SEDIMENTOLOGY OF THE LOWER CAMBRIAN SEDIMENTS AT ENA, NORDRE OSEN, SOUTHERN NORWAY

By
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Abstract.

The Lower Cambrian sedimentary rocks at Ena river comprise quartzitic and well-sorted sandstones, shale beds and some thin conglomerates.

The sandstones display several sedimentary structures, such as horizontal and vertical burrows (*Monocraterion*), ripple marks, load casts, diapiric structures and ball-and-pillow structures, besides some others of uncertain origin. Black, phosphatic fossil fragments occur scattered throughout the sandstones, but are especially enriched in two conglomerate beds. The pebbles of these are dominated by dolomite rocks with relicts of oölites and microfossils. The dolomite has a Lower Cambrian age, as indicated by Lower Cambrian phosphatic fossils. The formation of the dolomite rocks and their erosional products as well as the sandstones and shales are discussed on the basis of temporary eustatic changes in sea level during the transgressive phase in Lower Cambrian. The paragenesis of minerals formed during diagenesis is quartz-chlorite/sericite-calcite. Galena, pyrite and calcite poikiloblasts are epigenetic.

Introduction.

The bedrock east of the northern part of the lake Osensjø is largely soilcovered and exposures are scarce (Fig. 1). The geology of the area is known mostly through the classical paper of Schiøtz (1902). Holmsen and Skjeseth (in Holmsen, Skjeseth and Nystuen, 1966) reinterpreted the stratigraphy and tectonic evolution of the area on the basis of information given by diamond drilling near Tennåsen (Fig. 1).

Lower and Middle Cambrian sediments are exposed in the rivers Tverrena and Ena (Fig. 1). The beds are autochthonous and lie upon a Precambrian basement of red granite («Trysil granite»). The contact is

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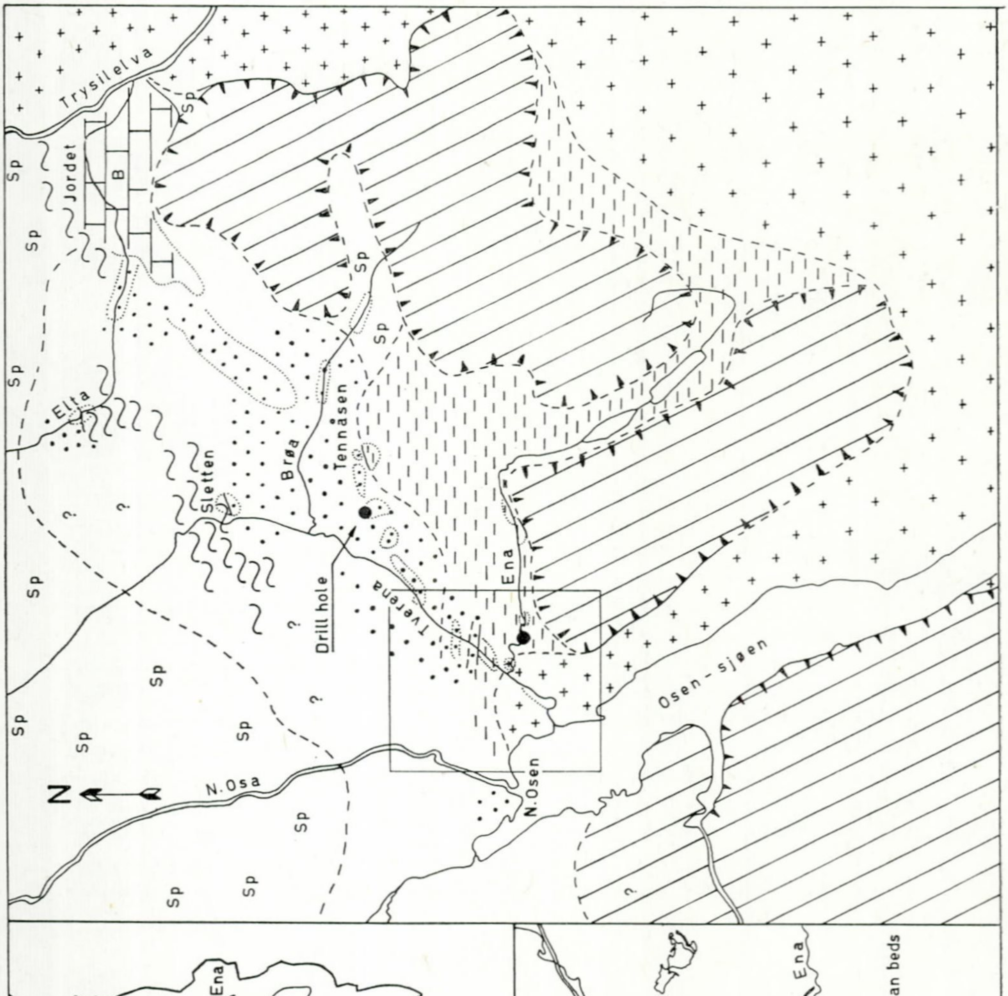
Trysilelva
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Locality of investigated Lower Cambrian beds
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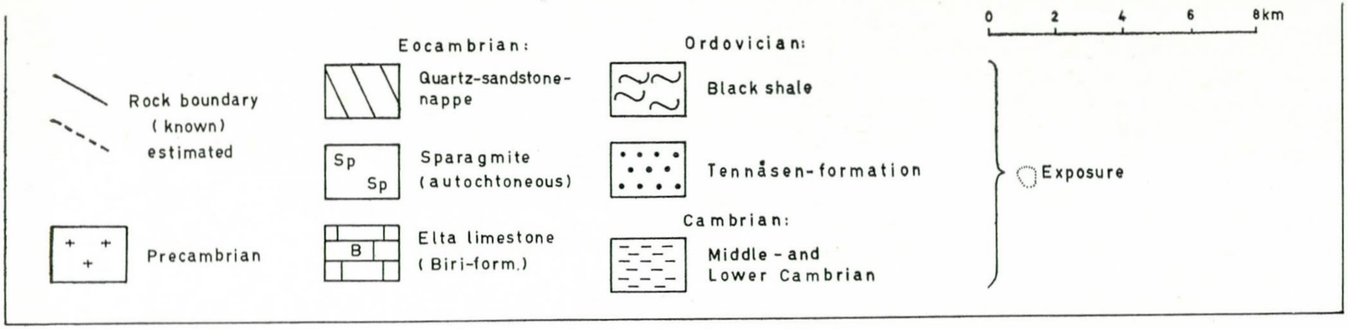

Fig. 1. *Location and geological setting of the investigated Lower Cambrian beds at Ena. Geological map after Holmsen and Skjeseth in Holmsen, Skjeseth and Nystuen, 1966.*

not exposed. Schiøtz (1902) referred the Lower Cambrian arenaceous beds to stage 1b and the overlying alum shale to stage 1c. In the lower beds, Schiøtz (1902) claimed to have found *Hyolithes sp.* and in the alum shale *Paradoxides sp.*, probably *Paradoxides tessini,* and some other trilobite fragments amongst which he suggested *Ptychagnostus gibbus* was present.

The location of the investigated Lower Cambrian strata is shown in Fig. 1.

I am indebted to Professor Steinar Skjeseth and Professor Nils Spjeldnæs for helpful discussions. Dr. Donald Provan has kindly corrected the English manuscript.

Stratigraphy and lithology.

In Ena river the Lower Cambrian beds outcrop with bedding planes dipping slightly to northwest. The sequence is almost tectonically undisturbed (Fig. 2). The lithostratigraphy of the beds is shown in Fig. 3.

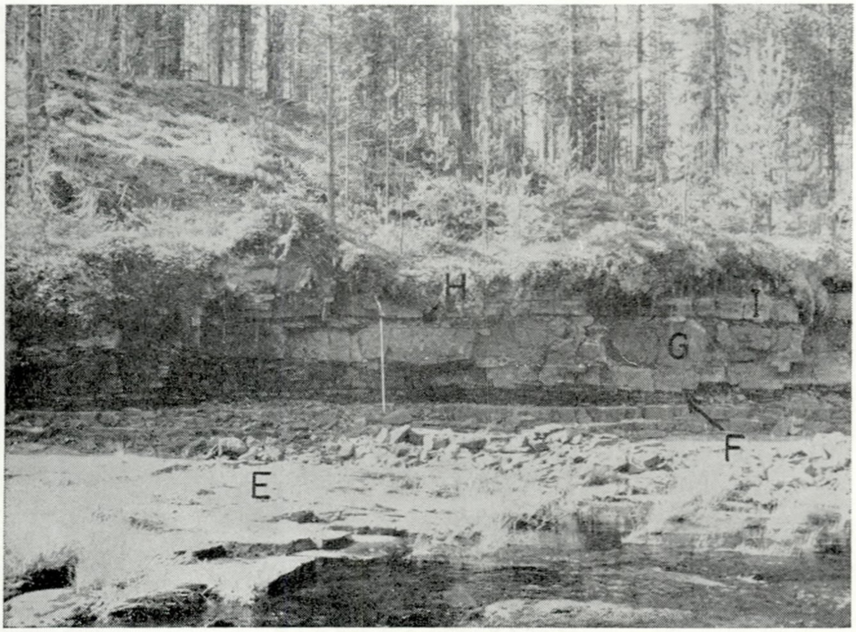

Fig. 2. *The river section at the main locality of the Lower Cambrian strata at Ena. The letters mark the members E—I in Fig. 3. The members A—D are situated below the water surface.*

The lowermost member (A) is exposed 150 m upstream from the main outcrop. The dark fine-grained sandstone appears rather massive, but displays a faint lamination when seen in thin section. The sandstone is irregularly spotted by white calcite impregnations, the size of which varies from a few millimetres to 2—3 cm. Small clusters and grains of galena are scattered throughout the rock. The exposed thickness is 2—3 m.

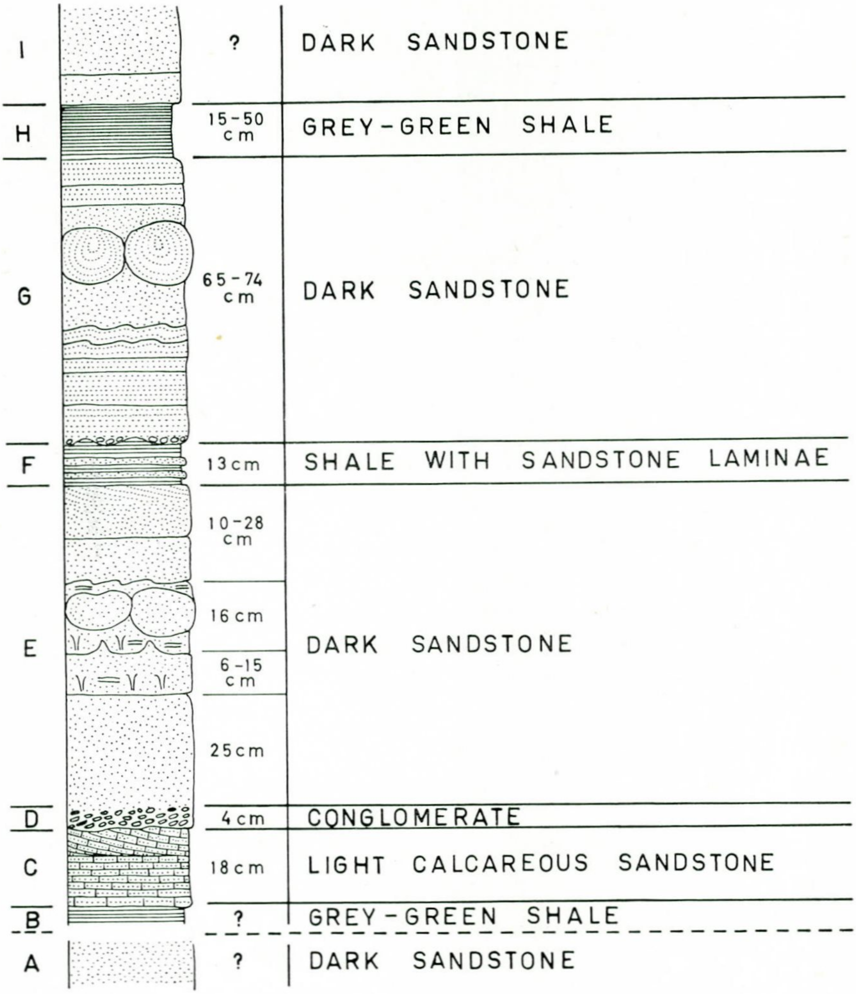

Fig. 3. *Lithostratigraphy of the Lower Cambrian strata at Ena. Description in the text.*

Grey-green shale (B) constitutes the lowest bed of the exposed river section at the main locality (Fig. 2). Its thickness and relation to the sandstone A is not known.

A light-grey calcareous and laminated sandstone (C) follows, with sharp lithologic contact, above the shale. The laminations are parallell to the bedding surface in the lower part of the bed, slightly inclined to it in the upper part. The thickness of individual laminae varies from less than 1 mm to about 6 mm.

The laminae differ in their content of detrital iron ore, and this is reflected in alternating dark and light colouration. The bedding planes reveal a marked parting lineation.

A thin conglomerate bed (D) overlies the calcareous sandstone with erosional disconformity. Sub-rounded to well- rounded, discoidal pebbles of grey dolomite predominate in the pebbly material. The flat discs are orientated in an imbricate arrangement. Well-rounded quartz granules also occur. A characteristic feature of the conglomerate is the enrichment in fossil debris. The debris is composed of black fragments representing several types of tube- and cornet-shaped, probably phosphatic fossils. The fragments vary from less than 1 mm to about 10 mm. According to preliminary determinations by György Hamar (personal communication), the fossils are *Hyolithes sp.* and *Torellella laevigata.*

Clusters of galena and pyrite are rather common in the conglomerate.

The conglomerate passes upwards into dark, fine-grained sandstone (E). The sandstone splits along bedding planes into well-defined flags, the thickness of which is indicated in Fig. 3. The sandstone is quite massive apart from the uppermost 3 cm, which is crosslaminated. Trace fossils frequently appear in the middle part of the sandstone. Horizontal and vertical *burrows* occur. The vertical ones have been identified as *Monocraterion,* the apertures of which are well preserved, and show the traces to have been made very close to the sedimentary surface (Fig. 4).

Assymetrical and linguoid *ripple marks* have been observed. They often show a irregular pattern, mainly due to the effect of load deformation (Fig. 5). Some other bedding plane markings of uncertain origin also occur. Straight, parallell-running shallow channels may, for instance, be groove casts, rill marks (Pettijohn and Potter, 1964) or kind of tracks made by some bottom-living organism. Some smooth spoon-shaped imprints likewise present a question of interpretation.

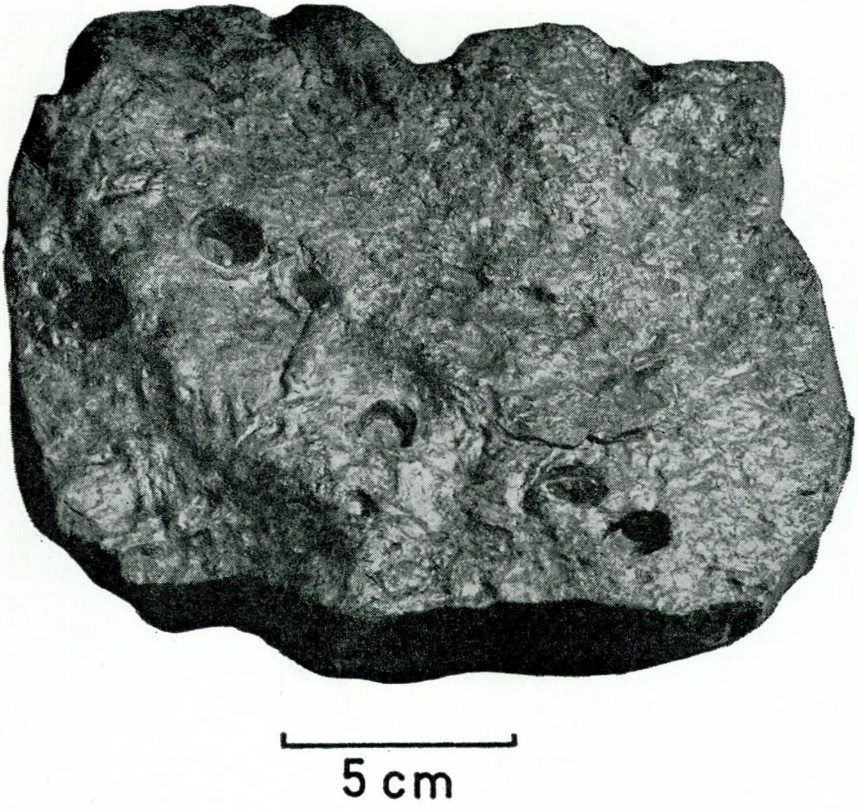

Fig. 4. *Vertical burrows, Monocraterion, from the sandstone E.*

These structures, however, show great similarities to the *rest marks* («Ruhespuren») made by burrowing trilobites (Seilacher, 1955 a, 1955 b). Schiøtz (1902) thought to have observed rain imprints, but this structure has not been identified by the author.

In the middle part of the sandstone the bedding surfaces are deformed into *diapirs* and *ball-and-pillow* structures (Fig. 5). A thin coating of grey shale enveloping the sand balls is occasionally observed. The primary horizontal lamination is deformed into a concentric arrangement inside the ball-and-pillow structures.

The sandstone grades upwards into a grey-green shale (H).

The uppermost member of the section is a dark, fine-grained, massive

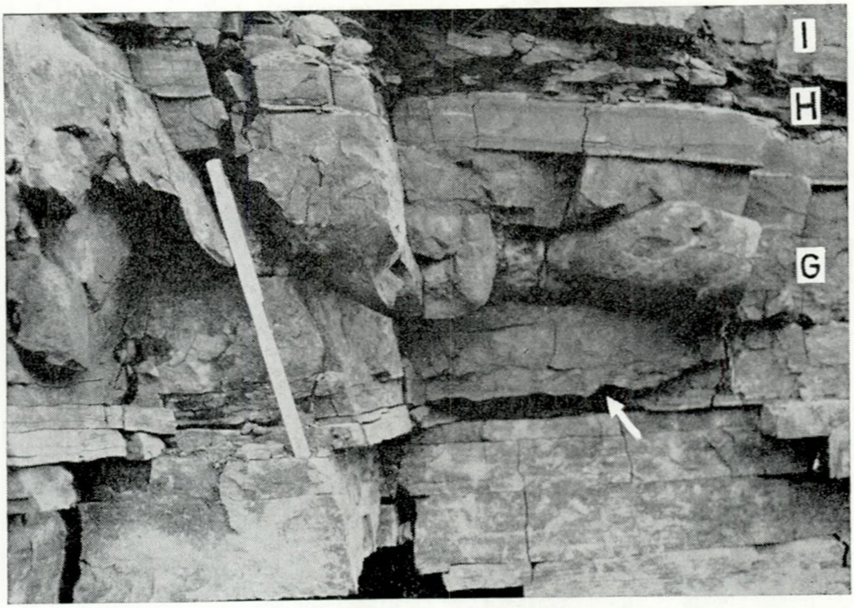

Fig. 5. *Ball-and-pillow structures in the sandstone G. Load-deformed ripple marks are shown by arrow.*

sandstone (I). The sandstone lies upon the shale H with a sharp contact. The exposed sandstone has a thickness of roughly 30 cm.

Textural composition of sandstones and shales.

Microscopic investigation indicates that the various sandstone members exposed in the section are very similar in texture. Using the point-counting technique, the length of the longest axis of 250 quartz grains in each of three thin sections taken from beds in lower, middle and upper part of the sequence was measured. The cumulative curves in Fig. 6 show the grain size distributions to approach lognormality. The slight deviations are probably due the relative small number of measurements, and uncertainties in defining the detrital outlines of the quartz grains.

The sorting parameter, given as $\sigma_I = (\varphi 84 - \varphi 16)/4 + (\varphi 95 - \varphi 5)/6{,}6$ (Folk and Ward, 1957), is 0,40 for all the three sediments represented by the curves in Fig. 6. Hence they all are *well-sorted* (Folk and Ward, 1957) as regards their quartz content.

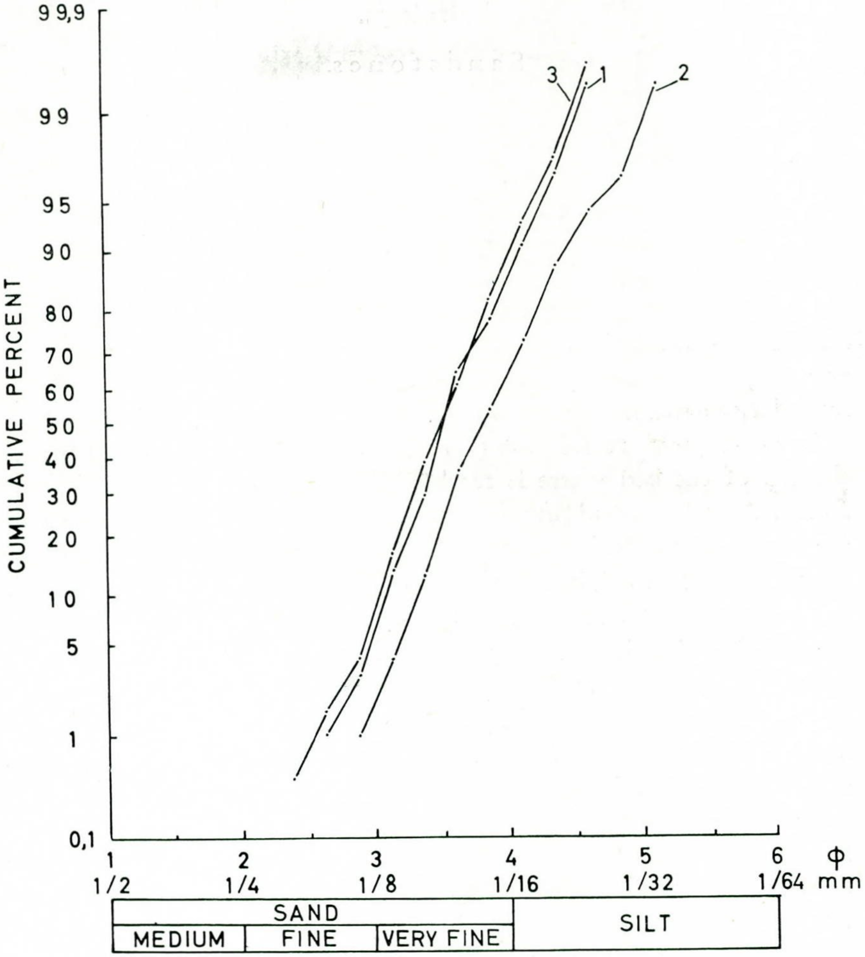

Fig. 6. *Grain-size distribution of samples taken from 1) sandstone A, 2) uppermost part of sandstone E and 3) sandstone I.*

The remaining arenaceous members of the sequence resemble samples 1 and 3 in Fig. 6 as regards grain size distribution. They are real *sandstones* in the sense of Folk (1954), while the more fine-grained sediment represented by Curve no. 2 in Fig. 6 is a *silty* or *muddy sandstone*. Using the same system of textural classification, the shales are *silt-shale*, *sandy silt-shale* or *sandy mud-shale*.

Petrology.

Sandstones.

Modal analyses were carried out on 10 thin sections taken from the various sandstone members in the profile. 500—1000 points were counted in each thin section.

The quartz content varies from 71 % to 92 %. It is lowest in the beds rich in calcite and phyllosilicates. The detrital grain contacts are mainly sutured, but straight and concavo-convex contacts also occur. Secondary enlargement by authigenic overgrowths is common, likewise interstitial fillings of anhedral quartz cement. The clastic grain boundaries may be outlined by dust rings or «clay» coatings. Both detrital and secondary quartz show replacement by calcite, chlorite and sericite.

In the calcareous sandstone (C) the *calcite* content increases towards the top of the bed where it reaches 25 %. The calcite occurs in two forms. Angular to subrounded calcite grains of the coarse silt grade are evenly distributed among the detrital quartz. This calcite is probably clastic. The original character of the carbonate is obscured due to recrystallization. The second type of calcite is present as interstitial cement, forming interlocking anhedral crystals. This type of calcite may represent a recrystallized primary carbonate mud filling the voids, or it may have been formed by dissolution of detrital calcite with concomitant reprecipitation in the interstices. Calcite with these two modes of occurrence constitutes 0—10 % of the other sandstones. A third type of calcite is found in the patchy impregnations. Each of the white spots is occupied by one single calcite crystal enclosing numerous, highly-scattered, corroded quartz grains. The quartz grains lying outside the calcite poikiloblasts are tightly packed, suggesting that the interspacing of the quartz arose during crystallization of the calcite.

Chlorite and sericite occur in fine-grained aggregates and are probably derived by recrystallization from a primary clay matrix. The total content ranges from accessory amounts in the sandstones to 20 % in the silty and muddy sandstones. Chlorite is also found as *pseudomorphs* after a detrital ferro-magnesian mineral. The chlorite-pseudomorphs are relatively infrequent throughout the sequence, but are enriched in heavy mineral zones in the uppermost sandstone members, G and I. The pseudomorphs often have the shape of a somewhat elongated prismatic mineral. The largest grain observed measured 0,5 mm. The grains were originally well-rounded. The chlorite of the pseudomorphs often grades into the interstitial voids, and also shows replacement contacts with the quartz grains. The alteration of the original ferro-magnesian mineral has therefore occurred, at least in part, during diagenesis. The chlorite is present as a very fine-grained aggregate in the pseudomorphs, which lack any traces of the original mineral. This was probably pyroxene or amphibole. In the uppermost bed the chlorite is largely altered to limonite.

Larger flakes of *muscovite* and some altered *biotite* are obviously clastic.

Iron ore is found as detrital grains and interstitial dust. It is occasionally present in amounts of 8—10 %, but generally it is an accessory. The iron ore is frequently altered to limonite. Limonite also occurs as pseudomorphs of pyrite.

Microcline never exceeds 1 %. The microcline has gridiron or perthitic structure. *Plagioclase* has been observed. Both the microcline and plagioclase appear quite fresh and unaltered.

Chert is present as detrital grains in all the sandstone members.

Besides the iron ore, several other *heavy minerals* are also represented. *Sphene, zircon, tourmaline, epidote* and *rutile* have been identified. The heavy minerals are mainly dispersed in the sandstones but also occur enriched in thin laminae and zones. In the lower bed of the sandstone E, the sphene content exceeded 3 %.

Fragments of phosphatic fossils have been found in the members A, E, G and I. In general, their structure has been largely destroyed by abrasion and dissolution.

Shales.

The mineral assemblage is practically the same as in the sandstones. The main constituents are quartz and an aggregate of sericite and chlorite, the phyllosilicates representing the primary clay content. Clastic muscovite flakes frequently occur. Calcite is present in accessory amounts.

Conglomerates.

The pebbly material of the lowermost conglomerate (D) comprises dolomites and quartzose dolomites besides some quartz granules. A peculiar rock is a dolomitized oölitic limestone. In one pebble of this rock type relicts are preserved of some microfossils (Fig. 7), of which the original skeletal substance is wholly replaced by dolomicrosparite.

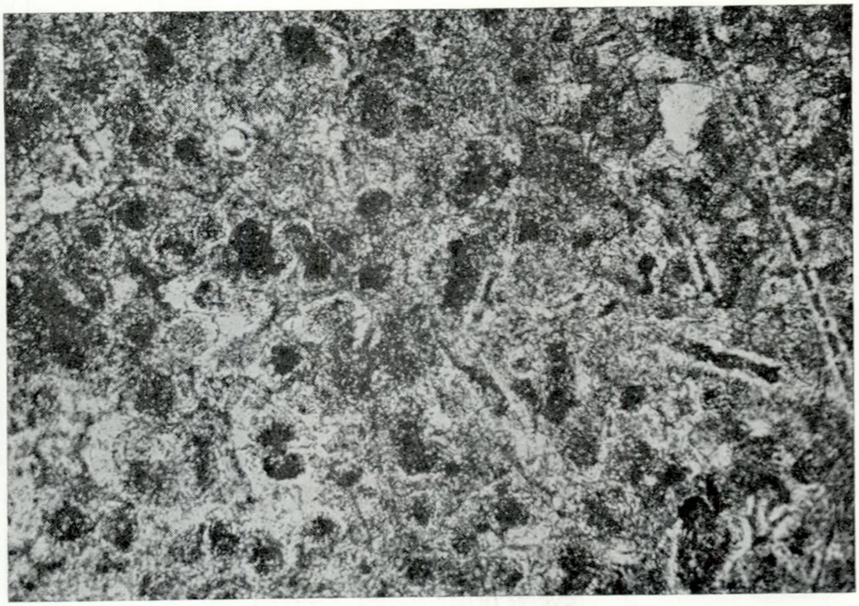

Fig. 7. *Dolomite pebble from the conglomerate D. Photomicrograph showing relicts of oölites and microfossils. The light microdolosparite is partly recrystallized to pseudodolomicrite (dark). X 140. Ordinary light.*

The oölites themselves range in size from 20μ—110μ. Some oölites have a nucleus consisting of an opaque substance surrounded by several concentric layers, but more frequently the nucleus is also replaced by dolomite. The oölites are usually compacted, forming a texture of interlocking polygons. A further stage in obliteration of the primary texture is a recrystallization of the dolomicrosparite which was formed during the first stage of dolomitization. The recrystallization acts as a grain diminution, forming a pseudodolomicritic texture (Fig. 7). This degradation of the grain size often starts in the centres of the oölites (Fig. 7). Steps of advancing recrystallization are observed in the pebbles. The end-product is a dense homogeneous pseudodolomicrite lacking any traces of the original texture (Fig. 8).

Besides the pebbles wholly dolomitic in composition, there occur pebbles composed of dolomitized oölites intermixed with silt-sized quartz grains and accessory muscovite flakes, chlorite pseudomorphs, chert and heavy minerals. The maximum quartz content approximates 20 %. In some pebbles there is a thin lamination generated from a variation

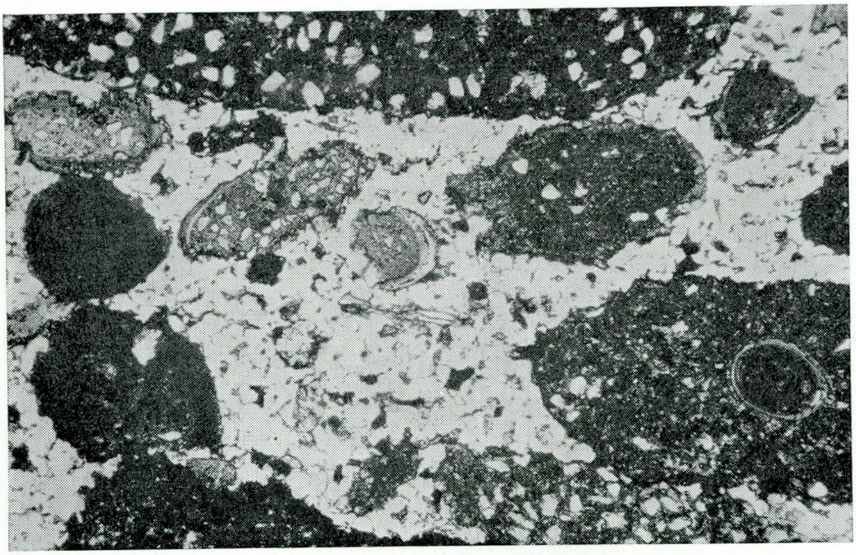

Fig. 8. *The conglomerate D. Photomicrograph showing dolomite pebbles and corroded phosphatic fossil fragments embedded in a groundmass of silt-sized quartz grains. The pebbles are mainly composed of pseudodolomicrite with variating content of quartz grains. Relicts of oölites are present in a pebble on the left, and in the lower right corner a pebble is containing a phosphatic fossil fragment. X 37. Ordinary light.*

in the ratio oölites/terrestric detritus. In one of these pebbles a burrow was observed. Phosphatic fossils of the same kind as in the conglomerate also occur in the dolomite pebbles (Fig. 8).

The pebbles are frequently bordered by a thin rim of recrystallized dolomite. This corona is post-depositional in origin but has undergone some dissolution, and is in places replaced by the calcite cement of the conglomerate.

The phosphatic fossil fragments in the conglomerate often show infillings of material corresponding to the composition of the various dolomite pebbles. During the stage of recrystallization of the dolomicrosparite to pseudodolomicrite the fragments were extensively dolomitized. In some fragments the dolomite infillings are replaced by calcite.

The groundmass of the conglomerate is composed of silt-sized quartz showing euhedral overgrowths which are partly replaced by the calcite cement. The groundmass is enriched in heavy minerals of the same assemblage as found in the sandstones. Intrastratal solution in the conglomerate has caused the formation of small stylolites marked by opaque carbonaceous matter.

The conglomerate found at the base of the sandstone G is in several respects very similar to the conglomerate D. The dolomite pebbles comprise, *inter alia,* quartzose dolomites of types corresponding to those occuring in the lowermost conglomerate. The conglomerate is likewise enriched in phosphatic fossil detritus.

The mutual contacts of the different mineral components in the sandstones, shales and conglomerates show a series of successive replacements. During the early (?) stages of diagenesis the quartz overgrowths and the silica cement were formed. This secondary silica is probably intrastratal in origin, formed by pressure solution at the points of contact between the detrital quartz grains. The emplacement of secondary quartz was followed by replacement of chlorite and sericite, and thus the calcite cement was introduced. The limonite replacement of pyrite and chlorite was apparently formed at a late stage of the rock's history, probably due to weathering processes.

The formation of galena and pyrite is a problem of ore genesis not to be discussed in this paper. Except for the late limonite, the sulfide minerals are, however, epigenetic in relation to the other minerals in the rocks. The association of sulfide minerals and poikiloblasts of calcite shows similarites to lead deposits of corresponding geologic environments in Sweden (Grip, 1960).

The fossil content of the dolomite pebbles in the conglomerates shows the pebbles to have been derived from *Lower Cambrian* carbonate rocks. The dolomitization of the original carbonate rocks and also of the fossil fragments predates the formation of the conglomerates.

Environment of deposition.

During the Lower Cambrian, the peneplaned region of Precambrian rocks on the eastern side of the lake Osensjø was transgressed by the sea from west or northwest. This feature alone indicates shallow water deposition of the sediments concerned.

The textural similarities between the various sandstone beds indicate deposition during relatively stable and homogeneous conditions of hydrodynamics, intermittently interrupted by lower energy environments favouring shale sedimentation. The alternation of sandstone and shale beds may thus reflect variations in the water depth of the depositional area.

The abundance of surface and near-surface traces in the sandstone E indicates a fairly continuous sedimentation with little or no penecontemporaneous erosion. Such conditions would prevail outside the region influenced by strong tidal currents. On the other hand, the lack of trace fossils in the other sandstone beds may be due to reworking in more agitated waters.

The conglomerate beds show that the Lower Cambrian sequence at Ena involves diastems or hiatuses. Temporary regressions caused erosion of previously deposited and indurated sediments. The fossil debris in the conglomerates is, at least partially, derived from a preexisting dolomite by a selective breaking down of the rock's constituents. The enrichments of heavy minerals, especially in the lowermost conglomerate, may be ascribed to a similar process of selection. The scattered fossil fragments in the sandstone beds may indicate a complex history of repeated reworking and redeposition of the detritus before the final settling.

The dolomite bed which furnished the pebbles to the lowermost conglomerate (D), may have lain above the calcareous sandstone (C) before its removal. On the other hand, if this were the case, it is probable that the highly permeable calcitic sandstone would also have suffered dolomitization.

The dolomite pebbles show different degrees of terrigenous admixtures. This feature indicates a gradation between a carbonate and quartz province, likewise the composition of the calcareous sandstone (C).

In recent carbonate deposits, oölites are known to be formed in shallow water agitated by tidal or wave currents (Hatch, Rastall and Greensmith, 1965). The oölitic limestone which gave rise to the dolomite of the Lower Cambrian sediments in the Ena area may have originated as a near-shore carbonate deposit, grading offshore into admixed carbonate and quartz sediments. The calcareous sandstone (C) may thus be interpreted as a offshore facies of the oölitic limestone. The terrigenous detritus may have been transported along shore into the carbonate province. Several examples of such a pattern of sediment distribution have been described (Sanders and Friedman, 1967).

The temporary regression, and thereby gradual emergence, would favour a dolomitization of the near-shore carbonate deposit. The dolomites formed in this way may have graded into offshore calcitic deposits (Friedman and Sanders, 1967).

In the late stage of emergence, the dolomite would be exposed to erosion. Dolomite pebbles, released fossil fragments, quartz and heavy minerals may thus have been transported into the offshore calcareous environment.

The presence of dolomite pebbles in the uppermost conglomerate may be ascribed to a similar succession of events.

The investigated strata form just a part of the total sequence of the Lower Cambrian beds at Ena. The total thickness is probably in the order of 10—20 m. Six km northeast of Ena the Lower Cambrian beds comprise about 2 m, but several diastems (or hiatuses) also occur here (Nystuen, in Holmsen, Skjeseth and Nystuen, 1966). The variations in thickness are probably due to uneven relief of the sub-Cambrian peneplane in this area. Rugged topography in the transgressed region would influence the drainage pattern, the coastal currents and hence the distribution of sediments in the depositional area.

Origin of terrigenous detritus.

The Lower Cambrian beds received their terrigenous material from Precambrian rocks to the south and/or east. The large amounts of stable components in the sandstones may be due to extensive mechanical and chemical decomposition of the granitic rocks of this region. The quartz detritus may also be ascribed to recycling of arenaceous rocks, perhaps with addition of fresh granitic material represented by the feldspars and the biotite. The Trysil-Dala sandstone, lying 30 km east of Ena, is the only known potential source rock of second generation quartz. The fine-grained porphyritic rocks of this eastern region, however, have not been recorded among the detritus in the Lower Cambrian sediments at Ena. The chert grains, on the other hand, may have been derived from chert occurring in the Precambrian rocks of Dalarna (Hjelmqvist, 1966). At present, the heavy mineral assemblage cannot be referred to any distinct source area, due to lack of information on the petrography of the Precambrian rocks concerned.

Conclusions.

The Lower Cambrian sedimentary rocks at Ena were deposited during the transgression towards the south-east of the Lower Cambrian sea.

Eustatic changes in sea level are thought to have caused physical environments favouring alternating sand and silt-mud sedimentation. Dolomite horizons may have originated by dolomitization of near-shore oölitic limestones during some temporary phases of regression. Subsequent erosion and decomposition of the dolomite beds gave rise to conglomerates containing dolomite pebbles and phosphatic fossil fragments. Differences in thickness and sedimentary facies within the Lower Cambrian sedimentary rocks in the region may be due, in part, to uneven relief of the sub-Cambrian peneplane. Paragenesis of diagenetic authigenic minerals is quartz-chlorite/sericite-calcite. Epigenetic minerals are galena, pyrite and poikiloblastic calcite. Some limonite has probably been formed by weathering. Further investigations are needed on the biostratigraphy, facies changes and origin of terrigenous detritus.

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