A Comment. Origin of Limestone Nodules in the Lower Palaeozoic of the Oslo Region

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Limestone nodules and certain limestone layers associated with from black to lighter-coloured shales in the marine Lower Palaeozoic of the Oslo Region are interpreted as being primarily of concretionary nature. Cementation is believed to have taken place by precipitation of calcium carbonate in pore space of favourable host beds at an early diagenetic stage close below the sea water–sediment interface (and thus primarily in a marine environment).

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A recent article by Bjørlykke (1973) adds significantly to our knowledge of Lower Palaeozoic limestone nodules in the Oslo Region, but their concretionary nature was not stressed to the extent that the present writer believes there is evidence for. The following discussion is an attempt to summarize some of the evidence and its implications.

Limestone nodules and layers in black shales

Nodules and stray layers of dark, bituminous limestone (anthraconite, 'stinkstone') occur in black, black-streaked, bituminous, and fissile shales ('alum shales'), characteristic of the Middle and Upper Cambrian and Lower Tremadocian in the Oslo Region. The nodules are generally concentrated in horizons and vary in shape from ellipsoidal to more or less irregular and plate-like. Brøgger (1882: 335–336) observed bedding in stinkstone nodules and suggested that their limestone was of the same primary origin as in the continuous layers. Evidence of early cementation both of nodules and layers is supported by the in general practically uncompressed nature of the contained fossils in most examples. Brøgger denied that the nodules were concretions, but nodules formed by local cementation are now regarded as typical concretions (cf. Pettijohn 1949: 151, Raiswell 1971). The stinkstone nodules have been recognized as concretions by, e.g., Holtedahl (1953: 186), Hadding (1958) in Sweden, and Larsen & Thiede (1971) in Denmark. Various structures convincingly demonstrate that they are concretions formed around a centre by precipitation of calcium carbonate in the pore space of the unconsolidated sediment. Thus nodules in the Oslo Region may show *inter alia* (1) septarian structures, (2) subsequent growth layers where growth was discontinuous, (3) laterally converging bedding planes and nodules thinning out laterally as evidence of growth during progressive compaction, (4)

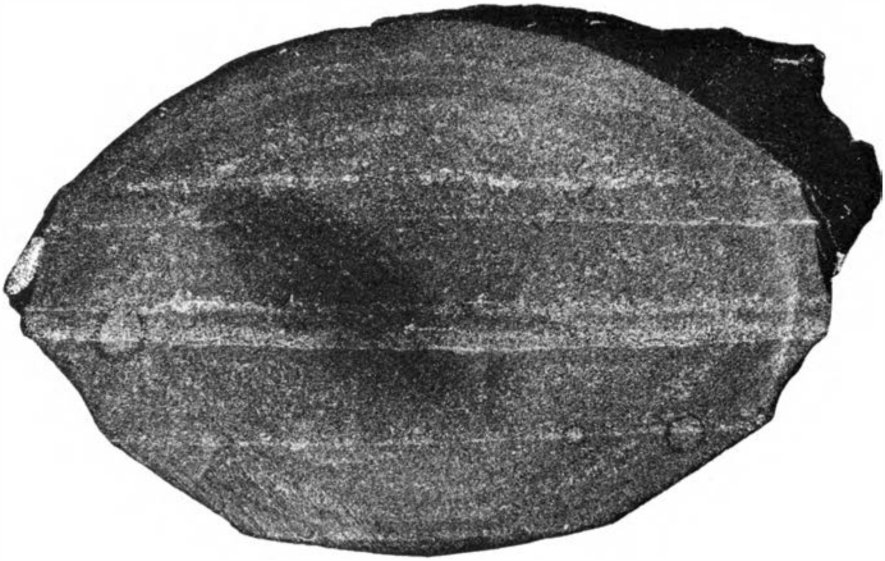


Fig. 1. Vertical cross section of Upper Cambrian stinkstone concretion showing bedding (white laminae = fossiliferous seams) and concentric banding. From Slemmestad near Oslo. × 1.4.

concentric banding around a centre (Fig. 1) and (5) coalescence of separate nodules into compound nodules during growth.

On remarking that the surrounding shale is generally devoid of shelly fossils and contains no carbonate, Bjørlykke (1973: 423–424, cf. also his fig. 3) explained the nodules as 'undissolved remains of primary carbonate beds' and suggested that the 'remains of the corroded carbonate bed would attain the thermodynamically most stable shape of isolated spheres with secondary overgrowths of coarse sparry calcite'. He further interpreted more or less discontinuous carbonate beds in the Upper Cambrian as intermediate stages in this process and stated that 'this phase in the formation of the nodules may be accompanied by concretionary processes'. The fossils in the nodules are uncorroded and have well-preserved surface details (cf. Henningsmoen 1957: pls. 9–30) showing that calcium carbonate could hardly have been dissolved before or during the cementation of the nodules. At least *the main concretionary growth antedates dissolution of carbonate* in the same horizon. Most likely calcium carbonate was dissolved in the unconsolidated host mud surrounding already consolidated concretions – apparently to be precipitated again in another horizon, cementing unconsolidated sediment into limestone (stinkstone) nodules and layers. The high content of calcium carbonate in the limestone (Bjørlykke 1973) may indicate that the original sediment contained some carbonate in addition to that in the fossils, although uncompacted clay may have a pore volume of up to 80–90 % (cf., e.g., Engelhardt 1973: 286); the stinkstone concretions evidently started to grow prior to significant compaction.

Early diagenetic stinkstone concretions (and other early diagenetic calcium carbonate concretions) may be regarded as samples of the original sediment (with its fossils), protected against significant compaction through impregnation by calcium carbonate, and thus showing close to the original dimensions of fossils and sedimentary structures, including thickness of beds. However, this does not imply that the original sedimentary substance has necessarily been preserved *in toto* or unaltered. Thus, in the case of the stinkstone concretions, much organic matter may have escaped later as oil and gas.

Single stinkstone nodules are more or less ellipsoidal (from almost spherical to more typically ellipsoidal, oblate spherical, or discoid), or more plate- or slab-like. Ellipsoidal nodules may be up to about 1 m thick and disc-shaped nodules less than 0.4 m thick may have a greater diameter of at least 3 m, but the majority of nodules are smaller.

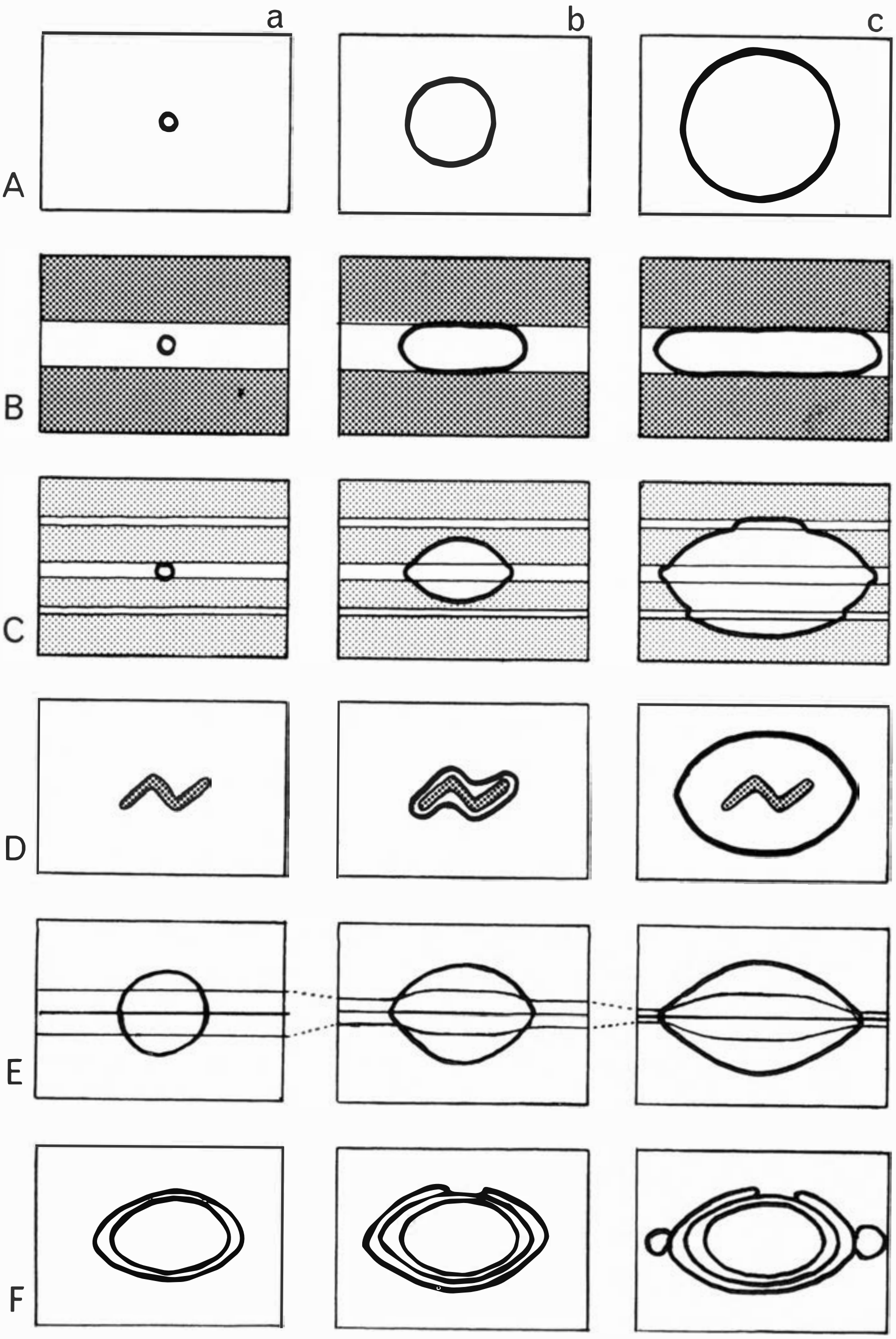
The general shape of concretions is controlled by several factors (Fig. 2), including permeability of the host sediment. Thus almost spherical concretions reflect almost isotropic permeability of the host sediment (cf. Raiswell 1971: 165) (Fig. 2A). Ellipsoidal and disc-shaped concretions reflect the more common condition where permeability was less across bedding than parallel to it. Commonly the greater diameter of such stinkstone concretions represents the horizon where concretionary growth was initiated (the nucleating horizon); in many cases this is a fossiliferous seam.

Ellipsoidal nodules may show ‘channelling’ (Brøgger 1882: 336: Canellirung) – a surface relief of ridges and grooves parallel to bedding (Figs. 1, 2C), apparently reflecting differences in permeability between the laminae of the host sediment. Ridges generally represent mm-thin, fossiliferous laminae. Apart from these, the stinkstone generally shows no distinct bedding and is rather uniform.

The up to about 15 cm thick plate- or slab-like concretions apparently developed between the lower and upper boundaries of a relatively thick, especially favourable host layer – commonly a fossiliferous layer or two or more closely stacked fossiliferous laminae.

Some stinkstone concretions have subparallel bedding planes, and, judging from the undistorted fossils, are from an early pre-compaction stage in diagenesis. Others display laterally converging bedding planes. As is well known from concretions elsewhere (cf., e.g., Tomkieff 1927, Raiswell 1971), this signifies gradually increasing compaction during concretionary growth and leads to shapes like oblate spheres with the long axes parallel to bedding, or flat ellipsoids (Fig. 2F). The shape and size of concretions are influenced by the degree of compaction, because compaction reduces thickness of host layers, and also reduces permeability. Decreasing permeability could gradually restrict precipitation to the initially more favourable laminae if such were present. Commonly at least one is present at the nucleating horizon. Both decreasing thickness of the host layers and decreasing permeability commonly lead to a vertical cross section with a more or less conspicuous bend at the greater diameter, rather than to a true elliptic cross section.

Whereas the cross sections of some stinkstone concretions show no or diffuse concentric banding, indicating continuous concretionary growth, others show distinct concentric lines (Fig. 1) or sutures, especially distally, indicating intermittent growth (Fig. 2F). The concentric bands (growth bands,



'shells') between the sutures may or may not completely encircle the previously formed part of the concretion. A suture may also be present between two stinkstone concretions where a concretion has encroached onto and more or less incorporated an earlier formed concretion (cf. 'hiatus concretions' as described by Voigt 1968 and by Kennedy & Klinger 1972).

Two, three, or more ellipsoidal stinkstone nodules occur in some cases laterally coalesced into compound nodules that morphologically are transitional to hummocky stinkstone layers (Fig. 3J) with corresponding bumps on their upper and lower surfaces. Aggregates of laterally coalesced platy nodules likewise are transitional to sheet-like stinkstone layers. The aggregates have a more or less irregular lateral outline, although convex lobes dominate. As might be expected, no suture is present where simultaneously growing concretions coalesced. It appears that when two growing concretions were close enough, concretionary growth filling in the space between them was favoured, as if this space was more strongly 'attractive' to precipitation than the space around a single concretion. As a result, an early stage of coalescence clearly showing the twofold origin could gradually become smoothed out to a longish ellipsoid, without narrowing between the two parts. Growth bands in cross section of some such longish ellipsoids reveal two initial centres, however.

Although the surface of a previously formed concretion was 'attractive' to new concretionary growth, the surface of a growing concretion was apparently even more 'attractive'. Thus the edge of a concretion or concretionary 'shell' that is superimposed on an earlier formed concretionary surface generally resembles the shape of the edge due to surface tension as in water on a glass plate. The greater 'attraction' of a growing concretionary layer explains why concretionary growth postdating a halt frequently resulted in localized additions and outgrowths, apparently initiated at a few favourable spots and producing strange-looking nodules, rather than forming a complete layer ('shell') entirely surrounding the 'old' concretion (Fig. 2F).

Some stinkstone ellipsoids near the Upper Cambrian–Tremadocian boundary have a 'beef'-like layer of coarsely crystalline anthraconite (Brøgger 1882, Hadding 1958, Bjørlykke 1973) at or near the margin. It appears to be related to 'beef' and cone-in-cone structures and may have originated at a fissure, perhaps between the concretion and surrounding sediment, probably

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Fig. 2. Growth of concretions.

A. In host sediment with isotropic permeability (sphere).

B. In host bed of restricted thickness and markedly more permeable than beds below and above (flat concretion).

C. Where some beds are more permeable than others. (Concretion surface 'channelled'.)

D. Around large fossil (large in relation to concretion). Db = 'thin-skinned' concretion indicating shape of fossil.

E. During compaction. Ea = pre-compaction stage. Three bedding planes are shown.

F. Subsequent growth after halts (intermittent growth). Fa with one complete subsequent 'shell'. Fb with one more, but incomplete 'shell'. Fc with local, subsequent growth. Heavy lines indicate growth stops.

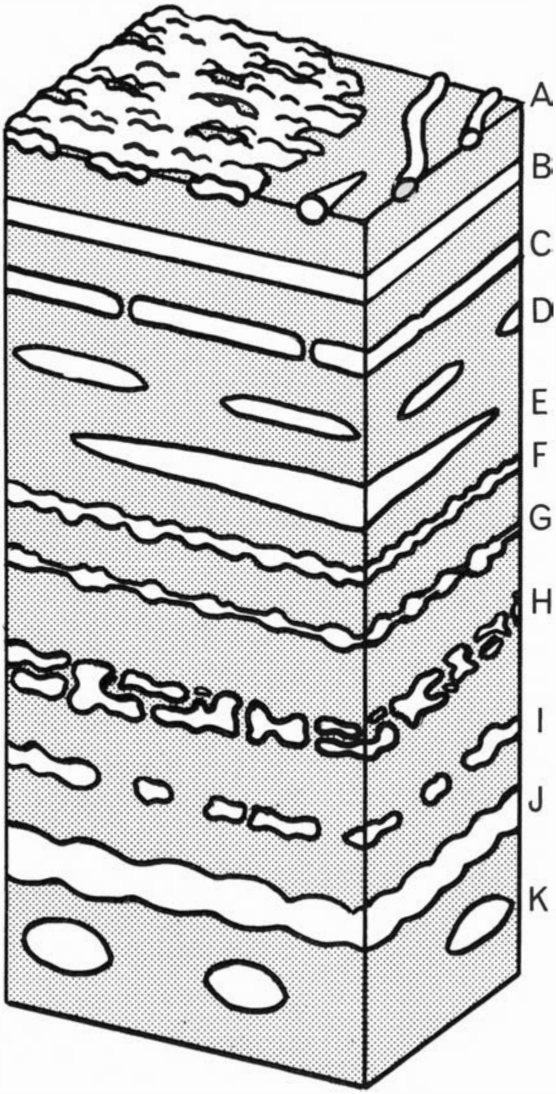

Fig. 3. Some morphologic types of concretionary limestone (white).

A. Exposed surface. Left: A nodular layer with 'holes'. Right: Concretionary limestone ('nodules') within two burrows and one cephalopod conch.

B. Plane-parallel layer.

C. Flat nodules close together; two are coalesced to the right.

D. Flat nodules.

E. Large discoidal nodule.

F. Continuous nodular layer.

G. Nodules joined by sheet-like limestone.

H. Two nodular horizons. Some compound nodules = coalesced nodules from both horizons.

I. Nodular horizon; nodules partly coalesced into compound nodules.

J. Continuous layer of coalesced ellipsoidal nodules.

K. Isolated ellipsoidal nodules.

while both were still soft. The layer is apparently a concretionary structure of the replacement and possibly also of the displacement type, whereas the main part of the concretion is of the cementation type. In connection with septarian structures, coarsely crystalline anthraconite may also be present well inside the concretion.

Some stinkstone concretions indicate that a certain degree of dissolution, generally combined with precipitation of iron sulphide, took place from the surface inwards of already formed stinkstone concretions. This is most characteristic where concretionary growth was last active; along the lateral margin 'blebs' of pyrite may be present. This could well have happened when the concretion became so deeply covered by sediments that it reached the zone where calcium carbonate in the surrounding soft mud (and in its fossils) was presumably dissolved.

Distribution of limestone nodules and layers within sedimentary cycles

The Cambrian and Lower Tremadocian alum shales in the Oslo Region are rather monotonous, but pure shales alternate with shales interbedded with stinkstone nodules and layers. The succeeding Ordovician and Silurian sequence is more distinctly cyclic, with cycles from black or dark grey, generally graptolitic shales through lighter-coloured shales with shelly faunas to nodular limestones although other lithologies occur as well. The distance between horizons of limestone nodules and limestone layers decreases upwards within a cycle, indicating a general increase in gross carbonate content, although there are numerous minor fluctuations. The cycles, from 10 to over 100 m thick, may be more or less completely developed.

The dark shales are commonly interbedded with dark grey limestone nodules and layers generally less than 25 cm thick. Some may weather rusty coloured. The nodules resemble the stinkstone concretions in shape (ellipsoidal, disc-like, plate-like) as well as in other features such as presence of septarian structures, successive growth structures, coarse concentric banding and laterally united concretions, transitional to continuous layers. The nodules in the dark shales are undoubtedly also cementation concretions. Some show an outer layer with cone-in-cone structure. The ellipsoidal concretions mainly occur in monotonous thick-bedded but fissile dark shale. The irregular plate-like concretions occur where the shale is more variegated and thin-bedded (commonly in its upper part) – and at some levels with silty layers. Many horizons of nodules are restricted to fossiliferous or silty beds. The transition from the dark to the lighter-coloured shales is generally gradual and interfingering.

The lighter-coloured shales are generally interbedded with moderately grey to bluish grey limestone nodules and layers with a characteristic pale, almost whitish weathering colour, in some instances with a rusty stain. These grey limestone nodules and layers are rarely more than 15 cm thick, and commonly less than 10 cm thick. Where the nodular horizons are well apart, the beds are referred to as nodular shale; where they and knobby limestone layers are closely stacked, the beds have been referred to as 'nodular limestone', although the amount of limestone rarely exceeds that of shale. Compact nodular limestones also occur, especially in the Silurian.

Origin of limestone nodules and layers in lighter-coloured shales

The nodules have *inter alia* been suggested to be 'essentially a product of solution in combination with bioturbation' (Bjørlykke 1973: 429), or examples of boudinage. Nevertheless, the present writer agrees with Holtedahl (1910: 44, 1953: 188) that these nodules, too, in general, are primarily concretions, as also maintained by Hadding (1958: 50) for similar nodules in Sweden. Evidence of this is indications of concretionary growth and the many similarities between the 'grey' and 'dark' nodules. Thus within a sequence from dark to lighter-coloured shales, the grey nodules take over after the dark. Similarly, the grey nodules occurring in horizons may be united into compound nodules (as transitional to limestone layers), and may show thinning lateral edges indicating growth during compaction (Fig. 3F, G, H, I).

The grey nodules differ from the dark ones in that: they do not occur as large ellipsoids and on the whole are more irregular; horizons of grey nodules more frequently lie closely stacked above each other; and the grey nodules on the whole are considerably more common. This may be due in part to the greater amount of calcium carbonate present (thus also the surrounding shale is commonly calcareous, cf. Bjørlykke 1973: 424) and in part to the thin-bedded and more diversified character of the lighter-coloured shales, reflecting more variegated sea floor conditions. Thus the grey shales display a more frequent alternation of type of sediment, greater differences in the initial sediments, more uneven bedding planes, and have a richer epifauna and especially infauna (as indicated by horizons of strong bioturbation). The nodules are not thicker than their original host layer. So, instead of developing into ellipsoidal nodules, the larger grey nodules became plate- or disc-like with a greater diameter – 2–3 metres or more – comparable to the plate-like nodules in dark shales. It is significant that small grey nodules, not reaching the maximum thickness of the initial host layer, may be more or less ellipsoidal. Laterally united nodules may form various odd shapes resembling those of Pleistocene concretions (cf., e.g., Tarr 1935), as already indicated by Holtedahl (1953: 188). In some examples neighbouring nodules of 2 or 3 closely stacked horizons apparently coalesced during growth into compound nodules (Fig. 3H), suggesting that precipitation of calcium carbonate and thus concretionary growth could at times even occur simultaneously in more than one horizon.

It appears that beds displaying strong bioturbation, especially of *Chon-*

drite-types, were favourable to the formation of nodules. Apparently the burrow in-fillings were more favourable to precipitation of calcium carbonate than the surrounding matrix. Precipitation commonly proceeded furthest away from the centre of the nodule within the burrows, giving the nodule an irregular, worm-nest-like or even spiny surface. This explains why limestone-filled burrows commonly penetrate the surrounding shale both *upwards* and downwards from the limestone nodule.

An early origin of the limestone nodules and layers is shown by their generally undistorted and well preserved fossils, including burrows. This could indicate either an early diagenetic origin of the nodules, as concretions within a host sediment, or that the nodules are solution relicts of an early consolidated limestone layer, but not of an unconsolidated calcareous layer.

If the nodules were solution relicts, one would expect to find concave corrosion marks, truncated fossils, and well-developed manganese or ferruginous rims, as in the massive Endoceras Limestone in the Oslo Region or in red 'Knollenkalk' of the Jurassic Ardnet Beds described by Garrison & Fisher (1969). Such features are generally not present in the nodules in question, although thin manganese and ferruginous rims have been reported (Bjørlykke 1973: 427–428).

A concretionary origin of the nodules in no way excludes the concept that certain nodular horizons were eroded soon after their formation, or that certain nodular horizons represent partly dissolved carbonate layers – but rather as exceptions than the rule. Good examples of erosional surfaces occur in the uppermost Ordovician (cf. Bjørlykke 1973: fig. 7). Horizons with closely-packed, straight-sided and paving-stone-like 'nodules' (especially in the Silurian) may well represent continuous limestone layers dissolved along cracks, e.g. mud cracks.

The nodules generally do not appear resedimented. Thus bedding planes and fossiliferous seams (where present) may be traced from one nodule to the next along a nodular horizon. In a few horizons, however, the nodules appear somewhat tilted and 'out of line' in relation to each other. Where not due to later tectonism, this could indicate either that more or less consolidated carbonate layers had been exposed to solution, leading to a rubble of resedimented pieces of limestone or limestone nodules partly imbedded in a residue of clay, as suggested by Garrison & Fisher (1969: 30) for certain Ardnet Beds, or it could indicate sediment flow of unconsolidated host sediment with imbedded consolidated carbonate nodules. However, such levels are not typical of the nodular shales and limestones.

On the whole it appears that the grey limestone nodules are primarily concretions and that their growth reflects conditions for precipitation of calcium carbonate. This is in accordance with their occurrence in specific horizons and location between pure shales and massive limestones within sedimentary cycles. It explains why nodules tend to be developed in the initially more permeable beds, such as highly fossiliferous, bioturbated, or silty beds, tend to have convex surfaces, and why neighbouring nodules are commonly coalesced. It further explains why their shape is apparently determined by the thickness and thus degree of compaction of the enclosing (host) bed and by other factors that affected permeability of this bed at the time of their formation. A part of the surface of a nodule may be delimited by a large brachiopod valve, or, a whole nodule may be delimited by a cephalopod conch (Fig. 3A) and in both examples the fossil apparently acted as an impenetrable wall. In other instances nodules appear to be delimited by large burrows, more or less of the type described by Winder in 1968 as 'giant *Chondrites*' – probably because sediment inside the burrow was more favourable to concretionary growth than the surrounding matrix (Fig. 3A). Furthermore, the shape of some nodules is determined by the shape of a large fossil or a fossil 'nest' in their middle (Fig. 2D). The rather variegated appearance of the grey nodules may be ascribed to the numerous factors controlling their shape.

Continuous limestone beds

There are various detrital and shallow-water limestones in the Ordovician and Silurian of the Oslo Region (cf., e.g., Jaanusson 1973, Bjørlykke 1974). In the following, only the thin layers, up to about 15 cm thick, usually single limestone layers (delimited by shale) in the 'nodular successions' are discussed. There are various transitions, both from horizon to horizon as well as within one horizon, from isolated, roundish nodules to continuous, knobby limestone layers and from flat-topped and flat-soled nodules to continuous plane-parallel limestone layers. In a small exposure, it may be hard to determine whether part of a large flat nodule or a continuous layer is present.

In some instances, what appear to be isolated nodules in sections across the bedding are really 'perforated' limestone layers where the nodules are connected, but where the host layer has not been completely cemented by calcium carbonate, leaving irregularly spaced 'holes' of shale (Fig. 3A). In others, limestone nodules formed before compaction are entirely connected by a sheet-like limestone apparently formed after some compaction of the host layer, resulting in a thin limestone layer with scattered 'bumps' (Fig. 3G). In both forms concretionary origin of the limestone layer is evident.

Continuous limestone layers apparently may be formed by fusion during growth of initially separate nodules, and perhaps to a greater extent than generally believed. Where there are no traces of the initial nodules on the surfaces of a continuous limestone layer, it may be hard to demonstrate whether it was formed by coalescence of nodules or not – especially since no border suture is developed where simultaneously growing concretions coalesce. However, even such layers had to obey the 'laws' of concretionary growth. Apparently supply of calcium carbonate was not a restricting factor as was the case for the nodules, but the layer had to be formed within the boundaries of a favourable host layer, and the sharpness of its boundaries would depend on the sharpness of the boundaries of its host layer; presence of bedding surfaces and laminae would depend on their presence in the host layer.

Since the nodules in some nodular limestones are rather small, and since nodules of neighbouring *horizons* may apparently coalesce during growth, it is possible that there is only a gradational transition from limestones formed by coalescence of nodules and 'non-concretional' limestones cemented by calcium carbonate.

Submarine carbonate cementation

The preservation of body and trace fossils suggests an early cementation of the limestone nodules and layers in the marine 'nodular succession' of the Oslo Region. Cementation apparently was initiated prior to any significant compaction, and thus probably close below the sea water–sediment interface. Since it is unlikely that the hundreds of horizons of limestone nodules and their limestone beds were raised above sea level as many times, the limestone is apparently due to submarine cementation by calcium carbonate, in the sense that the carbonate cement was precipitated from the water below the seawater–sediment interface.

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