

The stratigraphy and sedimentology of the early Llandovery Solvik Formation in the central Oslo Region, Norway

B. GUDVEIG BAARLI

Baarli, B. G.: The stratigraphy and sedimentology of the early Llandovery Solvik Formation in the central Oslo Region, Norway. *Norsk Geologisk Tidsskrift*, Vol. 65, pp. 255–275. Oslo 1985. ISSN 0029-196X.

The Rhuddanian to middle Aeronian Solvik Formation is a generally prograding sequence deposited on a storm-dominated shelf. Strata in the Asker and Holmestrand districts were deposited more proximal to western source areas than strata deposited in the Oslo District. Two small deepening events recorded in the proximal areas can be correlated with global sea-level changes in early and mid-Aeronian times. The base and top of the formation are only slightly diachronous, while considerable diachronism occurs laterally between the members. A hypostratotype of the Solvik Formation is proposed and two members, the Spirodden Member and the Leangen Member, are defined in the Asker District.

B. G. Baarli, Paleontologisk museum, Sarsgate 1, Oslo 5, Norway. Present address: Dept. of Geology, Williams College, Williamstown, MA 01267, USA.

Detailed research on the regional stratigraphy and depositional environments of the Silurian marine succession of the Oslo Region was carried out early this century by Kiær (1908). This classic study, especially its facies interpretations, was so advanced for its time that it was considered definitive during the following 50 to 60 years; research therefore mainly focused on the less well known Cambrian and Ordovician strata of the Oslo Region. Interest in the Silurian succession has been renewed in the last 15 to 20 years. A synopsis of this activity and a framework for a modern Silurian stratigraphy are given by Worsley et al. (1983a). Stimulated by this work, an array of detailed local studies has followed, of which the present study is one.

This study treats the stratigraphy and sedimentology of the Llandovery age Solvik Formation in the central Oslo Region. Local facies differences provide the basis for the definition of lateral members and a refined lithostratigraphy. Improved biostratigraphic correlations make it possible to interpret facies differences within the depositional basin at that time.

The Solvik Formation exhibits unusually abundant signs of storm activity and provides a good example of a storm-dominated platform sequence. Depositional changes through time may readily be correlated to sea-level changes. Structures generated by storm activity have proved useful for this purpose.

Earlier Work

The type area of the Solvik Formation at Malmøya in the Oslo District is situated within the city limits of Oslo itself. Exposures of the Solvik Formation comprise the lowest part of a long, fairly continuous section through the entire Llandovery Series. This area therefore has a long history of research and it has played a central role in the studies of Silurian stratigraphy in Norway. This history was recently reviewed by Johnson (1982) and only those parts concerning the rocks of the Solvik Formation will be summarized herein.

In 1844 the British geologist Sir R. A. Murchison visited Malmøya. At a meeting of the Scandinavian Natural Scientists, he expressed the opinion that the lower shales seen on Malmøya (i.e. the Solvik Formation) belonged to his 'Lower Silurian System'. Later Kjerulf (1857) subdivided the Lower Paleozoic succession of the Oslo Region in detail. He erected four groups including 8 'Etagen' which were further subdivided into units identified by Greek letters. However, he basically accepted the correlation proposed earlier by Murchison. In this system, the strata of the Solvik Formation were designated 'Etagé' 5β of the Lower Malmø Group. Murchison (1858) amended his earlier correlation of the Norwegian Silurian succession and for the first time the rocks of the Solvik Formation were correlated with the Llandovery strata of Wales.

Brøgger (1900) simplified Kjerulf's scheme of subdivision and assigned 'Etagé' 5A to 'Etagé' 5 and 'Etagé' 5B to 'Etagé' 6.

The work of Kiær (1908) established a more elaborate system where the old 'Etagé' system was retained, but each numerical unit was subdivided first by Roman and further by Greek letters. Kiær did detailed work in all districts, and was thus the first to thoroughly describe and correlate the rocks of the Solvik Formation outside the Oslo District. The resultant stratigraphical scheme used a mixture of biological and lithological characters. At Malmøya, for example, he defined 'the *Bilobites biloba* shale' (6ba), while in the Asker District he defined 'the zone poor in fossils with the thick siltstone layers' (6ba).

Kiær's stratigraphic scheme for the strata of the Solvik Formation has been in use until recently, and will therefore be referred to in the text where units of the Solvik Formation are described. Only lately has a modern lithostratigraphy been proposed by Worsley et al. (1983a).

The biostratigraphy of the Solvik Formation and the other Llandovery formations of the Oslo Region are treated in Worsley (1982) and Worsley et al. (1983b). A minor part of the fauna has been described in different taxonomical articles (see reviews in Worsley 1982). Very little work has been done specifically on the Solvik Formation outside the Oslo District. Faunal relationships in a limited part of the Solvik Formation at Malmøya were described in Worsley (1971). Two articles on algae from the Silurian of the Oslo Region (Lauritzen & Worsley 1974, Mørk & Worsley 1980) were mainly concerned with this formation and the immediately overlying Rytteråker Formation. Of interest for the local environmental setting in the area are a series of studies on the Ordovician/Silurian boundary in the Oslo District by Spjeldnæs (1957) and on the immediately underlying Ordovician strata by Brenchley & Newall (1975, 1977, 1980 and 1984), Brenchley et al. (1979) and Brenchley & Cocks (1982).

Regional setting

The 1,250 m thick marine Lower Paleozoic succession of the Oslo Region was deposited in a north-south oriented basin near the western edge of an extensive, shallow epicontinental sea which covered the Baltic platform. The basin was a narrow precursor to the Permo-Carboniferous Oslo Paleo-rift (Ramberg & Larsen 1978, Bocke-

lie 1978, Russel & Smythe 1983). The Lower Paleozoic succession found today is exposed in a graben structure coincident with the earlier rift system and the precursor basin. The marine succession of the Oslo Region consists of mixed carbonates and clastics and is considerably thicker than the carbonate veneer deposited on the Baltic platform to the east. The succession shows an accelerating sedimentation rate through time. Cambrian and Ordovician marine strata, which represent a time span of approximately 130 m.y. (Harland et al. 1982), constitute about half of the preserved thickness. The marine Silurian (i.e. Llandovery and Wenlock), representing less than 20 m.y. (Harland et al. 1982), constitutes the other half. The thickness of the Silurian strata is apparently closely related to the developing Caledonian orogenic zone (Nicolson 1979). Nappes were thrust towards the east and southeast during the Silurian (Bjørlykke 1983) and isostatic loading led to increasing rates of subsidence and sedimentation in the adjacent basin.

Through much of early Paleozoic time sediment was transported from the west into the basin. The source for the sediment has been interpreted as a north-south trending arcuate sand shoal lying between the continental margin and the basin of the Oslo Region (Brenchley et al. 1979). This trend is represented by facies patterns through much of the Lower Paleozoic (Størmer 1967). A series of facies belts has developed, with the shallowest facies in the west, north and south, while the deeper facies are situated in the central parts towards the east.

The Asker District, considered in this study, is located in the central Oslo Region (Fig. 1). It has an intermediate position between the proximal facies in Ringerike and the distal facies of the Oslo District towards the east. At the beginning of Silurian time, the high energy, proximal deposits of the Sælabonn Formation were developing in the west at Ringerike while the more distal deposits of the Solvik Formation were being deposited in the eastern part of the Oslo District. Sedimentary facies in the Asker District are intermediate between the two, but clearly must be assigned to the Solvik Formation.

Lithostratigraphy

The Solvik Formation is defined in the Oslo District as being characterized by dominant shales with very thin to thin siltstone and lime-

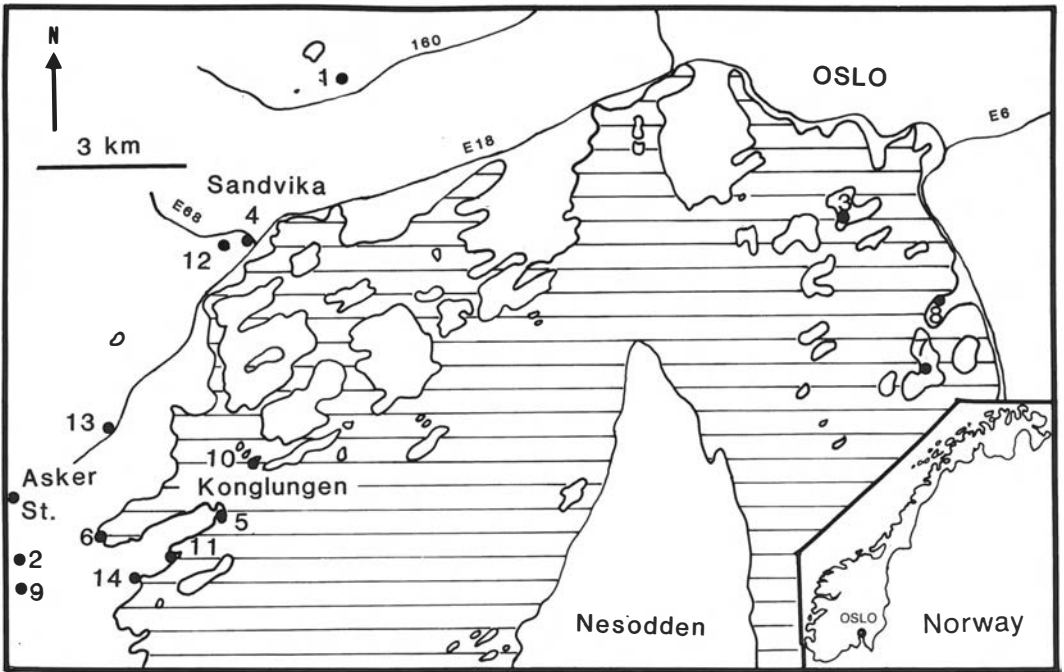


Fig. 1. Map showing the location of measured sections and sampling sites mentioned in the text. 1. Avløs 2. Bleikerveien 3. Hovedøya 4. Jongsåskollen 5. Konglungø 6. Leangbukta 7. Malmøya 8. Ormøya 9. Skytterveien 10. Spannlokket 11. Spirodden 12. Solhaugveien 13. Vakås 14. Vettrebukta.

stone intercalations (Worsley et al. 1983a). It is divided into a lower Myren Member and an upper Padda Member. (The quantitative terms which describe bedding and bed thicknesses herein follow the scheme of Ingram 1954.)

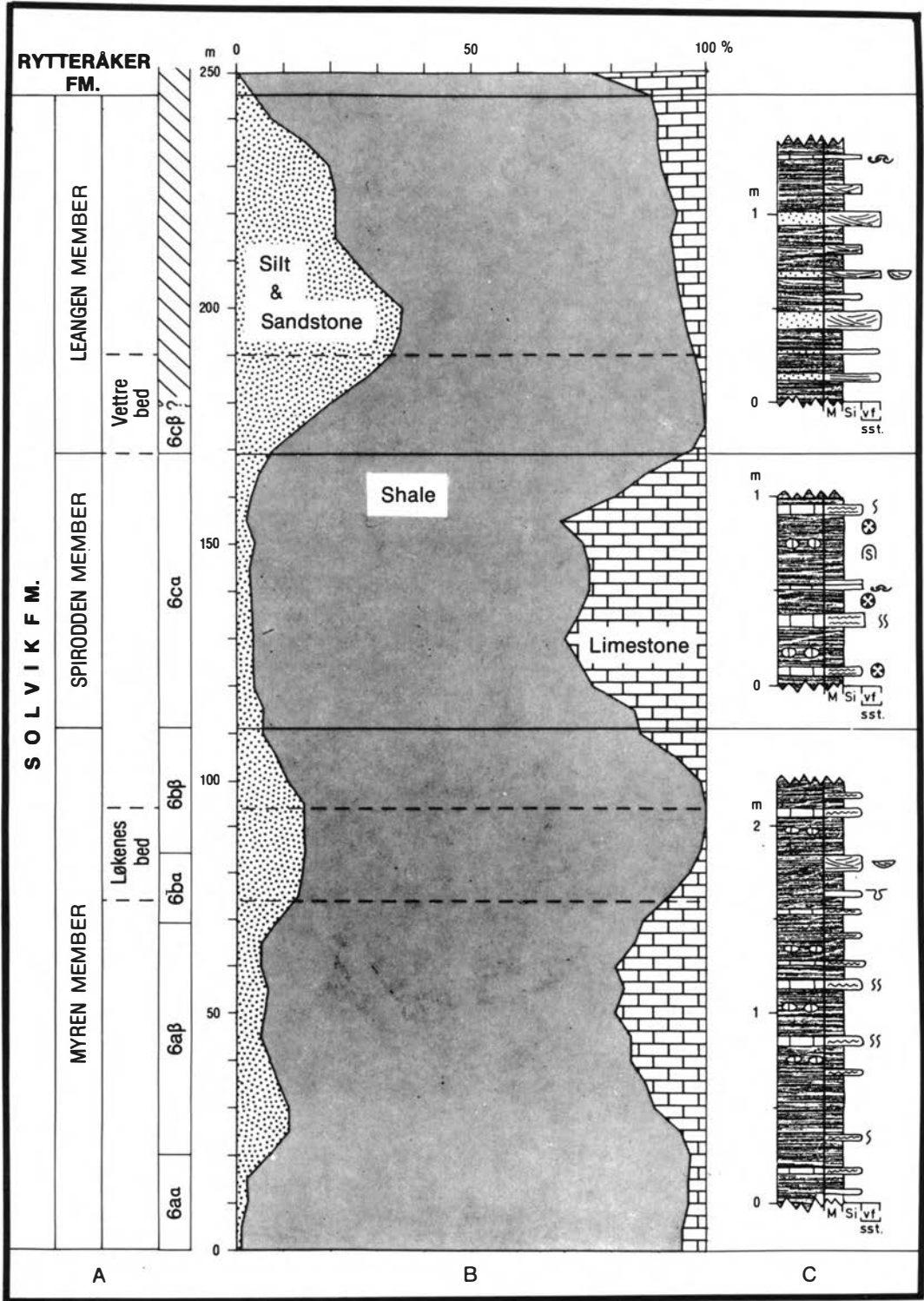
The equivalent Asker sequence differs from the development of the type area in a generally more lime-rich appearance and it shows a tripartite division, herein formalized as the lower Myren Member, the middle Spirodden Member, and the upper Leangen Member (Fig. 2).

Exposures in the Asker District comprise numerous shore outcrops and roadcuts at and near the peninsula of Konglungen and in the mainland east of Asker Station (Fig. 1). Good outcrops are also found near Sandvika at Kjørbo (grid ref. NM846403) and near Avløs (NM868431) in Bærum (Fig. 1). Nowhere is the whole formation exposed in one place, but several overlapping sections make it possible to piece together a composite hypostratotype with a total thickness of 245 m to 250 m.

Proposed hypostratotype area of the Solvik Formation in the Asker District

Best exposures are found on and near the peninsula of Konglungen. The basal hypostratotype is here defined at Konglungø (grid. ref. NM849347) where oolitic limestones and sandstones of the Langøyene Sandstone Formation (Brenchley & Newall 1975) are directly and conformably overlain by the shales of the Solvik Formation. Thickly bedded mudstones with very thin limestones and a few very thin siltstones are found locally at Konglungø. Limestone nodules which occur at the base of the formation in the Oslo District are not recognized here.

The transition from the Solvik Formation to the overlying Rytteråker Formation is exposed at Bleikerveien (NM814329), where the transition is more gradual than in the Malmøya area. The base of the Rytteråker Formation is placed where the limestone intercalations dominate over siltstone; this agrees with the definition from the type area at Ringerike.



The Myren Member

Definition and description. – The Myren Member (equivalent to 6a and 6b of Kiær 1908) is defined in the Oslo District by Worsley et al. 1983a as consisting of shales with minor laminae and very thin interbeds of siltstone. The development in Asker displays mudstones and very thin interbeds of siltstones, calcareous siltstones and silty limestones (Fig. 3). Although the lime content of both the shales and the intercalations is higher in Asker than in the Oslo District (30 % HCl soluble calcareous material in the shales of the Asker District compared with 10 % HCl soluble material in the Oslo District), the difference is not so large as to warrant the erection of a new member for the Asker District.

The lowermost 15 metres and the base of the member (which coincides with the formational base) are seen at Konglungø. The remainder of the member is found in a shore outcrop at Spirodden (NM840338). Here, the 100 uppermost metres are exposed in a sequence which continues up throughout the overlying member. The eastern part of the peninsula of Konglungen is thus chosen as the basal hypostratotype area for both the member and the formation.

A section with exposed base and top can be seen in the roadsection along the E18 motorway near Vakås (NM828357), but the exposure is faulted; moreover permission is required for visits along the motorway. This section does, however, support the correlation of the member between Konglungø and Spirodden.

The Myren Member is approximately 110 m thick in the Asker District. The amount of shale varies around 80 % of the sequence, mean thickness of the interbeds is 2.9 cm, and they are of fairly regular thickness (Fig. 2).

Fig. 2B shows how lime-, shale- and clastic silt-contents vary through the member. Fig. 2C gives a typical section from the Myren Member while Fig. 4A, 4C and 4D show the variance in frequency of interbeds of siltstone, fine limestone and coarse bioclastic limestone respectively. Fig.



Fig. 3. The Myren Member at Spirodden in the Asker District.

4B shows the variance in thickness of all interbeds while Fig. 4E shows how the maximum grain size of quartz (represented by the biggest visible diameter of the ten biggest quartz grains found in thin sections) varies up through the member. Fig. 2A shows that the units of Kiær (1908), although based on a mixture of biological and lithological criteria, can be traced on lithological grounds alone.

A section found from 73 to 93 m above formational base typically lacks limestone interbeds, but is rich in siltstones, some of which are medium thick. This part, which is only seen at Spirodden, is assigned to a discrete bed: the Løkenes Bed (Fig. 5). The base of the bed is set at the first occurrence of medium thick siltstone interbeds and is characterized by these thicker siltstone beds.

In the Myren Member at Malmøya (6a and 6b of Kiær 1908) the amount of shale varies around 75 % of the sequence and mean thickness of siltstone interbeds is 2.0 cm (Worsley et al. 1983a, Fig. 6). A 60 cm thick sequence of limestone nodules commonly occurs at the base of the member, but limestone interbeds are lacking in the overlying 130 m. Siltstone interbeds are prominent from the lowermost metres. They are generally very thin, but increase in thickness in the middle of the member. Occasional limestone interbeds are again found in the uppermost 30 m of the member (6bβ of Kiær 1908). This part is very shaly (85 % of the sequence) with only very thin siltstones and a few very thin limestone interbeds.

Lateral facies differences. – The Myren Member has a minimum thickness of 160 m at the type locality Malmøya (Worsley et al. 1983a) and is

Fig. 2. A composite section through the Solvik Formation in the Asker District showing, A: the relationship between the 'Etagé' system of Kiær (1908) and the new lithostratigraphic units proposed herein B: variation in the main components and C: examples of lithofacies for each member. The sections used are from 0–10 m: Konglungø, 10–170 m: Spirodden, 170–190 m and 210–243 m: Skytterveien, 190–210 m: Leangbukta and 243–250 m: Bleikerveien. All sections overlap more or less.

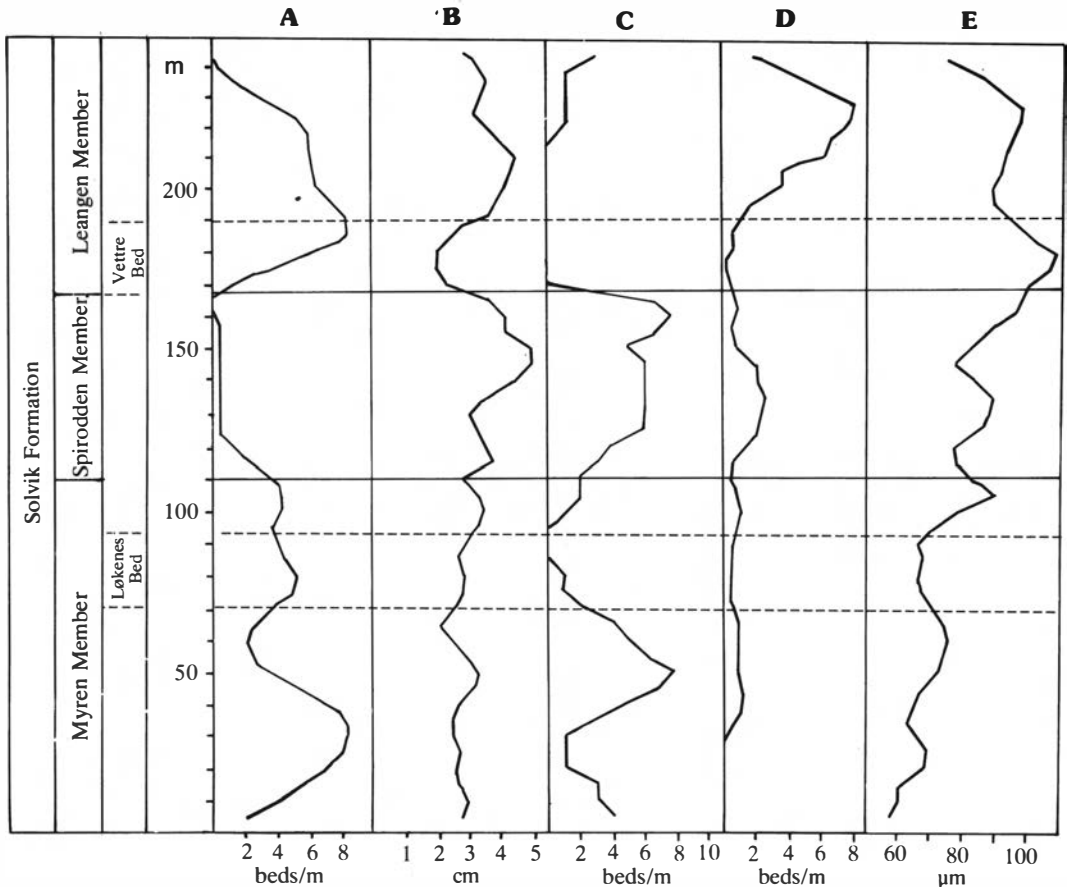


Fig. 4. Curves showing properties of the siliciclastic- and lime-intercalations in a composite section of the Solvik Formation. Each value on the curve represents the mean for 5 m smoothed out over 15 m. A. Frequency of silt and fine sandstone interbeds per m. B. Average thickness of silt and fine sandstone interbeds. C. Frequency of fine limestone interbeds per m. D. Frequency of coarse bioclastic interbeds. E. Average maximum grain size found as a mean of the maximum diameter of the 10 biggest grains in each thin-section.

thus considerably thicker than the 110 m found in the Asker District. In both districts the Myren Member is strongly dominated by shale, but the shale in the Asker District is generally much more bioturbated and lime-rich, and hence has a much lower degree of fissility than in the Oslo District. It is therefore regarded as a mudstone. The lime content is also much higher in the interbeds in the Asker District, resulting in calcareous siltstones or silty limestones. The calcareous content and high degree of bioturbation in all interbeds blur most of the sedimentary structures and bed interfaces, which thus contrast the pure siltstones with sharp borders found in the Oslo District.

The limestone nodules typically found in the

basal metres of the formation in the type area are missing in the Asker District. There are, however, some fairly pure, fine limestone interbeds present close to the boundary. These are replaced by clastic siltstone intercalations higher up in the sequence at most localities. Small local differences in facies in the lowermost 20 m of the formation exist in the Asker District. The silt content increases from less than 5% at Vakås (NM829364), 3 km northwest of Konglungen, to 10% at Konglungen, and finally 15% at Spirodden 1.5 km further southwest. Nowhere, however, is the silt content so prominent as at Malmøya. Moreover, at Konglungen and Hvalstrand (NM839365) limestone interbeds are prevalent in the first 3 to 4 m.

The next 50 metres of the Myren Member in the Asker District (6a β of Kiær 1908) show no significant lateral variation. Facies of the overlying Løkenes bed are, however, only found at Spirodden. At other places in the Asker District (i.e. Vakås, Sandvika), the same facies which top the Myren Member at Spirodden (i.e. 6b β of Kiær 1908) are developed instead.

The Spirodden Member

Definition and description. – The Spirodden Member (equivalent to 6c α of Kiær 1908) is defined at Spirodden (NM840338). Its base is placed at the first shale horizon which overlies the last occurrence of three or more siltstone interbeds without limestone intercalations (Fig. 6). The entire member is exposed at Spirodden. It consists of thin to thickly bedded mudstone with interbeds of thin to very thin limestone and limestone nodules (Fig. 2 and 7). Tabulate corals and stromatoporoids are abundant.

The sequence at Spirodden is 55 m thick and is exposed in its entirety. Mudstone constitutes about 70 % of the section and the thickness of limestone interbeds is fairly constant (mean 4.7 cm). Rare siltstone interbeds, which appear regularly about every 2 m, constitute 3 to 4 % of the section; siltstones often contain shell-lag deposits in their bases. Corals and stromatoporoids are so common that they may be regarded as rock forming, especially in the middle part of the member. The member is fairly homogeneously developed, apart from the uppermost 10 m where the limestone interbeds increase in frequency (see Figs. 2 and 4).

Lateral facies differences. – The Spirodden Member forms an easily recognizable lime-rich entity all over the Asker District but it is not found in the Oslo District. It is fairly similarly developed at all localities. However, the total thickness varies considerably – from at least 70 m at Kjørbo in the north to 55 m at Spirodden, 7.5 km towards south, decreasing further to 28 m at Skytterveien, 2.5 km due west of Spirodden. Although the total content of limestone interbeds per metre is roughly the same at Spirodden and at Kjørbo, the frequency is much higher at Kjørbo (sometimes double that at Spirodden), but the thickness of each bed is smaller. At Skytterveien the lime content steadily increases upwards until the uppermost 10 m, which show the same % lime as that found throughout most of the se-



Fig. 5. The Løkenes Bed at Spirodden in the Asker District.

quences at Spirodden and Sandvika. This increase is mostly due to a higher frequency of limestone beds.

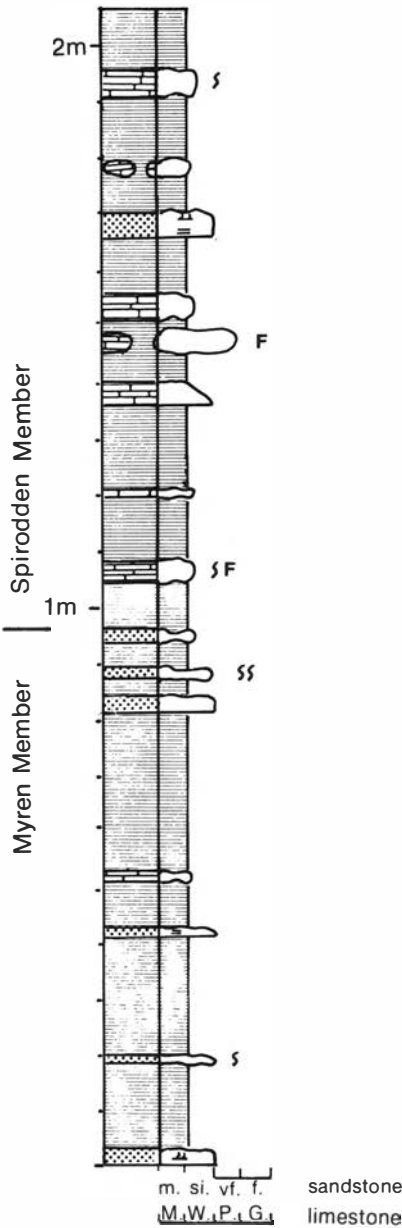
The number of thin bioclastic beds and lenses also shows some variation. At Spirodden and Skytterveien, one to two lenses occur on the average every metre and they form about 3 % of the member. At Kjørbo bioclastic lenses occur only rarely.

The siltstone content is the same at all localities, about one interbed every second metre. Sometimes, however, they are associated with bioclastic material to form couplets (Kelling & Mullin 1975), which are especially common at Spirodden.

The Leangen Member

Definition and description. – The Leangen Member is not completely exposed at any single locality. Its definition is therefore based on a composite section. Its basal stratotype is here defined at Skytterveien (NM820339) (38 m above section base) where thick shales overlie the uppermost limestone layers or limestone nodules of the Spirodden Member. The Leangen Member consists of dominant shales with very thin to thickly bedded siltstone and very fine sandstone interbeds (Fig. 8). The top is defined by the base of the overlying Rytteråker Formation.

At Skytterveien, where the section is slightly inverted, the lowermost 20 m and the uppermost 33 m are exposed while approximately 20 m in the middle are covered. A 75 m thick section of the Leangen Member in the innermost part of



| Lithology | Sedimentary structures |
|-------------------|--|
| limestone | irregular top and base |
| carbonate nodules | S bioturbation |
| siltstone | ripple lamination planar lamination erosive base |
| mudstone | F fossilrich |

the inlet at Leangbukta (NM825341) is almost complete, but misses the base of the member. In addition the top is tectonically disturbed.

Unit 6c β of Kjør (1908) equals the first 12 m of the 75 to 80 m thick Leangen Member. He erected his unit 6c β based on a faulted outcrop in Vetrebukta (NM834333), where the lower 12 m of the Leangen Member appear to directly underlie the Rytteråker Formation. The upper part of this member was known by him, but he assumed that it was a lateral development of unit 6ca.

Some variance in the thickness of the member is found in this area but a composite section gives a thickness of approximately 75 to 80 m. Shale content varies between 60 and 90 %. Silt and fine sandstone interbeds show variable thickness (mean 3.3 cm).

Fig. 2C displays a typical section of the Leangen Member. Fig. 2B shows the variation in relationship between shales and intercalations, while Fig. 4 shows how frequency, thickness, and maximum size of quartz grains in the intercalations vary up through the member.

The lower 15 to 20 m of the member comprise a highly shaly sequence (90 % per m) with very thin fine sandstone interbeds. The fine sandstone interbeds (mean thickness 1.6 cm) are strongly bioturbated and often associated with dark, bitumen-rich seams. This part is so distinctive that it is assigned to a separate bed: the Vetre Bed (Fig. 9). The Vetre Bed gradually passes up into the rest of the member which has a much higher content (30 % per m) of siltstones and fine sandstones with a mean thickness of 3.6 cm.

Lateral facies differences. – The Leangen Member is found throughout the Asker District; it also occurs at Bjørkøya in the Holmestrand District, but is not developed in the Oslo District. At the type locality in Skytterveien and at Leangbukta, the Vetre Bed contains 5 to 10 % very thin and strongly bioturbated fine sandstone interbeds; this increases to 15 to 20 % thin to very thin fine sandstone interbeds in the first 6–7 m at Spirodden and adjacent Vetrebukta. The section at Skytterveien is very fossiliferous. The fossils are whole and often concentrated in shell-lag deposits. At Leangbukta east of Skytter-

Fig. 6. Lithostratigraphic section of the basal stratotype of the Spirodden Member at Spirodden in the Asker District. Symbols used in the section.



Fig. 7. The Spirodden Member at the type locality Spirodden in the Asker District.



Fig. 8. The Leangen Member at Leangbukta in the Asker District.

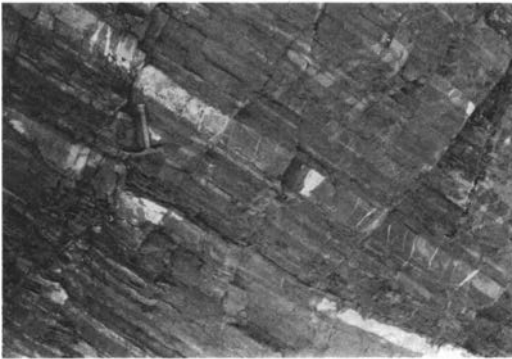


Fig. 9. The Vettre Bed at Leangbukta in the Asker District.

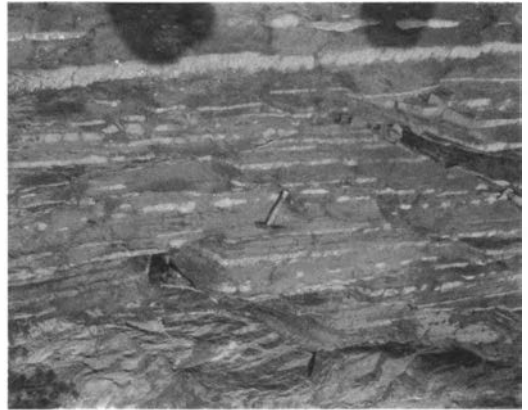


Fig. 10. The Padda Member on the west coast of Malmøya in the Oslo District.

veien, fossils are generally lacking, but a few very thin shell-lag deposits consisting of more-or-less fragmented shells occur. The content of bioclastic lenses represented by fragmented shell-lag deposits increases towards Spirodden, where they are characteristic. The thickness of the Løkenes Bed increases from 15 m in Skytterveien to a minimum of 20 m at Leangbukta. At Vettrebukta only 12 m of the bed are exposed. A 6 m thick profile at Avløs (NM868431), 10 km to the north, displays a very similar facies to that seen at Skytterveien.

A total of 33 m through the upper part of the member is exposed at Skytterveien, with 18 m at Bjørkøya in Holmestrand, 20 m is exposed at Solvikveien in Sandvika, but only 15 m at Bleikerveien (NM812333). The Skytterveien section in the southwest and Bjørkøya much further to

the south show more regularly occurring siltstone interbeds and fine limestone interbeds than at Leangbukta. Bioclastic storm-lag deposits comprise 20 % of the sequence in the uppermost part of the member in Leangbukta, while this decreases to only 5 % in Skytterveien. Both Bleikerveien east of Skytterveien and Solvikveien 7.5 km to the north resemble Leangbukta.

The Padda Member

Definition and description. – This member is exposed only in the Oslo District. It is the lateral equivalent of the Leangen Member. The content of shale is about 75 % of the sequence. Silty limestone interbeds and calcareous nodules dominate slightly over lime-rich siltstone interbeds with a mean thickness of about 2 cm (Fig. 10,

Worsley et al. 1983a, fig. 6). Limestone interbeds and very thin bioclastic sheets are more prominent in the upper 10 m, just below the junction with the Rytteråker Formation.

The impure very thin siltstone and limestone interbeds with blurred structures are reminiscent of the middle part of the Myren Member at Spirodden (6aß of Kiær 1908), but the shale is more poor in lime, and siltstone interbeds with erosive bases are common.

Age relationships

The Solvik Formation is rich in fossils, and several fossil groups may be used for biostratigraphic correlation. The most useful fossils include sparse graptolites, the evolving lineage of the abundant brachiopod *Stricklandia lens*, and conodonts.

In the Oslo District, graptolites are found 11 m above the base of the Solvik Formation at Ormøya (NM987392). The species *Climatograptus transgrediens* can be correlated with the upper *persculptus* to lower *acuminatus* graptolite biozones (Howe 1982). This would indicate that the base of the Solvik Formation in the Oslo District approximates the base of the Silurian System (Holland 1984).

No graptolites have yet been found in the basal Solvik Formation in Asker, but the initial shelly fauna consists of a mixed Ordovician and Silurian brachiopod assemblage, with dominantly Ordovician affinity (Baarli & Harper, in review). Conodonts belonging to the lowest Silurian *Icriodella discreta* - *I. deflecta* Assemblage zone of the British Isles are found from 8 m above the formational base at Konglungø (Aldridge & Mohamed 1982) including *Ozarkodina oldhamensis*, the species proposed to mark the base of the Silurian on Anticosti (Barnes 1982). It is therefore likely that the base of the Solvik Formation is approximately isochronous in the Oslo and Asker districts.

The evolving lineage of *Stricklandia lens* in the Solvik Formation was tentatively described by Baarli & Johnson (1982) and Worsley et al (1983b). At Spirodden the transition from *S. lens prima* to *S. lens lens* occurs between 8.5 m and 17 m above the base of the Spirodden Member. *S. lens prima* is not found elsewhere in the Oslo Region. The transition from *S. lens prima* to *S. lens lens* apparently occurs near the base of the A₃ beds of the Llandovery area or in the middle

Rhuddanian stage (Williams 1951, Cocks 1971).

S. lens lens occurs in abundance in the Spirodden Member at Spirodden and with certainty from 40 m above the base of the member at Kjørbo (NM846403) in Sandvika. The transition from *S. lens lens* to *S. lens intermedia* at Spirodden occurs 52 m above the base of the Spirodden Member (3 m under the base of the Leangen Member). At Kjørbo, the same transition is found between 40 m and 50 m above the base of the Spirodden Member (i.e. at least 20 m under the base of the Leangen Member since 70 m of the Spirodden Member is exposed here lacking the top of the member). The transition between *S. lens lens* and *S. lens intermedia* approximates the transition from the Rhuddanian to Aeronian stages in the Llandovery type area. This is in agreement with finds of the graptolites *Rhabidograptus toernquisti* and especially *Orthograptus obuti*. The former species is long ranging, appearing from uppermost *atavus* biozone (equivalent to the A₂ beds of the Llandovery area) to lowermost *sedgwickii* biozone (equivalent to C₁ beds at the Llandovery type area). The latter species is found in the Urals in beds of probable *cyphus* biozone age (equivalent to upper A₄ beds of the Llandovery type area).

Early variants of *S. lens intermedia* are not found in the Konglungen area, but they occur in the exposed upper 20 m to 30 m of the Spirodden Member at Kjørbo. This may indicate a hiatus between the Spirodden Member and the Leangen Member in the main Asker area but not in the Sandvika area. The first occurrence of *S. lens* at Malmøya is found 7 m under the base of the Padda Member. This is a clear *S. lens intermedia*. Later variants of *S. lens intermedia* occur through the Leangen Member until 40 m under the base of the Rytteråker Formation in Skytterveien and Leangbukta, where *S. lens progressa* replaces them. At Solhaugveien (NM844401) in Sandvika, the same transition is found somewhat higher up, between 12 and 5 m under the base of the Rytteråker Formation. On Malmøya, a few specimens of *S. lens*, probably belonging to the subspecies *progressa*, have been recovered from the upper 15 m of the Padda Member. The sample is, however, too small to be interpreted with certainty. The transition from *Stricklandia lens intermedia* to *S. lens progressa* approximates the *convolutus* graptolite Biozone or the mid-Aeronian stage in the Llandovery type area (Holland 1984). Discoveries in Asker both of graptolites throughout the Leangen Member and conodonts

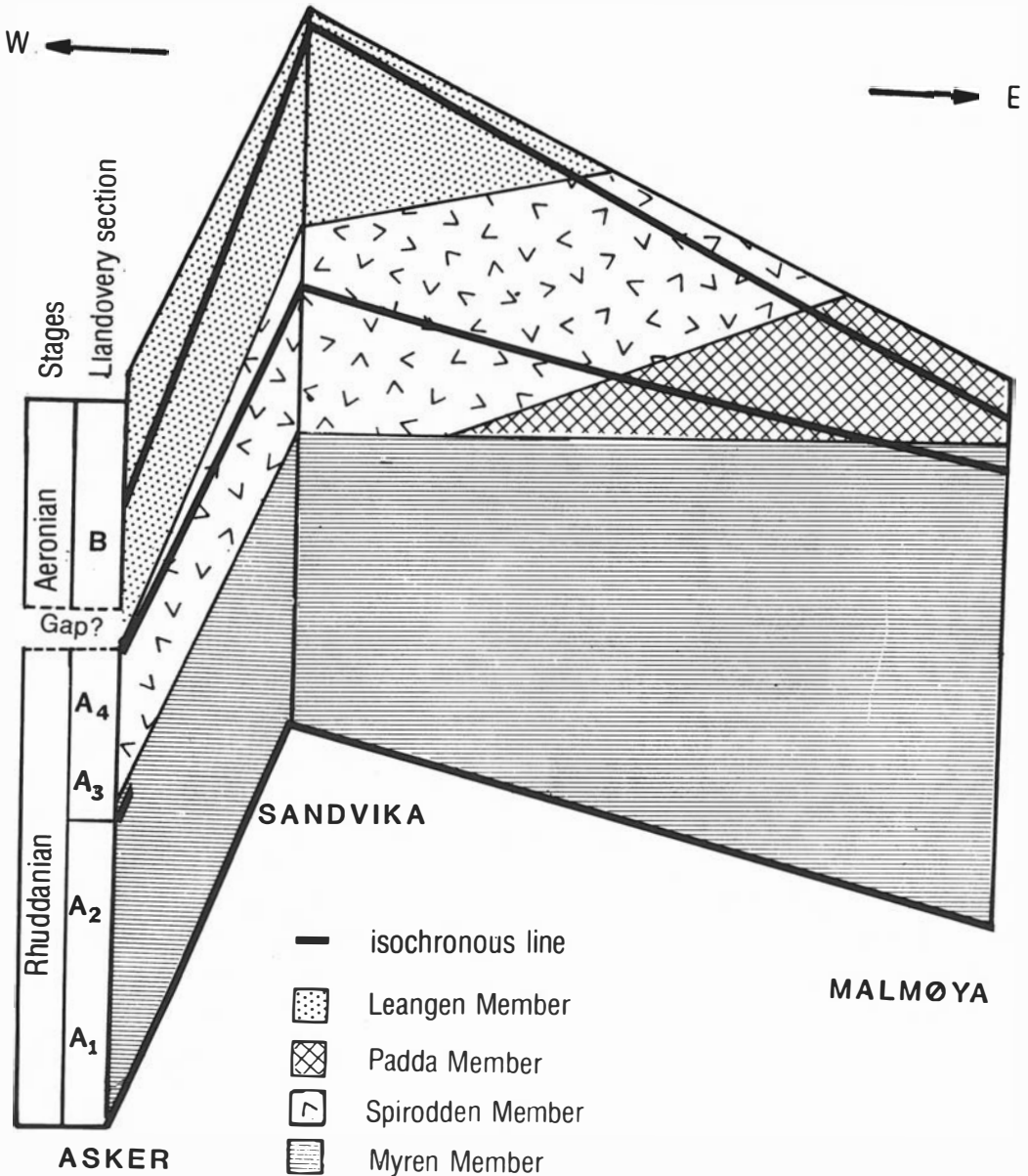


Fig. 11. A fence diagram displaying thickness variations of the members of the Solvik Formation and the age relationship between them shown by isochronous lines. The thicknesses of the Myren Member on Malmøya and the Spirodden and Leangen members at Sandvika are suggestive.

in the upper parts of the member, support the age relationships determined by the evolving lineage of *Stricklandia lens*. In Leangbukta at 32 m above the base of the Leangen Member, *Pribylograptus* ex. gr. *sandersoni-incommudus* and *Lagerograptus acinaces* occur, while at 42 m above the base *Coronograptus cyphus* appears (Worsley et al. 1983b). This assemblage suggests a

cyphus to *gregarius* biozone (equivalent to A₄ to middle B₂ beds of the Llandovery type area). At 56 m above the members' base at Skytterveien, the conodont '*Amorphognatus*' *tenuis* appears in abundance. This species is common in strata B₂ to C₂ in the Llandovery type area (Aldridge & Mohamed 1982). Just below the top of the formation at Bleikerveien, another conodont, *Dis-*

tomodus aff. *staurogathoides*, appears. Similar specimens are seen in lower *sedwickii* biozone aged beds of Britain or C₁ equivalent beds of the Llandovery type area (Aldridge & Mohamed 1982). Also the brachiopod *Gonatrypa hedei*, occurring from 57 m above the base of the Leangen Member in Leangbukta, is indicative of a near or incipient *sedwickii* biozone age (Copper 1982).

Fig. 11 summarizes the age and space relationship among the members of the Solvik Formation. The base of the formation is probably isochronous, while the top shows a slight diachronism with the base of the Rytteråker Formation most likely older in Asker than on Malmøya. (This is found using timelines proposed by stricklandids and comparing relative rates of sedimentation. The sedimentation rate is higher in Asker. An older base of the Rytteråker Formation is thus found even if the *S. lens intermedia* to *S. lens progressa* transition occurs lower down in the section in Asker, see Fig. 12.) The formation itself extends from the base of the Rhuddanian until mid-Aeronian (approximately the base of the earlier Fronian stage as defined by Cocks et al. 1970). Within the formation there is considerable diachronism. The top of the Myren Member was deposited around middle Rhuddanian time at Spirodden in the Asker District, while deposition continued well into Aeronian time at Malmøya in the Oslo Region. The Spirodden Member in the Konglungen area and part of this member in Sandvika are laterally equivalent to the upper parts of the Myren Member at Malmøya. Minor diachronism also probably exists between the Konglungen area and the Sandvika area. Early Aeronian age strata seem to be missing in the Konglungen area. This may suggest that a hiatus exists at the transition from the Spirodden Member to the Leangen Member in Asker. There is no evidence of such a gap in the Sandvika area.

Sedimentary structures and texture

Siltstones and fine sandstones

The siltstone interbeds of the Myren Member in the Asker District up to the base of the Løkenes Bed are generally very thin, planar beds; they are lime-rich, poorly sorted and without erosive bases and tops. Internal structures include rare

planar lamination, while small-scale cross lamination often changes into mudstone/siltstone inter laminations. The transition to overlying mudstones is gradual. Disturbance of beds is common especially by bioturbation, which often penetrates through the very thin beds. But these may also be caused by synsedimentary deformation processes producing structures such as convolute bedding, ball and pillow structures and loading.

The same kind of siltstone interbeds are seen in the lower 100 m of the Myren Member in the Oslo District, although the lime content is much lower and bioturbation is not so common. As a result, bed contacts and internal structures appear much more clear.

From the base of the Løkenes Bed in the Asker District and in the upper 100 m of the Myren Member in the Oslo District, an erosive base and a succession of planar lamination followed by small-scale cross bedding and mudstone/siltstone interlamination become common. Bioturbation does not penetrate the beds so often. Typical for the Løkenes Bed are thicker beds with guttercasts (Whitaker 1973), climbing ripples, and convolute bedding. Guttercasts are also found in the Oslo District in the Myren Member from about 70 m below the base of the Padda Member, but these beds are still very thin and the guttercasts are often incompletely filled and isolated.

Siltstone interbeds are not so common in the Spirodden Member, but when they occur, they are planar, continuous, and thinly bedded with erosive bases and bioturbated tops. Disturbance of internal structures is not so common as in the Myren Member. Often they are associated with bioclastic material so as to form bioclastic-quartzite couplets (Kelling & Mullin 1975).

In the Oslo District the siltstone interbeds of the Padda Member differ from the siltstone interbeds of the Myren Member in that slightly thicker beds are exposed and these show a much higher content of lime and higher degree of bioturbation. Both the lime content and the bioturbation blur the borders and the structures of the beds, but the erosive bases, and the same structures as seen in the Myren Member, can still be observed. Guttercasts are, however, not so common.

The clastic arenaceous interbeds of the Leangen Member are markedly different from the interbeds in the underlying members. The sorting is good and the grain size has increased (Fig. 4). In the Vettle Bed most of the beds are fine

Table 1. Mean trend of gutter and striation casts in the Asker District.

| Member | No. of beds | Gutter casts | | No. of beds | Striation casts | | Difference between means |
|---------|-------------|-----------------|-------------|-------------|-----------------|-------------|--------------------------|
| | | No. of readings | Mean trends | | No. of readings | Mean trends | |
| Leangen | 12 | 19 | 31° ± 14° | 8 | 8 | 55° ± 20° | 24° |
| Myren | 9 | 20 | 25° ± 14° | 16 | 16 | 46° ± 15° | 21° |

sandstone interbeds. The interbeds are very thin, planar, continuous, and strongly bioturbated. Structures are difficult to see, but planar laminations seem to be prevalent. In the upper part of the Leangen Member (where the interbeds are thicker), erosive bases, bioturbated tops and the same structures as observed in the siltstones below appear in almost all interbeds. In addition, hummocky cross-stratification and graded beds occur. Graded bedding or hummocky cross-stratification then precede the succession of structures observed in the lower members, viz. planar lamination, small-scale cross-stratification and mudstone/siltstone interlaminations. Megaripples with a wavelength of 1 to 7 m are frequently present and a few small shallow channel fillings are also observed.

Limestone interbeds

Both fine-grained beds and coarse bioclastic interbeds are seen in the formation. The interbeds are continuous and irregular due to uneven compaction. Structures are not observed. In the Myren and Padda members the fine limestone interbeds are mixed with a high percentage of silt, while in the Spirodden Member the limestones are more pure.

The coarse bioclastic material appears as shell-lag deposits. There are two types, one of which consists of mainly whole, but often disarticulated shells in one to a few shell-layer thick stringers (they can be up to 10 cm thick). The other type of shell-lag deposit consists of broken shells and fragments and they also often occur in thin lenses, but the thickness tends to be greater and can vary from one shell layer up to 15 cm. Sometimes strongly fragmented and sorted shell-lag deposits show planar lamination. These two kinds of shell-lag deposits seem to correspond to the swell-lag (for whole shell) and storm-lag (for fragmented shells) deposits of Brenner & Davis (1973). Small patchy swell-lag deposits are found at the top of the Myren Member as well as the

Padda Member of the Oslo District. In the latter they are more rare. In the Asker District, swell-lag deposits are mostly seen at the base of the Leangen Member, although not at all localities. Storm-lag deposits start to be common at the top of the Myren Member and in the Spirodden Member of the Asker District. There are local differences in the bottom portion of the Leangen Member, but they generally increase in prominence up through this member (Fig. 4D). A few layers of imbricated shells and edgewise coquinas of *Stricklandia* (which can be traced up to 4 m laterally) are also found in the upper parts of the Leangen Member. In the Oslo District there are storm-lag deposits in the upper 10 m of the Padda Member.

Current orientation

Sole structures such as guttercasts and striations can be used as indicators of paleocurrent direction. Striations and flutemarks occur frequently, associated with erosive bases. The same is true of guttercasts, which are only common on certain horizons. Guttercasts are found between 75 m and 90 m above the base of the Myren Member at Spirodden and through the top 60 m of the Myren Member at Malmøya. Guttercasts are also found occasionally throughout the Leangen Member of the Asker Districts.

Both striations and guttercasts show a very uniform orientation. They trend from SSW to NNE with a mean of 43°NNE in the Oslo District and a mean of 37°NNE in the Asker District (Table 1). The same prevalent direction (mean vector 50°NNE) was found by Seilacher & Meischner (1967) in the Middle Ordovician and by Brenchley et al. (1979) in the Upper Ordovician (mean vector 40°NNE). Using unpublished data provided to him by Worsley, Whitaker (1973 Tab. 1) found that the mean current direction showed a slight change in orientation up through the sequence on Malmøya. He also

found that current orientation obtained from striations deviated somewhat from the direction obtained from guttercasts. The orientation in the upper part of the Myren Member in the Oslo District is also found in the Myren Member of the Asker District, but without essential change through the section. The same deviation in orientation of striations relative to guttercasts is, however, present.

Processes of deposition

Lately a series of articles has been written on ancient and recent storm-induced sedimentation in storm-dominated platform environments (Harms et al. 1975, Walker 1979, Bourgeois 1980, Dott & Bourgeois 1982, Swift et al. 1983). Most of the sedimentary structures found in the Solvik Formation and discussed above can be associated with storm-derived deposits, although hummocky cross-stratification is the only structure exclusively associated with storm activity (Swift et al. 1983). Brenchley et al. (1979) found the same kind of fine sandstone interbeds (i.e. interbeds with erosive base and the same sequence of structures in the uppermost Ordovician of the Oslo and Asker districts). They interpreted their Ordovician interbeds as storm associated. In the Solvik Formation there are also other structures which indicate storm-influenced deposition. Swell-lag and storm-lag deposits are described by Powers & Kinsman (1953) and Brenner & Davis (1973). Storm-lags were interpreted by them as directly storm-transported debris associated with flushing of surge channels, while swell-lag deposits were interpreted as resulting from storm-swells passing over muddy platform areas leading to concentration of shell debris without much lateral transport. Kelling & Mullin (1975) have described limestone-quartzite couplets from Moroccan Carboniferous sediments and linked them with storm activity. Guttercasts have been connected with storm deposits by Goldring & Bridges (1973). Jones & Dixon (1976) described dunes surrounded by fine sediments from Silurian deposits in Canada as storm associated, while imbricated shell layers and edgewise coquinas are indicators of highly agitated water (Seilacher & Meichner 1964). By comparison, there is strong evidence of a storm origin for many of the interbeds in the Solvik Formation.

Deposition of clay or mudstone may represent daily deposition from suspension in fair-weather

periods. This is, however, difficult to envision where the shales occur regularly interbedded with strongly bioturbated fine-limestone intercalations, as seen in the Myren and Spirodden members of the Asker District and the Padda Member of the Oslo District. Here the limestone intercalations more likely represent daily in situ deposition in tranquil shallow environments, while shales and mudstones were introduced either because of minor tectonic adjustments in the source area (Wilson 1975) or as distal deposits after storm periods.

Swift et al. (1983) favour a combined-flow regime for formation of hummocky cross-stratification with a mean flow component and a wave-orbital component. They point out that geostrophic storm currents are characteristic of epicontinental seas, thus introducing a common unidirectional mean flow component on storm-dominated platforms. In early Silurian time, Norway was situated south of the equator within the belt of trade-winds (Ziegler et al. 1977). Brenchley et al. (1979) set up three models for the conditions prevailing on the late Ordovician platform in the Oslo and Asker districts. One of these models agrees with the view of Swift et al. (1983). The model includes storms blowing in the direction of the tradewinds from S-SSE toward a shallow or emergent source area in the west. This would cause long-shore surface currents which would be deflected to the left or towards the west, due to the Coriolis effect. Piling up of water towards land would result. This again would induce compensating, geostrophic bottom flows out from the shore towards the northeast, perhaps as downwelling jetlike coastal flows. The net result is production of currents oblique to bathymetric isobars. Since both the basin configuration and the current pattern are the same in the basal Silurian and uppermost Ordovician, there is no reason to search for another model in this case. Conditions were approximately equivalent, although the sea bottom seems to have been more agitated in the most proximal areas during the earliest Silurian in the Asker District because storm-lag deposits, edgewise coquinas, and couplets are more frequent than Brenchley et al. (1979) found for the uppermost Ordovician.

Storm-lag deposits and edgewise coquinas show the same variance in frequency as silt and fine sandstone interbeds up through the Solvik Formation. Since storms are interpreted as depositional agents for all features, the edgewise coquinas and storm-lag deposits are possibly associ-

ated with storms blowing in another direction than the trade winds responsible for transport of silt and fine sandstone interbeds in the model mentioned above.

Brenchley et al (1979) counted their silt and sandstone interbeds and calculated the frequency of clastic storm-deposited interbeds as one per 10 to 20,000 years. They reached the conclusion that the storms responsible for the deposition must have been of unusual intensity. In the Solvik Formation the equivalent frequency is higher; one clastic storm-deposited interbed per 5 to 10,000 years, but it still represents a very unusual event. Swift et al. (1983) pointed out, however, that it is not only the intensity which determines deposition but also a question of when a given spot on a shelf is at the right distance from a storm track of proper orientation to create a positive, horizontal velocity gradient. This study seems to show that it is also a question of sediment availability, which may determine whether or not a record of storm activity is left.

Proximity to source

The depositional conditions on the southeastern part of the Bering shelf have been described by Sharma (1975). This shallow epicontinental sea is in textural equilibrium and may thus serve as a model for older epicontinental seas with deposition of siliclastic material. The sediments are storm dominated and there is a continuous decrease in grain size and sorting from proximal to distal environments, reflecting increasing depths and diminishing energy input on the sea floor. A continuous decrease in grain size, grain sorting, percentage and frequency of coarse sediment per metre are also found in many old regressive shelf sequences (Harms et al. 1975).

A probable increase in proximity up through the Solvik Formation in the Asker District is indicated by increasing grain size (Fig. 4E) and sorting, but not so clearly by thickness of interbeds (Fig. 4B) and not at all by the frequency of beds (Fig. 4A). Sedimentary structures in silt and fine sandstone interbeds, sole structures and lag deposits, however, strongly reflect a generally increasing maximum energy level up through the Solvik Formation in the Asker District. These relationships suggest an increased proximity to the source area. An exception is possibly found at the base of the Leangen Member, where a lack of structures from a higher current

regime and presence of swell-lag deposits could mean a temporary decrease in energy level. This temporary decrease in energy level is supported by a clear decrease in thickness of interbeds. It is not supported, however, by maximum grain size, which reaches a maximum at this level. At the onset of the Rytteråker Formation deposition, there was a reversal in maximum energy level, which is clearly indicated by the strong decrease in maximum grain size, storm-lag deposits and siltstone interbeds.

In the Asker and Oslo districts, there was a strong unidirectional transport of siliclastic material towards the NNE, so a source must therefore have existed between the W to SSW. Although the frequency of beds is higher, the generally thinner siltstone interbeds and lack of fine sandstone interbeds in the Oslo District to the east indicate the more distal deposition of clastics in this district. Beds with guttercasts accentuate the difference in proximity and availability of sediment. Isolated guttercasts and guttercasts associated with very thin beds are more common in the Oslo District than in the Asker District, where many of the beds overlying guttercasts are relatively thick and show climbing ripples. The maximum energy level is clearly higher in the Asker District than in the Oslo District, since fine sandstones, hummocky cross-stratification, small channels and medium-bedded intercalations are not present in the Oslo District and storm-lag deposits are far less common.

An increasing energy level up throughout the Solvik Formation in the Oslo District is indicated by the appearance of erosive bases with guttercasts in the interbeds and swell-lag deposits in the Myren Member 60 m below the Padda Member, as well as storm-lag deposits at the top of the Padda Member. Thickness and frequency of beds show no equivalent pattern. Gradual shallowing up or progradation, which most often means increased energy level, was also recognized by Worsley (1971), who showed that transported faunas in the base of siltstone interbeds anticipated in situ faunas found in shales higher up in the formation.

The frequency and thickness of siliclastic interbeds are dependent on the source and availability of sediment. Worsley et al. (1983a) explain the higher frequency of beds at the base of the Myren Member in the Oslo District relative to the Asker District by invoking a possible sediment source to the east of the Malmøya area. This seems unlikely, however, since the orienta-

tion and direction of currents are the same in the two areas. Another possible explanation is that the more pure and fissile shales in the Oslo District have a much higher degree of compaction than the lime-rich and hence earlier lithified mudstones of the Asker District. The net result gives a longer time record per metre in the Oslo District. All frequency patterns cannot be explained, however, by proximality or difference in the compaction of interbeds.

Other means must be found to explain the frequent and occasionally medium-bedded siltstone interbeds in the Løkenes Bed near the top of the Myren Member, which occurs only at Spirodden in Asker. Another explanation must also be found for the general scarcity of siltstone interbeds in the Spirodden Member throughout the Asker District. These interbeds were deposited coevally to the siltstone-rich upper parts of the Myren Member in the Oslo District. Brenchley & Newall (1977) found considerable variance in facies and thickness in the Upper Ordovician of the Oslo and Asker districts, together with contorted bedding which they interpreted as induced by local tectonic adjustments in the basin. A similar explanation could be applied to the early Silurian depositional pattern in the same area. Bjørlykke (1974, 1983) suggests a strong tectonic influence at this time, probably associated with isostatic loading by nappes thrust towards the E and SE during Caledonian deformation.

Appearance of erosive bases are here used as an indicator of increased proximality and further increase is interpreted by hummocky cross-stratification which is typical of the transitional zone (Bourgeois 1980). The Myren Member up to about 75 m above its base in the Asker District and about 100 m below the base of the Padda Member in the Oslo District generally lacks the erosive bases of storm-deposited interbeds. The rest of the Myren, Padda, Spirodden, as well the Leangen members all frequently display erosive bases. Hummocky cross-stratification together with a rich record of high-energy events and storm stirring of the bottom, indicate that most of the upper parts of the Leangen Member were deposited in the transitional zone. The upper parts of the formation on Malmøya show no equivalent indications of high energy events. The Solvik Formation was thus deposited in a more proximal regime in the Asker District than in the Oslo District. So at a time when shelf conditions still were prevailing in the Oslo District, transi-

tional zone conditions were predominant in the Asker District.

Within the Asker District there are certainly some small local facies differences. At the very base of the Solvik Formation, limestone interbeds are more common at Konglungø than at Vakås to the west nearer the basinal margin. Brenchley & Newall (1980) showed that at the end of Ordovician time local block movements in the basement led to local highs where oolite banks developed. One of these local oolite banks is found at Konglungø, directly underlying the Solvik Formation. The transgression at the end of Ordovician time was very rapid and the shales of the Solvik Formation may be seen draping over and filling in the central parts of channels at Spannlokket (NM856358) in the Asker District. It is likely that the local topography developed at the end of the Ordovician was still influencing deposition at the beginning of Silurian time prior to maximum transgression.

At the base of the Leangen Member, lateral facies variations show there was an increase in storm-lag deposits from Skytterveien in the west (which is interpreted to be most proximal to the clastic source) towards Spirodden in the east. The same difference in recorded maximum energy level is seen all through the Leangen Member, although there is no record far to the east of Spirodden of the upper parts. This difference could indicate a shallower area or a bank existing near Spirodden, where strong storm waves frequently stirred up the bottom and swept away shell layers or even created surge-channels across the bank. The existence of a bank near Spirodden is supported by the difference in thickness of the lime-rich Spirodden Member, which is double the thickness at Spirodden in the east as compared to Skytterveien in the west.

The Spirodden Member in Sandvika is even thicker than at Spirodden in the Konglungen area. Age relationships indicate that this was due to continuous deposition in the Sandvika area, while there was a period of erosion or non-deposition in the Konglungen area. Thinner interbeds of limestone and the lack of storm-lag deposits suggest slightly deeper depositional conditions. The very similar development of the Leangen Member of Sandvika and the Leangen Member of the Asker District implies that the position on the shelf must have been much the same in the Sandvika and the Konglungen areas.

At Bjørkøya in the Holmestrand District, the

influx of siltstone is about the same towards the top of the Solvik Formation as in the Asker District.

The depositional sites of the Solvik Formation in the Sandvika area, Konglungen area, and the island of Bjørkøya in Holmestrand to the south appear to have been about the same distance from a coast or shallow shoal area parallel to the shelf. On the other hand, the Malmøya area seems to have been located further out on the shelf.

There is thus a general development from distal to more proximal deposition in the Solvik Formation of the Asker District, possibly with a minor reversal at the base of the Leangen Member and a renewed reversal at the transition to the Rytteråker Formation. The Solvik Formation of the Oslo District was also deposited more distally on the shelf than in the Asker District. The same general development upwards through the formation, as in the Asker District, can be seen in the Oslo District, although small reversals are not observed – perhaps because the more distal environments of the Oslo District were too deep to register small differences caused by variance in depth.

Fluctuations in depth

The distal proximity pattern is most often accompanied by a similar depth variation pattern. In the Solvik Formation, support for this is found in benthic community analysis. In lower Silurian strata, relative depth fluctuations have often been interpreted by changes in the benthic community scheme proposed by Ziegler et al. (1968). The range of this scheme is from deep to shallow: graptolite and scarce benthic fauna, *Clorinda*, *Stricklandia*, *Pentamerus*, *Eocoelia* and *Lingula* communities. In the early Llandovery, the *Pentamerus* and *Eocoelia* community habitats were occupied by the *Cryptothyrella* community (Cocks & McKerrow 1978). Detailed community analysis of the fauna of the Solvik Formation has been accomplished in the Asker District by the author and in the Oslo District by David Worsley; an article on this will be published elsewhere. However, it is possible to correlate the results of this work to the more general community scheme of Ziegler et al. (1968) and this will be summarized below.

Facies interpretations in the Asker District

suggest that the transgression initiated at the end of the Ordovician was still going on while at least the basal 20 m of the Solvik Formation was deposited. This can, however, neither be supported nor disclaimed by community analysis, since the faunas in this part of the sequence are of a mixed Ordovician/Silurian character not found elsewhere. Exactly when the transgression stopped is difficult to say, but there is a clear trend towards more proximal conditions from about the middle of the Myren Member and to the top of the Spirodden Member, suggesting a shallowing up trend. This is supported by the communities present (see Fig. 12). The faunas in the Myren Member are of a *Clorinda* community type, while the *Stricklandia* community prevails in the Spirodden Member.

The possibility of a small deepening at the initiation of the Leangen Member is indicated by the distal/proximity pattern. This is clearly supported by the community pattern which changes from a *Stricklandia* community into a clear *Clorinda* community a few metres into the member. A renewed shallowing-up pattern is seen through the rest of the Leangen Member both from the distal/proximity pattern and from the communities; the *Clorinda* community of the Vettre Bed is replaced by a *Stricklandia* community and further up by a *Cryptothyrella* community. The last small deepening in the top of the formation suggested by the sedimentology is supported by re-establishment of the *Stricklandia* community in the top 10 m of the Solvik Formation in the Asker District. The Solvik Formation in the Oslo District apparently shows a continuous shallowing-up sequence throughout, both when interpreted from distal/proximity patterns and from the benthic communities (see Fig. 12). In the lower part of the Myren Member, a graptolite and scarce benthic fauna prevail. This is succeeded by a *Clorinda* community through the upper 60 m of the member, while the shallower *Stricklandia* community is found in the Padda Member. Periods with small fluctuations of sea level may have also occurred in the Oslo District. Measurements of atrypids may indicate a slight deepening in early Aeronian time on Malmøya (Worsley 1969). However, at greater depths further out on the shelf, they were certainly not as likely to be recorded.

The Ordovician glacial deposits in North Africa are well documented by Boeuf et al. (1971). Related glacio-eustatic sea-level changes record-

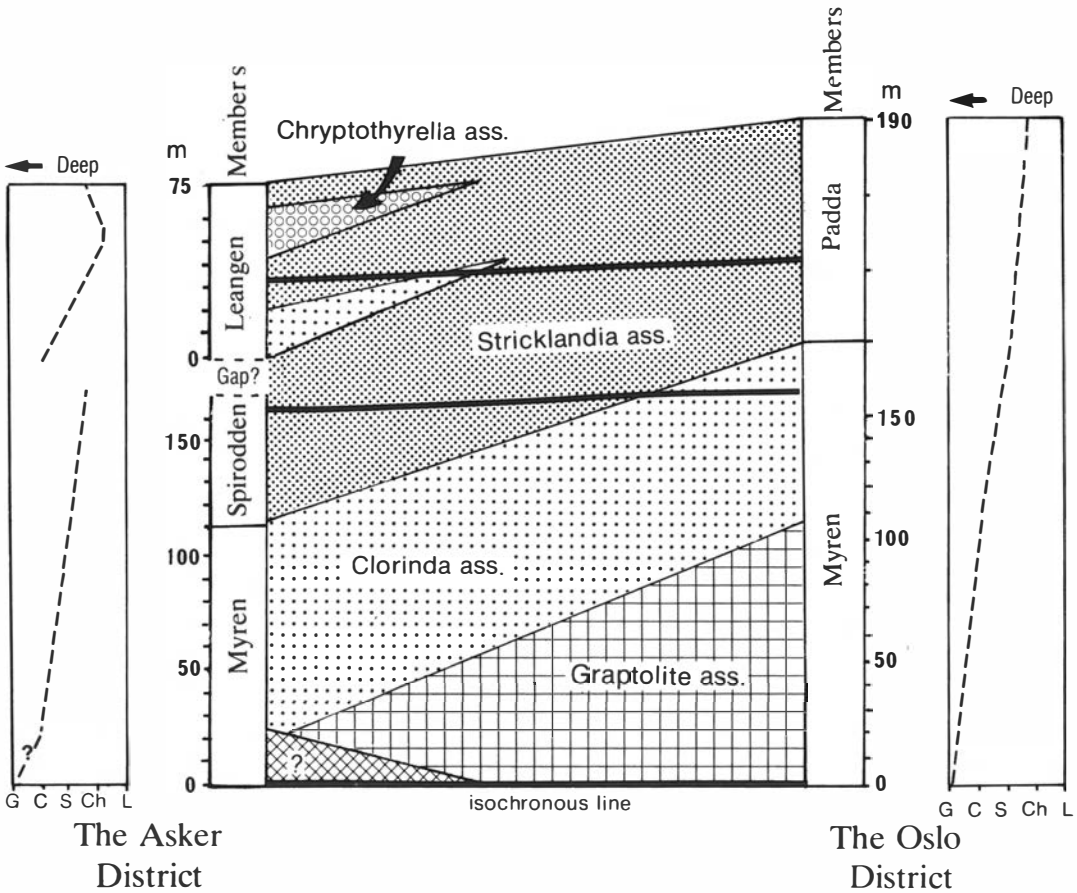


Fig. 12. Stratigraphic profile from the Asker District in the west to the Oslo District in the east. It shows stratigraphic distribution of the faunal associations, the interpreted connection between them and the age relationship represented by the isochronous lines. Notice the difference in scale in the section of the Oslo District (for further explanation see the text). The lower association in the Asker District is of mixed Ordovician and Silurian character not found elsewhere. Interpreted depth curves from the fauna associations for each district are shown. G = graptolite and scarce benthic fauna. C = *Clorinda* ass. S = *Stricklandia* ass. Ch = *Chryptothyrella* ass. L = *Lingula* ass.

ed at the very end of the Ordovician have been recognized by many workers and on many continents (Berry & Boucot 1973, Brenchley & Newall 1984, Rong 1984). In Norway, Brenchley & Newall (1979 and 1984) among others, have shown a strong regression in the Ashgill followed by a very rapid transgression initiating deposition of the Solvik Formation. They relate this sea-level change to the Ordovician deglaciation. The transgression seen in the base of the Solvik Formation may therefore be linked to a global event, although it certainly also may have a local tectonic component (Bjørlykke 1983).

Based on occurrences of the brachiopod *S. lens* in the Sandvika area, the deepening event

seen in the base of the Leangen Member seems to have occurred early in Aeronian time, although not from the onset. A simultaneous deepening or regression is found in the laterally equivalent Sælabonn Formation in the adjacent but more proximal Ringerike District (Worsley et al. 1983a). Globally, a simultaneous small deepening can be seen in Poland, and Nova Scotia (McKerrow 1979) as well as Michigan, Manitoulin Island, the Bruce Peninsula, and Anticosti Island in North America (Johnson et al. 1985). Evidence is also found for the same event in central and southwestern China (Rong et al. 1984). Although a deepening is not known for all the localities in Norway, the record of simulta-

neous deepening in early Aeronian time is so widespread that it was probably caused by a more global change in sea level.

The last small deepening in the top of the Solvik Formation is seen in the Asker District only. This can, however, be correlated with the better documented global deepening recognized in mid-Aeronian (previously known as early Fronian) time (McKerrow 1979, Johnson et al. 1985). It is thus possible that all three deepenings recorded in the Solvik Formation of the Asker District were influenced at least partly by globally eustatic sea-level changes.

Summary of facies interpretations

1) The facies development of the Solvik Formation in the Asker District justifies the erection of two new members: the Spirodden Member and the Leangen Member. A hypostratotype of the Myren Member is also defined.

2) The lower boundary of the Solvik Formation is approximately isochronous in all districts where the Solvik Formation occurs, but lithofacies developments within the formation show a considerable degree of diachronism between the Asker District and the Oslo District. The Myren Member and the Spirodden Member of the Asker District are equivalent to the lower parts of the Myren Member of the Oslo District. The Leangen Member of the Asker District is equivalent to the uppermost part of the Myren Member and the Padda Member of the Oslo District. The upper boundary of the Solvik Formation or the base of the Rytteråker Formation seems to have been deposited slightly later in the Oslo District than in the Asker District. In the Konglungen area of the Asker District, there exists a possible diastem between the Spirodden Member and the Leangen Member.

3) The source of siliclastic material lay probably to the SSW and W during deposition of the Solvik Formation. Thus, the Asker District was more proximal to the source area than the Oslo District.

There is also a general development from distal to proximal deposition up through the Solvik Formation, both in the Asker and the Oslo districts. In the Asker District a possible small reversal is seen at the base of the Leangen Member and also a clear small reversal is recorded at the very top of the formation.

4) Storms were important depositional agents

which set up geostrophic counter currents from the siliclastic source and transported siliclastic material oblique to the basinal slope. Winds blowing from other directions were responsible for deposition of storm-lag deposits and swell-lag deposits.

Possible local tectonic movements caused variation in the influx of siliclastic material and disturbed the everyday deposition of fine limestone.

5) The Solvik Formation of the Oslo District was deposited further out on the shelf than the Solvik Formation of the Asker District. The Solvik Formation at Bjørkøya in the Holmestrand District, as well as the Konglungen and the Sandvika areas of the Asker District, were deposited parallel to each other at about the same position on the shelf.

6) In the Asker District, small local facies variations at the base of the Solvik Formation indicate that the relief of the uppermost Ordovician strata still influenced the pattern of deposition. Higher up in the Solvik Formation, facies differences indicate the presence of a local bank in the Spirodden area.

7) Deposition of the Solvik Formation commenced with a transgression associated with globally glacio-eustatic sea-level changes which occurred at the end of the Ordovician. The transgression continued to influence the deposition of the basal parts of the Solvik Formation. It is also possible that the small reversals seen at the base and top of the Leangen Member in the Asker District may be linked with more global sea-level changes typical of the early Aeronian and mid-Aeronian ages.

Acknowledgements. – The full support of the Norwegian Research Council for Science and the Humanities (NAVF) is gratefully acknowledged. The author also expresses her appreciation to Drs. D. Worsley and M. E. Johnson for criticism of and comments on this paper, and for their help with the language.

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