

Evidence of synsedimentary tectonics in the Lower Silurian (Llandovery) strata of Brumunddalen, Ringsaker, Norway

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Lower Silurian sediments exposed along the Brumund-river indicate an episode of tectogenetic basement movements around the Idwian/Fronian transition. This primarily affected the incompletely lithified uppermost layers of the sedimentary cover, which show slumping, sliding and differential brecciation. The lower to mid-Llandovery succession shows three clearly defined lithological units. The sharp facies changes between these units contrast to more gradual transitions seen in other districts of the Oslo Region. They may be explained by the interplay of local crustal movements and regional, epeirogenetically induced relative changes in sea-level. Structural measurements suggest a differentiation between the early Silurian deformation structures and those produced by the later orogenic overprint.

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Early investigations of the Lower Palaeozoic sediments of the Oslo Region were largely restricted to palaeontological and stratigraphical studies (Kjerulf 1857, Kiær 1906, Henningsmoen 1960). Geological interest in the last decades has been more and more directed towards sedimentological analyses (e.g. Major 1945, Seilacher & Meischner 1964, Broadhurst 1968, Brenchley & Newall 1980). Recent syntheses of the Silurian succession (Worsley 1982, Worsley et al. 1983) give both a new stratigraphical scheme and a rough outline of the sedimentational history and the palaeogeographic development of the succession.

Pronounced facies changes in the Silurian sequence seem to be related to distinct shallowing or deepening events and this is particularly true around the Ordovician/Silurian transition. Facies changes seen in this interval have been explained either by eustatic sea-level changes (Brenchley & Newall 1980) or by local tectonic movements (Spjeldnæs 1957, Skjeseth 1963, Bjørlykke 1983). In any single case it may be difficult to decide which of these two main factors caused the shallowing or deepening phase concerned. Indeed, the total effect may result from a superposition of these two factors. A better knowledge of the interplay between global sea level changes and the spatial and chronological distribution of Caledo-

nian orogenic movements demands closer study of all kinds of evidence for synsedimentary tectonics within the succession.

Bjørlykke (1983) envisages a relationship between rapid basin subsidence accompanying deposition of the coarse clastic Bruflat Formation in the Upper Llandovery and emplacement of the first Caledonian nappes to the north of the Oslo Region.

Data presented here on synsedimentary to early syndiagenetic deformation in the sedimentary succession of Brumunddalen (Ringsaker) provide evidence of syndepositional tectonism in the northern districts of the Oslo Region as early as the mid-Llandovery.

In the course of field studies as part of a sedimentological investigation of the carbonates of the Rytteråker Formation (Worsley et al. 1983) throughout the Oslo Region, I studied three exposures in Brumunddalen (Fig. 1). This is still a relatively poorly known area and the present brief preliminary note calls attention to structures which have not been reported previously. This paper does not claim to be a complete comprehensive study, but the information presented herein may hopefully contribute to the ongoing discussion of the relation between tectonics and sedimentation in the Oslo Region's Lower Palaeozoic succession.

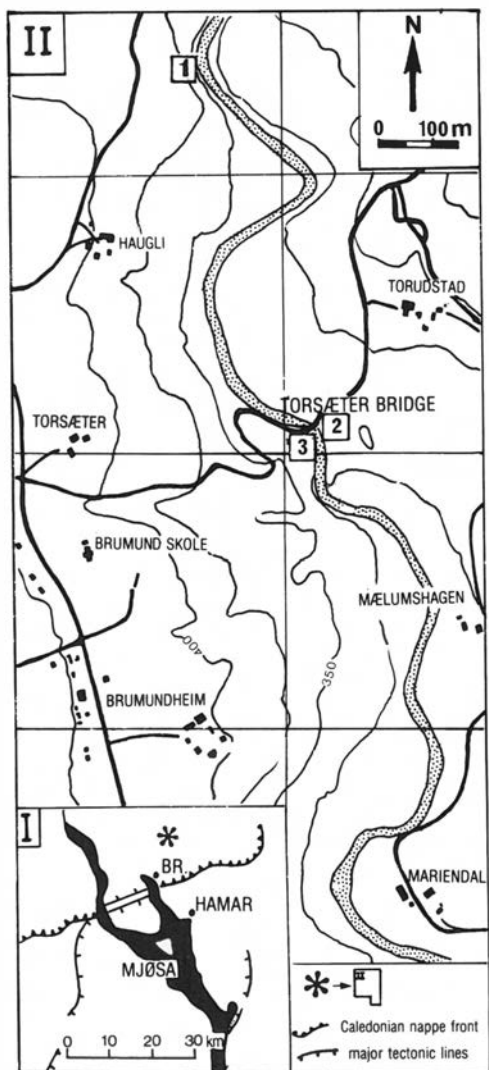


Fig. 1. Location map. The asterisk in the index map marks the position of the large scale map (Br. = Brumunddal). The arabic numerals in the large scale map indicate the position of the investigated sections.

Local setting

The Lower Palaeozoic succession of the Ringsaker district (Henningsmoen 1960) belongs tectonically to the Osen-Røa nappe complex (Nystuen 1981). This has generally been regarded as the southernmost of the Caledonian nappes in the north of the Oslo Region. The Ringsaker succession has thus a unique position in relation to the rest of the Oslo Region's Lower Palaeozoic

rocks, which is also reflected in its different sedimentological development. The main Scandian deformational phase has recently been placed in the middle Silurian to Lower Devonian interval (Nystuen 1981, Roberts 1984). It caused mesoscopic folding of décollement type with roughly E-W-striking fold axes.

The Silurian strata rest unconformably (*sensu lato*) on the middle Ordovician Mjøsa Limestone. My own observations around this contact largely conform to earlier descriptions of the Lower Palaeozoic strata in the Mjøsa district (Kiær 1904, 1908, Skjeseth 1963, Spjeldnæs 1982). I was, however, not able to find 'a weathered surface of the Mjøsa Limestone' (Skjeseth 1963, p. 84) at the contact to the overlying Silurian sandstone. The uppermost Mjøsa Limestone is rather developed in nodular limestone facies, which might reflect the effect of pressure solution in response to tectonic stress (Wanless 1979). Apparent stratification of the nodules might therefore be a secondary phenomenon and

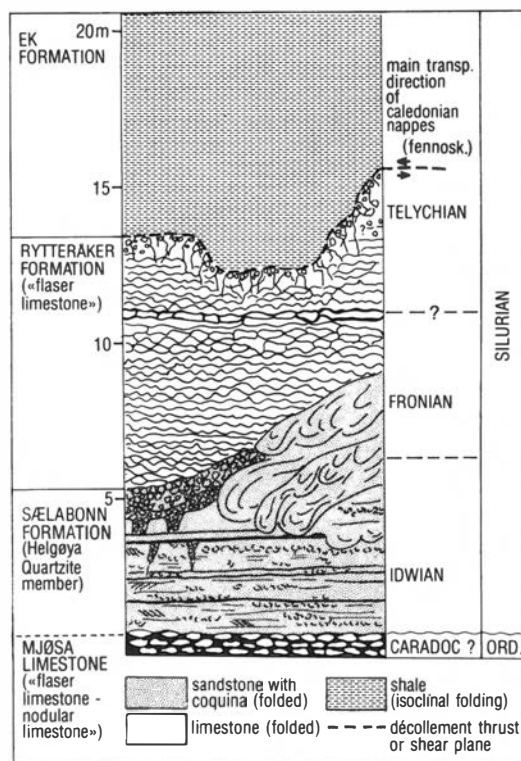


Fig. 2. Generalized facies diagram for the lower Silurian strata of Brumunddalen (stratigraphic position extrapolated from Worsley et al. (1983, Fig. 5) and Bruton & Williams (1982)). Without horizontal scale.

it is not possible to exclude an original weak angular unconformity at the contact between Ordovician and Silurian strata.

The facies diagram (Fig. 2) shows the three Silurian lithostratigraphical units exposed in Brumunddalen with formational names taken from the stratigraphical scheme proposed by Worsley et al. (1983). As noted below there is some nomenclatorial confusion regarding names to be used for the lower two units. Resolution of this problem is, however, outside the scope of this paper. Basal sandstones have been assigned to the Sælabonn Formation by Worsley et al. (1983) or to the Helgøya Quartzite (Skjeseth 1963), although facies differences may suggest that neither of the above terms are appropriate in Brumunddalen. Lithologically they consist of thin to medium bedded (2–50 cm), moderately to well-sorted red fine sandstone, rich in carbonate. They display features typical of shallow marine deposition as described by Füchtbauer & Müller (1977, p. 55) including small scale bimodal cross-bedding, wave ripples, planar lamination (mm and cm scale) bioclastic laminae or lenses (cm scale) and locally intense bioturbation. In the uppermost parts intercalations of shale beds (up to 15 cm thick), fissures infilled with intraformational breccia and larger breccia bodies appear. Locally the bedding is disturbed by load and slump structures (Figs. 3,4,14,15).

The sandstones are overlain by limestones assigned to the Rytteråker Formation by Worsley et al. 1983. This unit was earlier called the Pentamerus limestone (Kiær 1908) and informally termed the Limovnstangen Formation in the map sheet Hamar by Høy & Bjørlykke (1980). In the vicinity of locality 1 it appears to rest conformably on the uppermost sandstone beds. The sharp contrast in facies suggests, however, that the contact represents at least a minor break in sedimentation. The Rytteråker Formation comprises a monotonous pelitic nodular limestone, more precisely termed 'flaser limestone' (Weber 1969, p. 82), showing no other sedimentary structures than intense *Chondrites* type bioturbation. Microfacies analyses suggest that these rocks can be classified as wackestones (Dunham 1962, Embry & Klovan 1972) or biomicrosparites (Folk 1959, 1962). The occurrence of microscopic blue-green algae (*Girvanella*) suggests deposition within the photic zone (Lauritzen & Worsley 1974). A few centimetres below the contact to the overlying Ek Formation this monotonous development is replaced by intraformational breccia

and conglomerates with various types of matrix. The Rytteråker Formation shows lateral thickness variations from 8 to more than 10 m (exact measurements prohibited by outcrop conditions). The possible reasons for this variation will be discussed later. Fig. 2 shows the apparent thickness as observed in section 2, not corrected for stratigraphical loss owing to homothetic faulting.

The contact between the limestone and the overlying shale is strongly tectonized, probably as a result of Scandian phase décollement folding and thrusting within the Ek shale. The Ek Formation consists of dark graptoliferous shales containing sporadic limestone concretions. Primary stratification is weakly indicated by bedding parallel changes in cleavage plane density, some more calcareous beds (showing a higher degree of consolidation) and the bedding parallel long axes of elongate concretions. It is not possible to give a reliable estimate of the thickness of the formation in Brumunddalen because of strong deformation and insufficient degree of exposure. Worsley et al. (1983) quote 95 m for the formation thickness in its type area on Helgøya (Hamar district).

Description of localities

Loc. 1, Brumundelv N

Locality 1 (Fig. 1) shows the uppermost Mjøsa limestone, the Helgøya Quartzite and the Rytteråker Formation in several partial exposures. In the northern part the strata form a closed syncline, which passes into an open asymmetrical anticline towards the south.

The Helgøya Quartzite thickens from 5.5 m in the northern limb of the syncline to 6–7 m in the southern limb of the anticline, probably as a result of intraformational slumping and sliding. Only one horizon in the northern limb of the syncline shows contorted bedding. This was interpreted as load casting by Skjeseth (1963, p. 85). However, the lack of a sufficiently thick shaly horizon below and the presence of erosional contacts within the structure suggest that it was rather caused by some kind of slide movement within the hydroplastic coherent sediment.

This structure passes laterally into several distinct slump sheets towards the southern limb of the anticline. Within each of these units the beds have been contorted into irregular close or wide, partly dish-shaped, slump folds. The units are

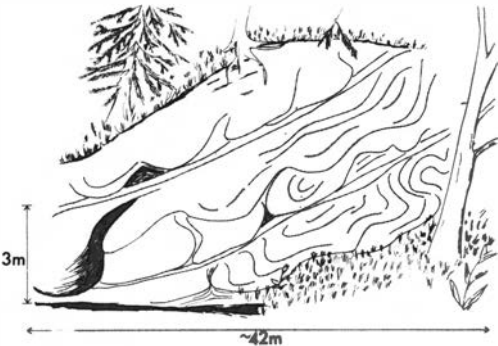


Fig. 3. Simplified field sketch of the southern part of section 1.

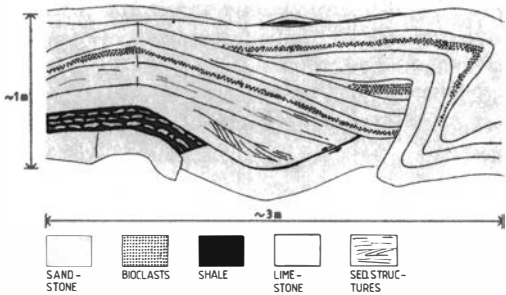


Fig. 4. Field sketch showing one of the slump structures exposed in section 1. Note the shear contact between the lowermost beds, erosional and structural unconformities, indicating that the structure was generated in several phases of sliding, erosion, deposition and folding.

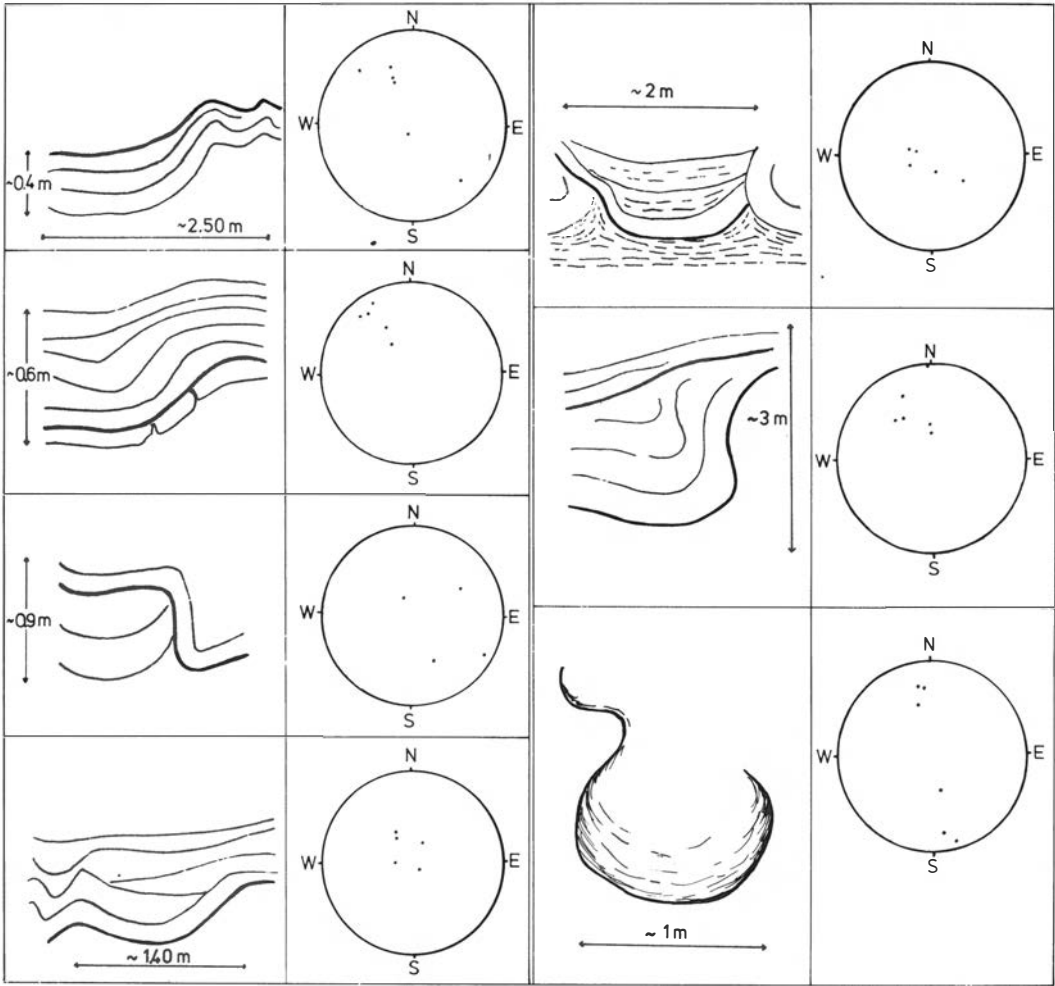


Fig. 5. Field sketch of the seven most easily accessible slump-structures, exposed in section 1, and Schmidt equal-area projections showing the poles of measured bedding planes. Note the pronounced irregularity, prohibiting any meaningful construction of fold-axes directions.

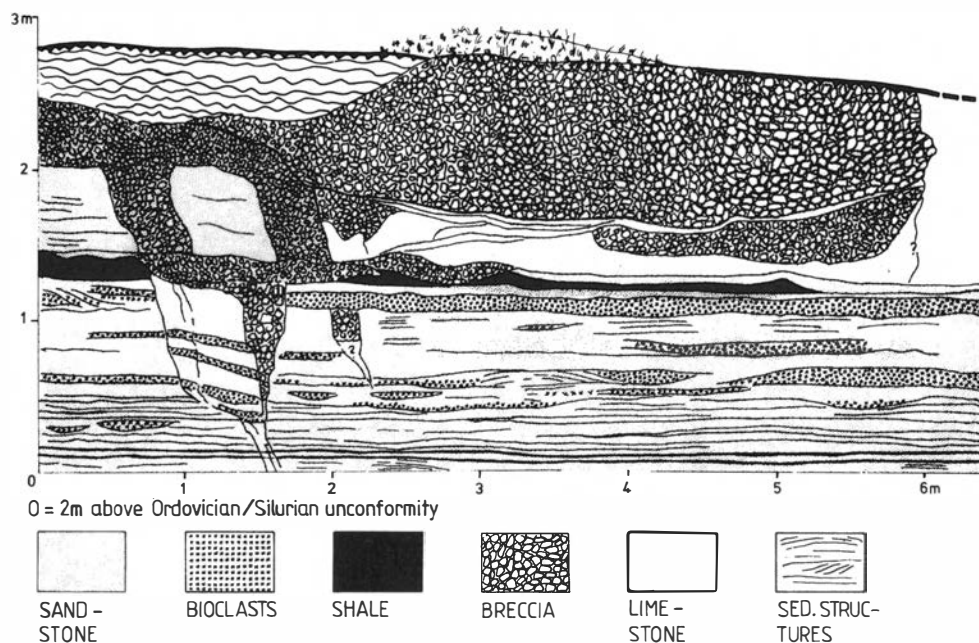


Fig. 6. Field sketch, showing an interpretively simplified two-dimensional projection of the upper part of section 2, below the shear plane. Sampling points (sample 1 and 2) are marked with arabic numerals. Compare Fig. 9.

separated by smooth undisturbed beds or slide planes that form an angular unconformity with the main regional stratification. These slide planes become progressively steeper in down-dip direction, i. e. towards the south (Fig. 3).

Several small erosive unconformities can be observed within many of the slump folds (Fig. 4). Locally such erosion surfaces appear to truncate pre-existing folds. The distinctly smooth basal planes of the undisturbed beds which separate the slump units also appear to be erosive.

A Schmidt equal area projection (Fig. 5) shows the irregular geometry of the slump folds as compared to the larger, younger tectonic folds.

A 30 cm thick sandstone bed immediately below the Rytteråker limestone is preserved in the northern limb of the syncline. This bed contains fragments of the thick-shelled pentamerid *Borealis borealis* (cf. Mørk 1981) and thus suggests that the Sælabbonn Formation is not younger than Idwian in this area (Baarli & Johnson 1982).

Loc. 2, Torsæter bridge (eastern river bank) (Fig. 9)

The uppermost beds of the Mjøsa limestone, the overlying Helgøya Quartzite and the base of the

Rytteråker Formation are exposed here. They form a homothetically downfaulted block in the northern limb of a closed anticline, the core of which consists of massive Mjøsa limestone. A further homothetical shear plane occurs directly over and partly truncates the sedimentary contact between the Helgøya Quartzite and the Rytteråker Formation. This has probably led to a loss of strata within the overlying unit (Fig. 6). The Helgøya Quartzite is here 4.30–4.50 m thick. Average bed thickness increases rapidly from base to top of the unit (2–3 cm in the lowermost beds to more than 50 cm in the uppermost). V-shaped fissures appear for the first time about 2.80 m above the base of the formation. These are bounded by joints and are infilled with intraformational 'in situ breccia' (Sample 1, Table 1).

At 3.25 m they are overlain by an undisturbed shale bed, which again is succeeded by an equally undisturbed 10 cm thick sandstone bed. A second thin shaly horizon is overlain by a 60 cm thick sandstone bed, which again is incised by breccia infilled fissures (Fig. 6). This bed is erosively overlain by several bodies of sedimentary breccia (sample 2, Table 1), all with erosive bases. These are preserved in a total thickness of up to 1 m, and are truncated by the shear plane noted above in the southern part of the exposure.

sample 1 (stained acetate peel, Fig. 10)	sample 2 (stained acetate peel, Fig. 11)	
locality: 2	locality: 2	
niveau: 3.20 m above the base of the Sælabbonn Formation	niveau: 4.50-4.60 m above the base of the Sælabbonn Formation	
classification: intraformational quartzite breccia	classification: intraformational quartzite breccia	
fabric: clast-supported (90 % clasts), extremely poor sorting, boundaries of adjacent bigger clasts often fit together and show parallel direction of sedimentary planar lamination. Variability of planar lamination in hand specimen: 70°	fabric: clast-supported (50-80% clasts) poor sorting, two deformation episodes, closely spaced "in-situ"-rock fragment structure in the lower right part of the sample changes upwards and towards the left into a more open spaced structure, richer in matrix and with distinctly separated clasts.	
clasts	clasts	matrix
<p>2 types of clasts</p> <p>type 1 (>90%) type 2 (<5%)</p> <p>- compacted fine -muddy sandstone sandstone, al- (40-50% clay matrix) most free of</p> <p>- free of carbonate</p> <p>- preferred orientation of elongate grains</p> <p>- angular but indistinct edges</p> <p>- up to 4.5 mm in diameter</p> <p>- long axes at right angles to sedimentary lamination</p> <p>- angular to subrounded, sometimes with slightly corroded edges</p>	<p>compacted fine sandstones, most of them almost free of siliciclastic matrix and carbonate, but some containing up to 20% recrystallized fossil debris</p> <p>- sedimentary planar lamination</p> <p>- single, well-rounded grains of feldspar (0.5-1 mm) within the clasts or as isolated components, strongly strained</p> <p>- all transitions from brecciated but still coherent rock to isolated coarse sand to gravel-sized clasts</p> <p>- clasts often + isometric, otherwise long axes perpendicular to sed. lamination</p> <p>- angular to subrounded, contacts to the matrix vary from distinct and straight to undistinct and irregular</p> <p>- qualitative mineralogic composition: quartz, feldspar, opaque min.; zircon white mica, apatite, calcite (recryst. fossil debris)</p>	<p>- calcareous sandstone, consisting of:</p> <p>- 50% siliciclastic sand (quartz, fsp. heavy minerals)</p> <p>- 10-30% carbonate bioclasts (fragments of trilobites, brachiopods, crinoids, rugose corals and bryozoans)</p> <p>- 20% calcite cement</p> <p>- bioclasts bored, micritized and recrystallized, irregularly distributed in the sample, clusters of coherent, cemented bioclasts occur, forming intra-clasts</p> <p>- siliciclastic grains angular to subrounded</p> <p>- sutured and non sutured pressure solution seams with concentration of Fe-oxides and hydroxides</p>
deformation:	deformation:	
a) <u>syndimentary</u> to <u>eogenetic</u> : local brecciation of two successive sandstone beds, one of them being considerably richer in muddy matrix than the other. Clasts of the mud-rich bed are squeezed and crushed between the clasts of the harder, purer sandstone bed, the latter showing abundant internal fracture deformation.	a) <u>syndimentary</u> to <u>eogenetic</u> : differential brecciation of a sandstone layer, containing intercalations of coquina and comprising different degrees of consolidation. Minor succeeding intrastratal movement probable.	
b) <u>meso-</u> to <u>telogenetic</u> : no younger deformation structures observed	b) <u>postsedimentary</u> : formation of a fracture system, which is influenced by the primary inhomogeneities of the breccia fabric, fractures are infilled with coarse crystalline Fe-2+-calcite.	

Table 1. Description of two samples of intraformational breccia from the Sælabbonn Formation.

In the northern part an irregular surface on top of the breccia is conformably overlain by the lowermost nodular limestone beds of the Rytteråker Formation, preserved below the continuation of the shear plane (Fig. 6). The shear plane itself is overlain by an 8 m thick section of almost undisturbed nodular limestone.

No equivalent to the *Borealis* bed of locality 1 was found in this locality.

Loc. 3, Torsæter bridge (western riverbank) (Fig. 7)

This exposure reveals the uppermost 1-2.5 m of the Rytteråker Formation and a part of the overlying Ek Formation. The contact is poorly exposed and is mostly covered by talus. The limestone appears to have an erosive top, the erosion reaching 1.5 m deeper in the northern than in the southern part of the exposure. The lithology here is finegrained and dark, but somewhat more massive than on the other side of the river. Where the contact can be laid bare, the overlying shale is crushed and shows no planar structures. In the exposed part of the shale, only a few metres above, a large recumbent fold can be discerned by means of the criteria for primary stratification mentioned above.

Measurements of folded and unfolded bedding planes are plotted on Schmidt projections (Fig. 8). Thin sections and acetate peels of samples taken from the limestone with intervals of 50 cm show intensive fracture deformation, which increases upwards, changing into complete tectonic brecciation directly below the formation boundary (sample 30 b, Table 2). Within the fracture system of this deformation episode, mineralization of Fe-rich dolomite, quartz and analcime can be observed.

The same mineralizations occur in the uppermost limestone beds which are exposed on the eastern bank of the river. This suggests that the boundary of the exposure corresponds to the formation boundary in this place (vegetation covers weathered shale) and leads to the estimate for the thickness of the Rytteråker Formation shown in Fig. 2.

In order to find a possible relationship between the deformation of the limestone and the shale, the limestone below the contact plane was sampled at different levels of erosion. In the southern part of the exposure, where the thickest limestone sequence is preserved, the uppermost limestone bed is developed as lag deposit. It comprises an intraformational conglomerate containing rounded wackestone-intraclasts within a bio-

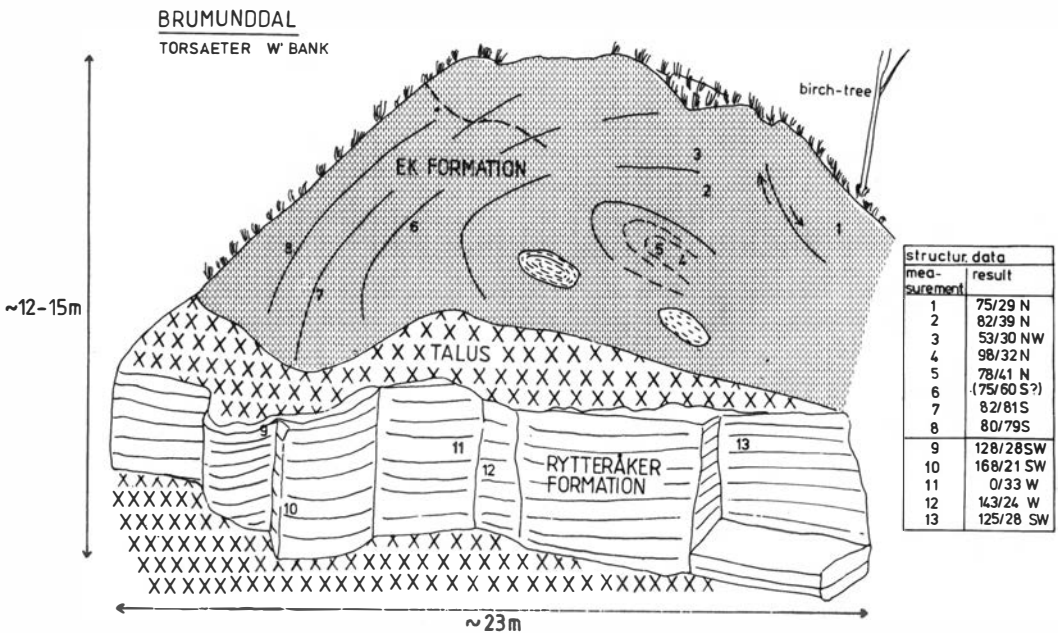


Fig. 7. Field sketch of locality 3, showing the main visible structural elements as well as points and results of structural measurements. The talus covering the contact between the two formations was removed in some places for the investigation.

sample 29 (stained acetate peel, fig.12)	sample 30 b (stained acetate peel, fig.13)	
locality: 3	locality: 3	
niveau: uppermost bed of the Rytteråker Formation, 2.5 m above the first exposed limestone bed	niveau: uppermost bed of the Rytteråker Formation, 1.3 m above the first exposed limestone bed	
classification: intraformational limestone conglomerate	classification: intraformational and tectonical limestone breccia	
fabric: clast-supported (50 % intraclasts, 25% bioclasts), primary layered structure (bedding parallel orientation of elongate intraclasts). 2 deformation episodes, both of them superposing the primary conglomerate fabric. A broad zone of strong recrystallization cuts through the upper part of the hand specimen. Contacts between intraclasts and grainstone matrix are bounded and strongly modified by pressure solution seams	fabric: clast-supported to matrix-supported (30-50% clasts) - some adjacent clasts contain coral fragments, which originally belonged to one single larger fragment of a favositid tabulate coral. Orientation of the corallites indicates rotation of the clasts within the matrix. Three deformation episodes: the original breccia fabric is superposed by a later fracture system.	
c l a s t s	c l a s t s	m a t r i x
<ul style="list-style-type: none"> - varying from clay bearing wackestones (biomicrosparites) to packstones - 10-50% bioclasts (echinoderms, trilobites, ostracodes, brachiopods, bryozoans) - up to 2.5% siliciclastic grains - no internal stratification - elongate shape (length up to 53 mm, height up to 5 mm) - rounded but modified by pressure solution - contacts to the matrix distinct and sharp, often developed as pressure solution seams 	<ul style="list-style-type: none"> - varying from clay-rich wackestones (biomicrosparites) to packstones: ~20-40% bioclasts (echinoderms, trilobites, ostracodes, bryozoans, brachiopods, aragonitic shell fragments, tabulate corals) - up to 2% siliciclastic grains - no internal stratification - diameters from <1-15 mm - angular to subrounded (clay-richer clasts show better rounding) - isometric to slightly elongate shape - edges partly modified by pressure solution - contacts to the matrix distinct and sharp 	<ul style="list-style-type: none"> - varying from clay-rich microspar or carbonate-rich clay (pressure solution residues) to zones with coarse crystalline pseudospar calcite - contacts between clay-rich parts and calcite are pressure solution seams - clay-content increases towards the top - up to 2% siliciclastic grains - the calcite in the matrix is throughout richer in Fe-2+ than in the clasts
deformation : a) synsedimentary to eogenetic: fracturing of the incompletely lithified rock. Infiltration of shale in the fractures and strong recrystallization in the zones of strongest deformation (fracture fills and recrystallized zones consist of Fe 2+-calcite) b) younger than a: development of straight fractures cutting through the older system, being infilled with a Fe 2+ richer generation of Fe-2+-calcite pressure solution pre- and postdates both deformation episodes	deformation: a) synsedimentary to eogenetic (?): 1. development of a fracture system (filled with Fe 2+-calcite) - 2. Fragmentation of the whole limestone bed into clasts and succeeding slight movement, mixing the clasts with the surrounding softer sediment. b) meso- to telogenetic (?): development of a fracture system, which is influenced by the preexisting breccia fabric. Fractures envelope the smaller clasts but cut through the larger. Fractures are infilled with Fe-2+-calcite pressure solution pre- and postdates both deformation episodes	

Table 2. Description of two samples from the uppermost beds of the Rytteråker Formation in section 3.

clastic grainstone matrix (sample 29, Table 2). This primary sedimentary texture was later modified by tectonic fracturing.

Two separate brecciation phases were recognized in all the samples (Table 2), the first clearly taking place before the rock was completely lithified. This may be related to an erosional episode causing local removal of the uppermost beds of the Rytteråker Formation, predating deposition of the Ek Formation, rather than to much later tectonic disturbance at the junction between these competent and incompetent units.

Discussion

Regional geological implications

The sedimentary succession of the Ringsaker district displays an intermediate position between the weaker deformed parautochthonous to autochthonous Lower Palaeozoic succession of the Oslo Region and the fully orogenic regional metamorphic Paleozoic succession of the Caledonides. Because of its position on the southernmost nappe unit it belongs tectonically to the Caledonian orogen. However it is also closely genetically related to the remainder of the Oslo Region by facies similarities and degree of deformation and metamorphism (no burial metamorphism, thermal alteration weaker than in large parts of the Oslo Region).

Compared to the contemporaneous successions of the central and southern Oslo Region, the sequence described herein is strongly condensed and incomplete. However, although it contains several sedimentary breaks, it still reflects the same typical succession of relative shallowing and deepening phases of the depositional environment and the same sequence of carbonate and siliciclastic dominated sedimentation periods.

Within the two lowermost Silurian formations (Fig. 2) there is a transition from shallow marine siliciclastic to shallow marine carbonate deposition. This facies change is sharp and pronounced in the Ringsaker succession. In spite of the apparent conformity of the bedding a considerable hiatus is suggested between the two formations. The corresponding facies change in the successions of the central and southern Oslo Region is more gradual and shows a continuous increase in carbonate content over several metres in the profile.

The composite thickness of those units in Ring-

saker is about 10% of corresponding successions in the central and southern Oslo Region. The overlying sediments display a dominance of shale throughout the region, but in the southern and central parts they are lighter in colour, have a higher carbonate content and a more diverse benthic fauna. This suggests well-oxygenated depositional conditions (the Vik Formation, Worsley et al. 1983). The facies and faunas of the contemporaneous black graptoliferous shales of the Mjøsa district (Ek Formation) indicate deposition in a deeper and more poorly aerated basinal setting.

In summary the Brumunddal succession is relatively condensed and displays sharp facies contrasts and boundaries between the lithological units. These features, when seen together with evidence of slumping and brecciation, may indicate syn- and postdepositional *crustal movements*. Correct analysis of the contained structural information has thus significant implications: the effects of the main dynamic endogenetic processes affecting the area in the Silurian can be studied within a less than 20 m thick succession.

Tentative reconstruction and chronological separation of dynamic processes

In the following I will discuss the most conspicuous facies changes and characteristics of the composite section of the Ringsaker succession (Fig. 2) in sequence from base to top.

The facies contrast between the Ordovician limestone and the Silurian sandstone might here as elsewhere in the world be explained by eustatic changes in sea level (Brenchley & Newall 1985, Worsley et al. 1983, Ziegler et al. 1979), regression in the late Ordovician being followed by transgression in the early Silurian. Eustatic changes may adequately explain this facies change elsewhere in the Oslo Region, but not in Ringsaker, where the whole late Ordovician is lacking. Local tectonic activity may well have had an overriding effect on the development of this area – and such activity is clearly suggested by the overlying sediments. Furthermore, there is no typical transgressive contact in this part of the Ringsaker succession.

Breccia-infilled fissures and slump structures in the Helgøya Quartzite can neither be explained by purely autocyclic depositional processes nor solely by the younger Caledonian jura-type décollement folding. To understand the assumption of synsedimentary to early syndiagenetic crustal

movements as a triggering mechanism for the genesis of the observed structures, some considerations concerning the depositional and diagenetic history of the sandstone are necessary.

Field observations and microfacies analyses show that the sandstone is inhomogeneous, even in its undisturbed, evenly bedded parts. Some layers consist of relatively pure fine sandstone, almost free of carbonate and clay, whereas others contain laminae and lenses of concentrated bioclastic material or concentrations of heavy minerals. Single horizons show relatively high concentrations of clay matrix (primary or intermingled by bioturbation). These inhomogeneities may have had a considerable influence on early diagenetic processes.

The very thin sequence indicates a rather low net sedimentation. The abundance of coarse bioclastic lenses and laminae grading upwards into planar laminated, well-sorted fine sand layers points, however, to a rapid settling out of suspension for the individual beds. This may best be explained by deposition in an environment characterized by an approximate compensation of depositional and erosional processes, leading to generally low net sedimentation rates. This shallow marine environment was only periodically swept by more powerful currents entraining and transporting fine sand bioclastic material in suspension. During the subsequent return to lower energy conditions the graded and planar laminated calcareous sandstone beds were rapidly deposited and thus achieved a high preservation potential with respect to the prevailing lower energy equilibrium conditions. The general facies of the sandstone suggests a shallow, storm-dominated sublittoral depositional setting.

In these conditions we may assume that single sandstone beds could remain exposed at the sea floor through long periods of non-deposition and erosion. The main induration processes such as dewatering, cementation and compaction could then start early, near to the sediment/water interface, and reach relatively advanced stages before the beds became deeply buried. How fast carbonate- or silica-cementation proceeds depends on porosity and permeability and thus on sorting and composition of the sediment. Chemical composition plays an important role in providing local microenvironments, which favour or catalyze mineral precipitation.

In inhomogeneous anisotropic rocks such as the Helgøya Quartzite, cementation was probably initiated at numerous dispersed local centres

within each single bed. The matrix-poor, well-sorted parts of the sandstone could thus achieve high degrees of induration within a relatively short time, whereas cementation was delayed or even prohibited in clay-rich parts. Microscope studies of samples reveal considerable amounts of carbonate cement in those parts containing high concentrations of bioclastic carbonate. The cemented pore volume is characteristic of an almost uncompacted sandstone. This and the observation of resedimented early cemented clusters of bioclasts (sample 2, Table 1) supports the suggestion of early, *near-surface* lithification and subsequent brecciation.

The microtextural features of the investigated breccia samples (Table 1) are most easily explained by the assumption of tensional deformation, causing the opening of V-shaped fissures and local brecciation within inhomogeneous, partly indurated, partly soft sandstone layers. Primary differences in the degree of lithification probably also account for some of the slump structures, which reflect strata-bound differences in competence. Erosion surfaces, truncating folded slump beds (Figs. 3,4) additionally support the idea of near-surface deformation, which was both syndimentary and syndiagenetic. The angular shape of the breccia clasts and their strong lithologic affinity to the neighbouring rock shows that they were not or only insignificantly transported. Resedimentational processes appear to have been largely restricted to stationary rotational fall- or slide movements, just sufficient to cause mixing of rock fragments from different levels within the *same sandstone bed*. The correlation of slump structures and intraformational breccia suggests a genetical relationship as shown in Fig. 2.

It seems logical to regard the deformation structures as a response of the near-surface mobile strata to tectogenetic block movements in the deeper basement. An explanation by purely sedimentary processes (instability of a sediment pile because of high submarine relief in an area of rapid sedimentation) seems unlikely because of the condensation and inferred early lithification of the sediments. Moreover such processes could hardly account for the genesis of the fissure breccia. To date no comparable structures have been reported from the Sælabonn and Solvik Formations of the southern and central Oslo Region. The Sælabonn Formation of Ringerike does, however, contain structures interpreted by Whitaker (1977) as metadepositional slump- and thrust-structures.

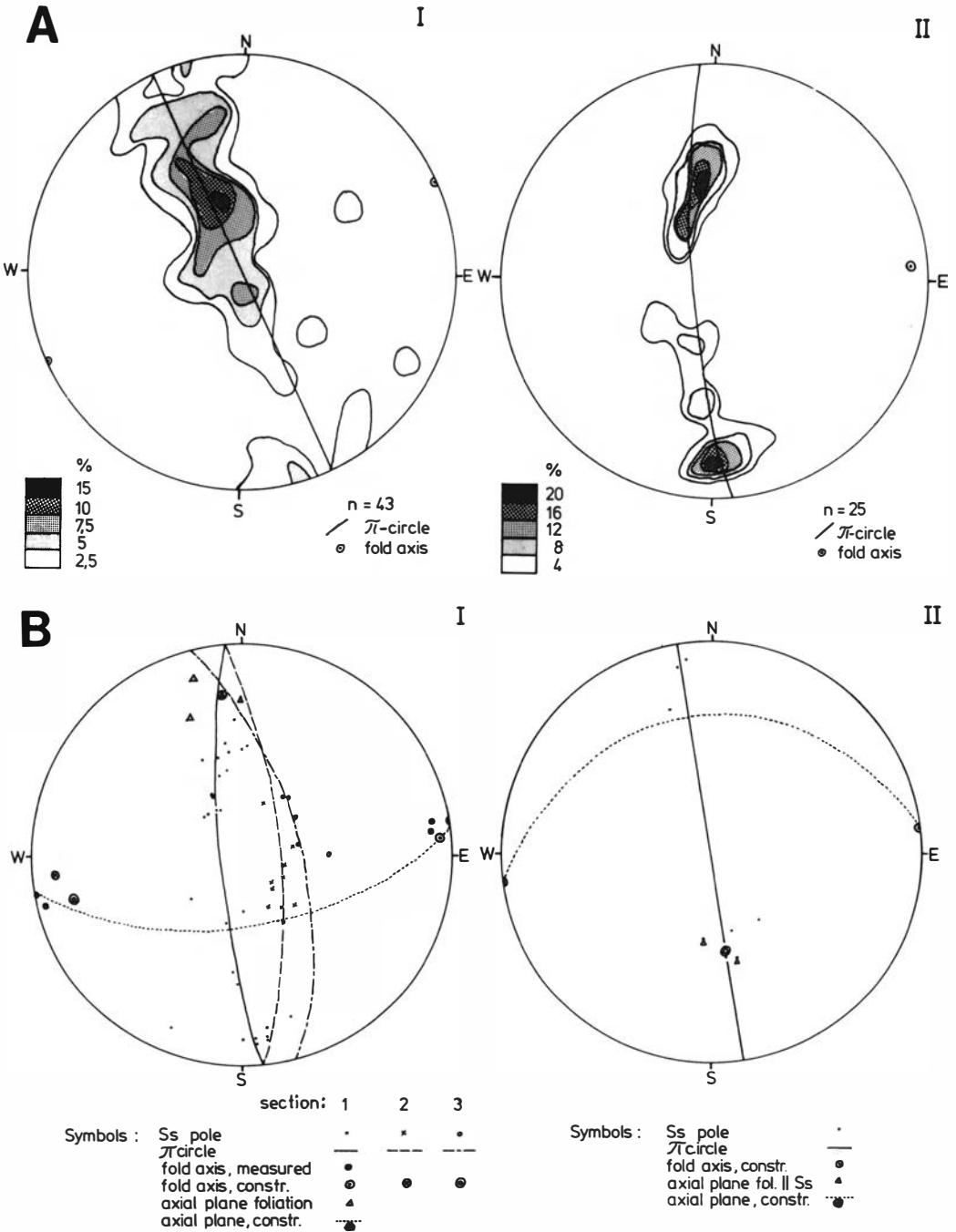


Fig. 8. A I: statistical interpretations of all the measurements, taken from the slump folds, allowing the construction of π circle and average slump fold axis. This deviates horizontally by $10-20^\circ$ from the tectonic folding, probably owing to the local paleotopography.

A II: statistical interpretation of the measurements taken from undeformed beds within the slump-outcrop, showing a considerably clearer defined folding with more uniform directions than A I.

B I: late tectonic folding in the Mjøsa Limestone, Helgøya Quartzite, and in the Rytteråker Formation. The values for the fold axes show only minor deviations and belong thus most probably to one single deformation episode, which was not (or only very weakly) overprinted by a later, larger regional folding.

B II: folding in the Ek Formation. The axis of the mesoscopic fold conforms with the fold axes of the underlying strata. The axial plane shows, however, considerably weaker inclination and dips towards the north.

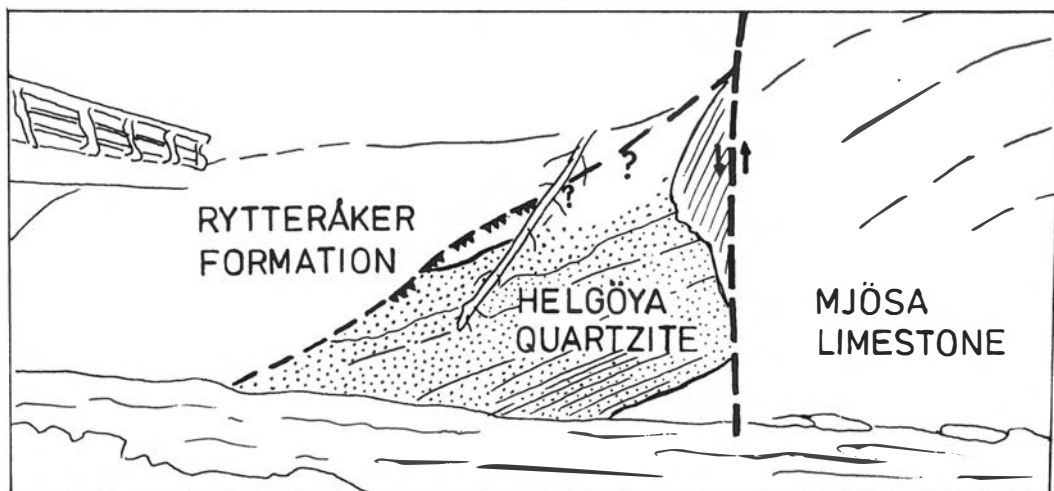
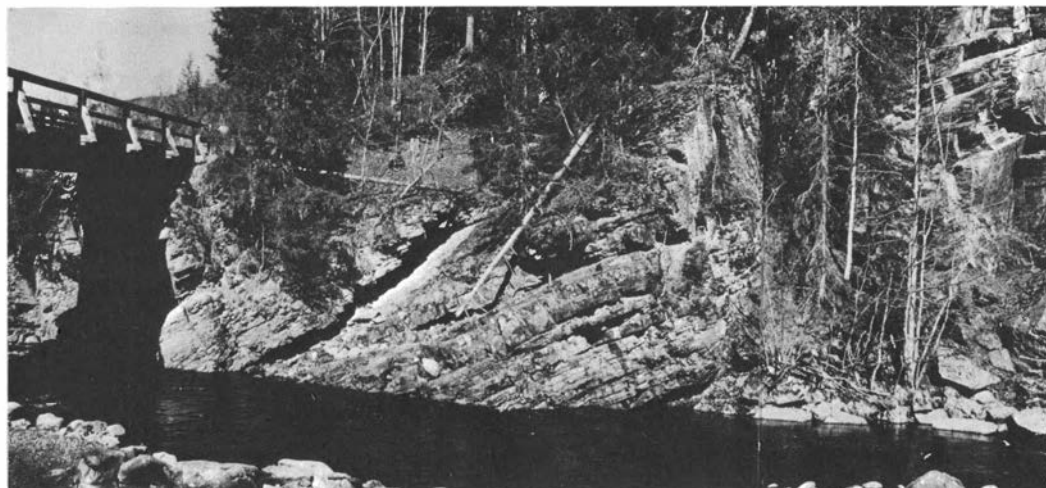
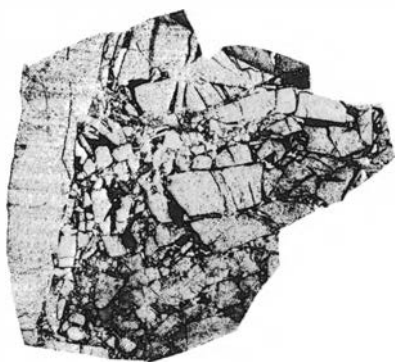


Fig. 9. Locality 2, Torsæter bridge. The rough sketch below shows the boundaries of the three exposed units and the main tectonic lineaments (thick intersected line = fault, dentate intersected line = shear plane).

The sharp facies contrast between the Helgøya Quartzite and the Rytteråker Formation cannot be explained satisfactorily by the result of this investigation. However, comparisons with the corresponding successions in the rest of the Oslo Region give additional information, and the study of the overall facies development aids to a theoretical approach of the problem – the assumption of a transgressive cut-off from clastic supply (Worsley et al. 1973) concurring with a gradual change towards more dry climatic conditions. This fits quite well with recently published palaeogeographic and palaeoclimatic data (Ziegler et al. 1977, 1979), although no reliable climatic indica-

tors are preserved in the Llandovery of the Oslo Region. The Rytteråker Formation in Ringsaker, as in the rest of the Oslo Region, represents a period of quiet, uniform carbonate sedimentation. This was not influenced by local tectogenetic movements, but only by regional epeirogenetic basement movements. The intraformational conglomerate in the uppermost layer (sample 29, Table 2) can probably be correlated with similar lithologies found in the upper part of the Rytteråker Formation in the Oslo Region. It reflects a relatively rapid transgression in the lower Telychian (Møller in prep.).

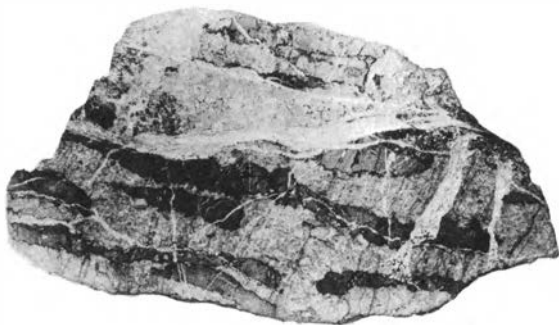
The erosional process, which removed parts of



~ 2 cm

Scale 1:2.0

Fig. 10. Stained acetate peel of sample 1, Fe²⁺-calcite appears black. (Description in Table 1).



~ 1 cm

Scale 1:0.93

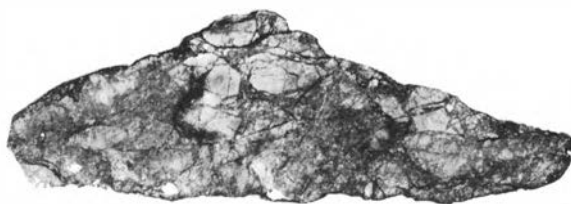
Fig. 12. Thin section of sample 29. (Description Table 2).



~ 2 cm

Scale 1:2.7

Fig. 11. Stained acetate peel of sample 2. Differences in colour intensity of the dark parts reflect different age of Fe²⁺-calcite generations, the darkest of which infills the youngest fractures. (Description in Table 1).



~ 2 cm

Scale 1:2.1

Fig. 13. Stained acetate peel of sample 30 b. Fe²⁺-calcite appears dark, while low-Mg calcite remains light. (Description in Table 2).



Figs 14 and 15. Slump structures. ~ 58 cm



Scale 1:29

the uppermost limestone beds of the Rytteråker Formation, was apparently postlithificational as the erosional contact follows bedding planes and joints. However, the age relationship between this contact and the décollement overthrusting in the shale is unclear. The brecciation of the limestone directly below the contact occurred in at least two phases (Table 2), the older of which occurred while the rock was still incompletely lithified, thus allowing a certain degree of mixing of the material of successive different sedimentary beds. It may be related to the erosional event mentioned above. The younger fracture system most probably consists of two components, which could not clearly be differentiated by the methods used in this investigation: a younger less pronounced component, which is also found in the stratigraphically deeper limestone beds, and an older one, displaying a dense net of wide fractures, which is restricted to the beds directly below the contact. The younger of these components was certainly the result of Permian rift tectonics, which affected the whole limestone formation in the same way. The older may have resulted from décollement overthrusting and mesoscale folding in the latest Caledonian (Scandian) main phase.

Locality 3 shows a distinct structural unconformity between the Rytteråker and the Ek Formation. Although the direction of fold axes is virtually the same, the limestone shows gentle to open folds, whereas the mesoscopic fold in the overlying Ek Formation is isoclinal, with an axial plane dipping to the north. This indicates a post-depositional movement at the formation boundary. The structural data (Fig. 8) point to a near-surface overthrusting of décollement type from the north. This corresponds to the main transport direction of the Caledonian nappes in this area. Consequently the deformation episode can be assigned to the Scandian main phase.

The facies of the Ek shale indicates a considerably deeper depositional environment than the underlying limestone, with a distinctly pelagic character. If the shale was largely autochthonous, in spite of the tectonized basal contact, this suggests an episode of rapid basin subsidence between the deposition of the two formations.

Conclusions

Pronounced facies contrasts, strong condensation and intraformational deformation structures re-

flect the influence of early Silurian crustal movements on the northernmost parts of the Oslo Region. The late Ordovician and earliest Silurian is represented by a depositional break. In Idwian times the area (lying farther north than today) became the site of discontinuous, sporadic but rapid deposition of shallow marine sandstones. This depositional phase was disturbed by tectogenetic movements around the Idwian/Fronian transition. Depending on their varying degrees of diagenetic induration, beds reacted differently to this instability; local fracturing and brecciation occurred in more lithified beds, whereas several types of load and slump structures were produced in softer ones.

The same tectonic activity might have been responsible for the succeeding cut-off of clastic supply, which – together with climatic changes – initiated a period of quiet, monotonous lime-mud deposition. This period was terminated by a rapid transgression, leaving no trace but a thin lag-deposit (Fig. 12), which is parautochthonously(?) overlain by pelagic graptoliferous shales.

It is tempting to assume that evolution of the Ek shale depositional basin was related to isostatic subsidence in front of the advancing higher Caledonian nappes. However, regional studies reveal traces of a Telychian *transgression throughout* the Oslo Region and consequently purely eustatic causes cannot be excluded. Future biostratigraphic studies will hopefully provide both a more exact dating of the recorded deformational events and environmental data, which may solve this problem.

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