

## A reply. Origin of limestone nodules in the Lower Palaeozoic of the Oslo Region

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Henningsmoen's comments on my papers have contributed many relevant observations concerning the formation of limestone nodules in the Oslo Region.

These papers represent the first discussion of such phenomena in this region since Brøgger's short description in 1882. As Henningsmoen has pointed out, a variety of concretionary forms are present; some contain septarian structures and other features that are more generally absent from Cambrian and Ordovician nodules. Since I dealt only with the most common nodule types I shall also restrict myself to them in this reply, and clarify points that were perhaps not clearly expressed.

Henningsmoen argues that the concretionary nature of the nodules was understressed in my paper, relative to the evidence he claims for this, so I shall concentrate on demonstrating that the nodules I described differ from most concretions described in the literature, and referred to by Henningsmoen (i.e. Tarr 1935, Raiswell 1971).

The term concretion is defined by the American Geological Institute as 'A nodular or irregular concentration of certain authigenic constituents of sedimentary rocks and tuffs; developed by localised deposition of material from solution, generally about a central nucleus. Harder than enclosing rock'.

This definition is by no means clear and may cause considerable ambiguity. When the above-mentioned authigenic constituents are carbonates or sulphides in a clastic matrix their concretionary nature is clear and the nodules stand out from the matrix, which contains only small amounts of these authigenic materials.

During concretionary growth the authigenic phase fills the available pore space. The volume of these authigenic minerals can be taken as a measure of the rock porosity during that period. Should the host sediment contain only small quantities of carbonates, the porosity will be indicated by the amount of carbonate within the concretions. Raiswell (1971), in his detailed study of Cambrian and Liassic concretions, showed that the host sediment is essentially non-calcareous (for Cambrian concretions  $< 0.01\%$  CaO). He discovered that the primary porosity varied from 40 to 60 % in the Cam-

brian concretions and up to 70 to 80 % in the Liassic ones. The Cambrian concretions from the Oslo Region contain 90 to 95 %  $\text{CaCO}_3$ , with sulphides and other authigenic constituents accounting for most of the remaining 5 to 10 %. Therefore the host sediment of these Cambrian 'concretions' was a relatively pure carbonate sediment which included trilobite tests.

These nodules are therefore created by the cementation of primary carbonate sediments. It is then pertinent to ask if the host sediments were deposited as isolated lumps of carbonate material that was subsequently cemented. It is difficult to see how this carbonate deposit (including the trilobite tests) could form itself into such discrete clumps on the sea floor. The thin olenid tests show no signs of reworking by currents (Henningsmoen 1957, Bjørlykke 1974) and were deposited in a very low energy environment. One may therefore assume that carbonate deposition occurred as a fairly continuous layer, and that parts of this bed were cemented and thereby avoided further compaction, while the remaining carbonate was dissolved out of the non-cemented sediments. This left nodules of carbonate. The author agrees with Henningsmoen that no subsolution took place in the nodules that were cemented.

In the case of the Ordovician limestone nodules we are presented with a somewhat lower carbonate content of 40 to 80 %. However, their surrounding matrix also contains considerable amounts of carbonate (20 to 50 %  $\text{CaCO}_3$ ) and we must therefore assume a calcareous host rock. Here we are dealing with carbonate cementation of carbonate-rich sediments. Again, it appears that this cementation was of an irregular nature, producing patchy or discontinuous clumps. The non-cemented parts of the carbonate beds were probably subjected to a degree of dissolution but this is more difficult to prove than for the Cambrian nodules. Even without a dissolution, partial and discontinuous cementation of carbonate beds would result in the compression of the non-cemented parts, and produce disc-shaped nodules and discontinuous beds. However, the cement found in the nodules has probably been derived from the non-cemented beds by solution.

The author considers that the use of the term concretion could be confusing if applied to the cementation of a carbonate bed. If the term is used, it should be pointed out that these are concretions of a different type to those normally referred to by that name in the geological literature.

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