burial. The last stages of solution may, however, have taken place after burial when the carbonate beds were no longer in direct contact with sea water. Coarse, sparry calcite (anthraconite) later precipitated around the undissolved remains of the primary carbonate beds.

Henningsmoen (1957) considered the Cambrian limestone nodules to be concretions around organic matter due to the higher pH of decaying organic matter, as described by Weeks (1953) from the Cretaceous shales of South America. These concretions are formed around fossil fish and resemble 'marleik' concretions in Quaternary clays of Scandinavia and North America as described by Tarr (1935).

The trilobites are evenly distributed in the continuous limestone beds, and it seems unlikely that they should have been deposited as clusters in the mud and served as nuclei for concretions.

The Cambrian and Lower Ordovician black shales are indicative of stagnant conditions during deposition, and the adaptation of a trilobite fauna to such an environment has been discussed by Henningsmoen (1957) and Størmer (1967). It is possible that the sea floor was uninhabited by trilobites for long periods, although these may have lived in the upper more oxygen-rich water layers. Shells falling on to the stagnant bottom may then have been dissolved before burial. In periods of more ventilated conditions the ocean floor would be invaded by trilobites, resulting in the formation of a carbonate layer. Following the return to stagnant conditions the pH would be lowered and the carbonate layer would slowly start to dissolve. During this process the remains of the corroded carbonate bed would attain the thermodynamically most stable shape of isolated spheres with secondary overgrowths of coarse sparry calcite.

In the Upper Cambrian beds one can observe a number of more or less discontinuous carbonate beds which may be interpreted as intermediate stages in this process.

This phase in the formation of the nodules may be accompanied by concretionary processes and some nodules have a high sulphide content replacing carbonate.

The limestone nodules of the grey shale facies

The nodules in the Ordovician and Silurian consist of light limestone surrounded by a darker grey shale matrix. The matrix is also commonly calcareous and in many cases there is no abrupt change in carbonate content between the light grey nodules and the dark grey matrix. *Chondrites* types of burrows are common in these sediments (Seilacher & Meischner 1964), and around the nodule margins they may show up particularly well as light grey specks in the dark grey matrix (Fig. 6). These white infillings are formed by burrowers transporting light lime mud into the darker matrix. This suggests that the light calcareous nodules had already been formed in a darker matrix at the time of burrowing. Simpson (1956, p. 494) in a study of *Chondrites* in the Blue Lias of England also pointed out that these burrowers indicate that the formation of the nodules was subsequent to the deposition of the clay which enclosed them, but prior to a sediment accumulation sufficient to cause appreciable compression. The nodular limestones in the Upper Ordovician rocks and in the Silurian commonly alternate with layers of calcarenite. One can here observe layers with nodular limestones that are sharply truncated by overlying calcarenite beds (Fig. 7). This primary erosional contact shows that the nodules were formed before

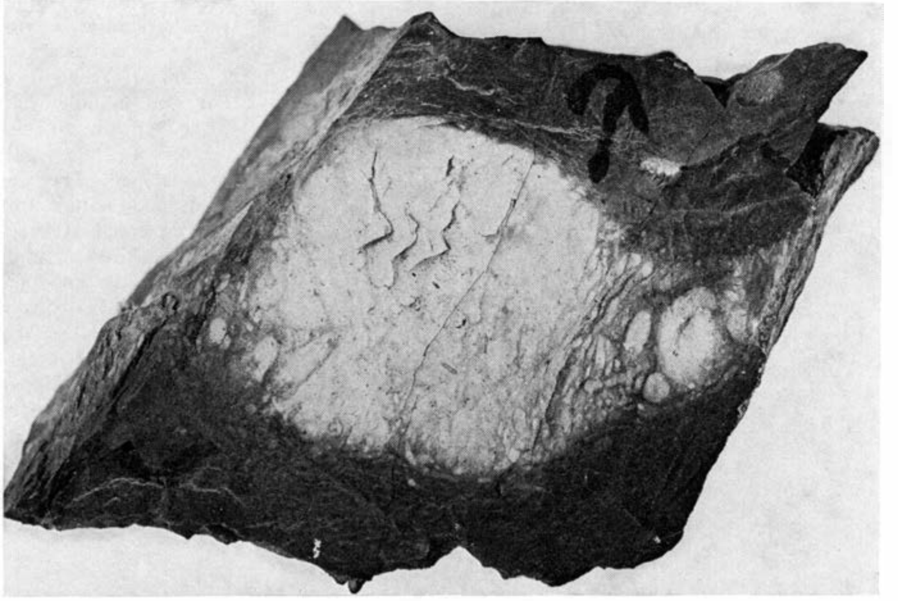

Fig. 6. *Chondrite* burrows around limestone nodules (diameter 5 cm) showing up particularly well around the margin of the nodule suggesting that the contrast between the light nodules and the darker matrix was established at the time of burrowing.

the deposition of the calcarenite bed. The undeformed nature of the erosional contact excludes the possibility that later diagenetic or tectonic deformation could have played an important role in the formation of the nodules. Lauritzen & Worsely (pers. comm.) have observed stromatoporides sitting on top of isolated limestone nodules in the Lower Silurian suggesting that the nodules had formed prior to burial.

Most nodules consist of lime mud, but some contain calcarenite and show internal current structures or horizontal lamination (Fig. 8); these structures are very similar to those found in continuous calcarenite beds, suggesting that the nodules are remains of a continuous layer that was later partly dissolved.

Isolated limestone nodules with septarian structures are also found in the Oslo Region, but these types are not very common.

Dissolution of carbonates

Ocean water is today normally saturated with respect to calcium carbonate only in low latitude areas and in the upper few hundred metres of the ocean (Berner 1965). As also pointed out by Hudson (1967) the depth at which all carbonate is dissolved (about 4500 m) is not related to calcite or aragonite solubility but to rates of solution and sedimentation. Aragonite, however, is more soluble in sea water than calcite (Friedman 1965). Carbonates may dissolve at shallow depth as the solubility of carbonates in ocean water is not directly related to depth, but rather to a complex set of

Fig. 7. Micritic limestone nodules truncated by a layer of calcarenite suggesting that the nodule had formed prior to the erosion by the calcarenite bed. The undeformed nature of the erosional contact excludes the possibility that the nodules should have been formed by later deformations of carbonate beds. Upper Ordovician limestones at Sandviken.

parameters including temperature, pH, and alkalinity. Carbonates may accumulate in environments where all carbonate minerals are unstable, such as in the cold waters of the Skagerrak (Alexanderson 1972). Also in warmer seas the sea water may be undersaturated with respect to calcium carbonate in seasonal or even diurnal cycles (Scmalz, R. F. 1967, Scmalz, R. F. & Swanson, F. J. 1969, Alexanderson 1972).

Alexanderson pointed out that in an environment of undersaturated sea water, micritization does not take place and early diagenetic changes will be destructive and include leaching.

Submarine leaching will be selective, dissolving first the finer particles with large specific surfaces and the more soluble carbonate minerals (aragonite). This explains why subsolution of calcareous sediment does not necessarily produce a very sharp contact between volumes of sediments affected to a different degree by dissolution.

Detailed studies by Hollman (1962, 1964) of Jurassic nodular limestones in northern Italy have produced strong evidence for subsolution in carbon-

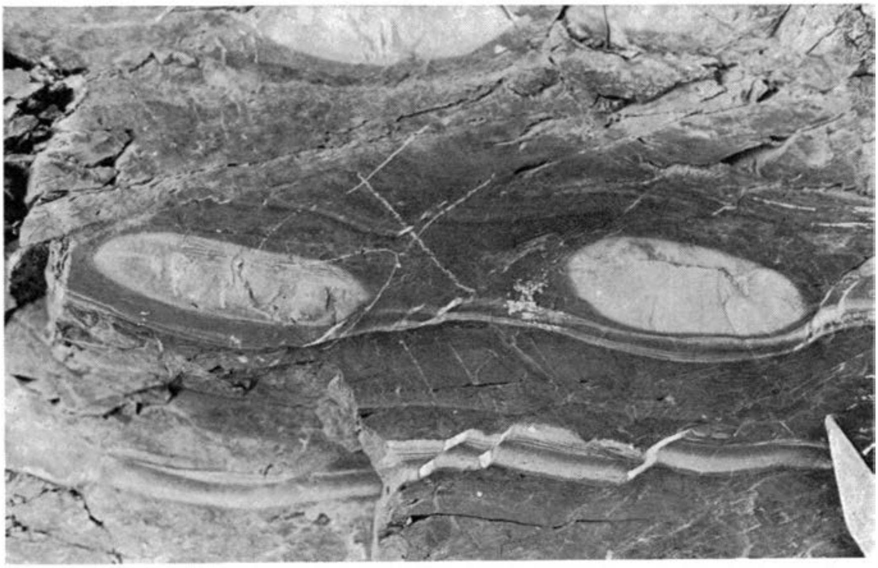

Fig. 8. Limestone nodulex of fine-grained calcarenite with primary lamination passing into the matrix. It is suggested that the two nodules are remains of a once continuous carbonate layer. Middle Ordovician nodular shale at Frognerkilen, Bygdøy.

ates. Hollman interprets nodules as solution relicts of continuous beds deposited on the sea floor. On the basis of studies of dissolved and corroded fossils he arrived at the conclusion that solution took place both while the carbonate layer was exposed on the sea floor and also after burial.

Hallam (1964) has studied the Blue Lias of England, which is also developed as a nodular limestone with regular alternations between limestones and shales over large areas. Hallam considers the nodules to be due to segregation during diagenesis soon after deposition. This segregation would then have taken place during an early recrystallization of carbonate mud. Hallam (1967) considers that the Jurassic nodular limestones of the Alpine region were formed in the same way as those of the Blue Lias of England.

Hollman and Hallam thus represent two contrasting views on the origin of limestone nodules. Hollman considers the nodules to be essentially due to solution, while Hallam favours an early diagenetic segregation process. Garrison & Fischer (1969) in a discussion of these two interpretations point out that a number of the characteristics of the nodules cannot be explained in terms of concretionary segregation. In their study of the Adnet Beds they did not see any cases of primary lamination passing from the nodules into the matrix, a feature which they consider to be characteristic of concretions.

Evidence of subsolution in Ordovician and Silurian limestones

Also in the nodular limestones of the Ordovician of the Oslo Region, the primary laminations, where present in the nodules, are truncated by a sharp boundary to the matrix. One also often finds a thin brown manganese and ferruginous rim around the nodules. This is evidence of solution which has also been observed by Garrison & Fischer (1969). From the present author's study it is also apparent that the nodular limestones contain higher concentrations of MnO than the shales and the homogeneous limestones.

Hollman considers the Adnet Beds to have formed hard grounds that were often but not always subject to submarine corrosion. Present day hard grounds have been reported by Gevirtz & Friedman (1966), and Fischer & Garrison (1967). Hard ground from the Ordovician limestones in Sweden has been described by Lindström (1963), who concludes that the limestones were folded, then hardened and bored while exposed on the sea floor. Jaanusson (1961) has also discussed the formation of discontinuity surfaces.

Both ancient and modern nodular limestones and hard grounds form in environments with very slow average rates of sedimentation. The estimate for the Jurassic of the Alpine region is about 5 mm/1000 years (Garrison & Fischer 1969) and is in the order of 2–7 mm/1000 years for the Lower and

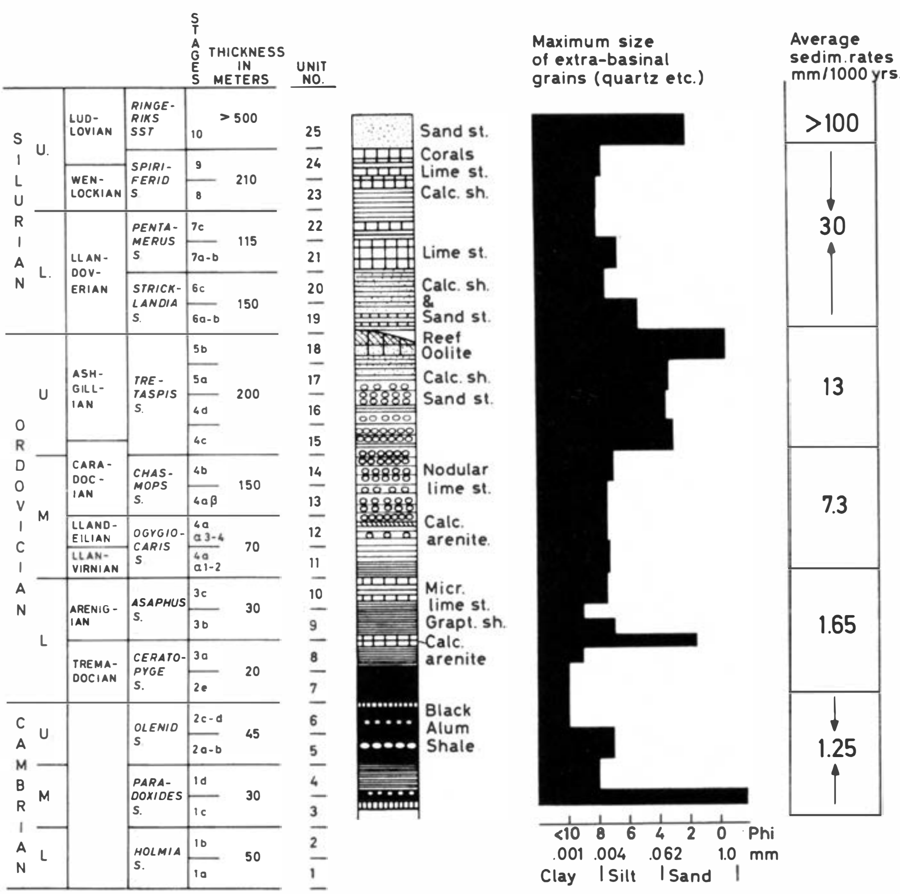

Fig. 9. A simplified presentation of the stratigraphy, lithology and calculated average sedimentation rates of the Cambro-Silurian of the Oslo Region.

Middle Ordovician in the Oslo Region (Fig. 9). In the Oslo Region, however, there is no direct evidence that the nodules formed hard grounds. Evidence of burrowing and occasionally also of erosion of limestone nodules mentioned above suggests that lithification took place subsequent to the formation of the nodules.

An obvious consequence of such slow sedimentation rates is a long period of exposure of each bed deposited on the sea floor. The rhythmic alternation of shales and limestones indicates quite clearly that carbonate sedimentation was not continuous. In periods corresponding to the deposition of the shales only small amounts of carbonate were deposited or subsolution dissolved a greater percentage of the carbonate accumulated. This rhythmic sedimentation represented by the alternation of nodular limestones and shales may have been controlled by climatic cycles. The calculated sedimentation rate of 2–7 mm/1000 years (Fig. 9) suggests that it may have taken an average of 15–50,000 years to deposit a 10 cm thick unit of limestone and shale. This figure may have been somewhat lower as possible larger breaks in sedimentation are not taken into account. In epicontinental seas with very gentle slopes not exceeding a few cm/km (Irwin 1965), a very small variation in climate or sea water circulation will result in a long horizontal shift in the intersection between the pycnocline and the sea floor affecting the rate of carbonate sedimentation.

Even if the Oslo Region has a position close to the equator in Ordovician times (Spjeldnæs 1961) temperatures might have been lower at least periodically, especially in light of the evidence of glaciation in North Africa and South Europe in this period (Beuf et al. 1971). This could also produce a rhythmic pattern of carbonate sedimentation.

In periods of low temperature the deposited carbonate layer, in most cases lime mud, would have been in contact with ocean water undersaturated with respect to calcium carbonate.

In the Ordovician and Silurian of the Oslo Region there is ample evidence of bioturbation and this process must have contributed considerably to the solution of the carbonate by steadily exposing fresh lime mud to the sea water. The fact that many nodules are surrounded and partly penetrated by chondrite burrows may suggest that the limestones were gradually eaten up by a combination of bioturbation and solution processes. This burrowing process could also explain an apparent reorientation of the fossils in the remaining nodules. The abundant evidence of burrowing also explains why the boundary between the nodule and the matrix is sometimes sharp and distinct, and in other cases diffuse (Fig. 6).

The nodules consist in most cases of fine-grained carbonate mud which shows very little sign of recrystallization, and in a few cases of fine-grained carbonate sand or silt.

The author considers the limestone nodules of the grey shale facies in the Lower Palaeozoic of the Oslo Region to be essentially a product of solution in combination with bioturbation.

Summary

Limestone nodules of the Cambrian alum shale and of Ordovician shales and limestones are the products of different degrees of subsolution which occurred after deposition, but for the most part prior to burial.

The absence of carbonate and commonly also of calcareous tests of fossils in the Cambrian alum shale suggests that subsolution has been complete here and that nodules are the remains of dissolved carbonate beds. This interpretation is supported by the similarity between the lithology of the nodules and that of the continuous limestone beds.

The nodules in the Middle Ordovician to Silurian limestones consist mostly of fine-grained biomicrite in a matrix of calcareous shale. Here subsolution has been less complete and more selective, dissolving the finer particles and the more soluble carbonate minerals in long periods of exposure to sea water which was periodically undersaturated with respect to calcium carbonate. Bioturbation is believed to have contributed significantly to this process.

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