# Stratigraphy and biota across the Ordovician–Silurian boundary in Hadeland, Norway

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The uppermost Ordovician and lowest Silurian succession in Hadeland is divided into three formations with both lithofacies and biota reflecting changes in sediment supply and sea level. The lowest unit studied, the Kalvsjøen Formation, comprises nodular limestones and shales which are the host sediments for at least five debris flow deposits. The overlying Klinkenberg Formation (new name) is a mixed carbonate-siliciclastic unit characterised by its heterogeneity and is broadly Hirnantian in age. It is overlain by the dominantly siliciclastic Sælabonn Formation which contains the trilobite *Acernaspis elliptifrons* near its base suggesting that the lower formational boundary is close to the base of the Silurian. The Klinkenberg and Sælabonn formations together comprise the Skøyen Group. Low stands in sea level are marked by karst surfaces at or near the tops of the Kalvsjøen and Klinkenberg formations. A major sea level rise is reflected in the rapidly deposited sediments of the Sælabonn Formation.

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The events of the latest Ordovician to earliest Silurian have attracted a great deal of interest in recent years. Particular emphasis has been placed on the definition of the base of the Silurian (Cocks & Rickards 1988) and on the global changes in environment and biota. The various effects of the late Ordovician glaciation have been a major focus of attention and have been linked to the very profound faunal extinction events at this time (see Rong & Harper 1988; Owen et al. in press; Robertson et al. in press). The subsequent radiation extended well into the Llandovery.

The Ordovician lithostratigraphy of the Oslo Region has been revised and summarised by Owen et al. (1990). The uppermost Ordovician of the Oslo–Asker district is particularly well known from the work of Brenchley and his co-workers, who have placed considerable emphasis on litho- and biofacies distribution (Brenchley 1985, 1988; Brenchley & Cocks 1982; Brenchley & Cullen 1984; Brenchley & Newall 1975, 1977, 1980, 1984; Brenchley et al. 1979). As a result of these studies, the Oslo–Asker district is now regarded as a standard in global studies of the latest Ordovician events. In contrast, equivalent levels elsewhere in the Oslo Region are much less well known and yet can provide important tests for the regional and global environmental models.

The Silurian of the Oslo Region was reviewed by Worsley et al. (1983) and, again, the lowest Silurian of Oslo–Asker is the most fully documented. The lower Llandovery Solvik Formation here was described by Baarli (1985) and its equivalent in the Ringerike district, the Sælabonn Formation, studied by Thomsen (1982).

The Hadeland district extends northwards from about 50 km north of Oslo (Fig. 1) and the uppermost Ordovician and Silurian stratigraphy was outlined by Kiær (1908) and Holtedahl & Schetelig (1923). Størmer (1945) concentrated on the Middle and Upper Ordovician and Hagemann (1957, 1966) discussed Silurian stratigraphy and petrography. Major (1945, 1946) described the sedimentology of the succession around the Ordovician-Silurian boundary in Hadeland as well as the lowest Silurian in the Mjøsa districts to the north. Owen (1978) revised the stratigraphy of the Upper Ordovician and Lower Silurian of central Hadeland (see also Owen et al. 1990) but the detailed litho- and biostratigraphical changes across the Ordovician–Silurian boundary need to be assessed and placed in a broad environmental context. The present paper results from bedrock mapping and the lithological logging and petrographical study of 30 stratigraphical sections. The detailed sedimentology will be given elsewhere.

## Stratigraphy

The lithostratigraphical units described here were termed the Kalvsjø Formation and Skøyen Sandstone Formation by Owen (1978). The spelling of the former name was emended to Kalvsjøen Formation by Owen et al. (1990) in their revision of the Ordovician stratigraphy of the Oslo Region. The Skøyen Sandstone is here elevated to group status and divided into the Klinkenberg and Sælabonn formations (Fig. 2). The term Klinkenberg Formation is new but the overlying Sælabonn Formation was originally defined by Worsley et al. (1983) for the lower part of the Silurian sequence in Ringerike to the southwest of Hadeland. This use of the term Sælabonn Formation for the upper part of the Skøyen Sandstone was also suggested by Worsley et al. (1983, p. 18). Fig. 1 shows the outcrop of the Kalvsjøen Formation and Skøyen Sandstone Group along with the locality numbers and names referred to in the text. Grid references and locality spellings given in the text relate to the 1:50,000 M711 Series Sheet 1815I, Gran.

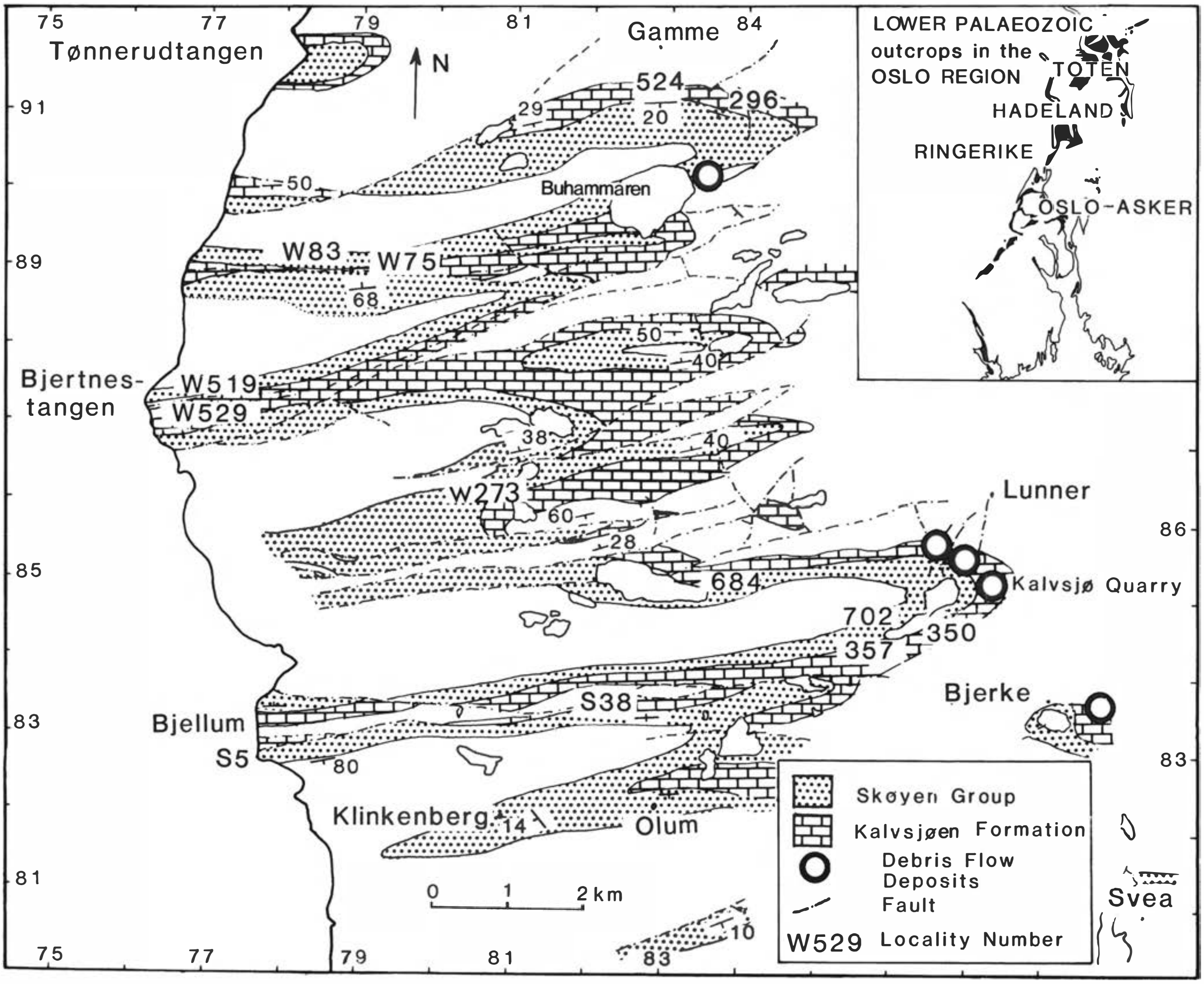



*Fig. 1.* The location of Hadeland and the outcrop of the Kalvsjøen Formation and Skøyen Group. Locality numbers referred to in the text are also shown.

## The Kalvsjøen Formation

(Owen 1978)

*Basal boundary stratotype.* By the track, 125 m SE of Grinda (=Grina) (NM 845872; Owen 1978, p. 19, Fig. 9). The boundary lies at the base of 1.8 m of nodular limestone within a gradational change from the shales and muddy limestones of the Kjørren Fm. to the dominantly nodular limestones of the Kalvsjøen Fm.

*Hypostratotype (top).* This is located beneath the basal boundary stratotype of the Klinkenberg Fm. (see below) in the Bjertnæs road cutting (NM 767869 = Loc. W529 on Fig. 1) where nodular limestones of the Kalvsjøen Fm. are overlain by thin calcareous siltstones and sandstones together with sandy nodular limestones of the Klinkenberg Fm. (Fig. 3B). Owen's hypostratotype south of Gammehaugen is now heavily weathered and is therefore abandoned as a reference section. The sandy and dolomitic horizons at the top of Owen's Kalvsjø Fm. are here reassigned to the overlying unit.

Two lithofacies are here recognised within the Kalvsjøen Fm.: the nodular limestones and the debris flow complexes (Fig. 2).

### *Nodular limestones*

This lithofacies is nowhere completely exposed but its thickest development (about 40 m) is in the west of Hadeland. Its lithostratigraphical equivalents are the silty grey shales with irregular limestone beds of the Langåra Fm. in western Oslo–Asker (Brenchley & Newall 1975) and the bedded and nodular limestones with interbedded shales of the Bønsnes Fm. in Ringerike (Owen 1979; Owen et al. 1990).

The limestone nodules in Hadeland are enclosed in shales and siltstones with the limestone forming 50–70% of the succession. Nodules are generally elongate and parallel to the bedding. All the nodules are fossiliferous although the coarseness and abundance of bioclasts varies, giving lithologies from wackestones to grainstones. The bioclasts largely consist of abraded and mic-

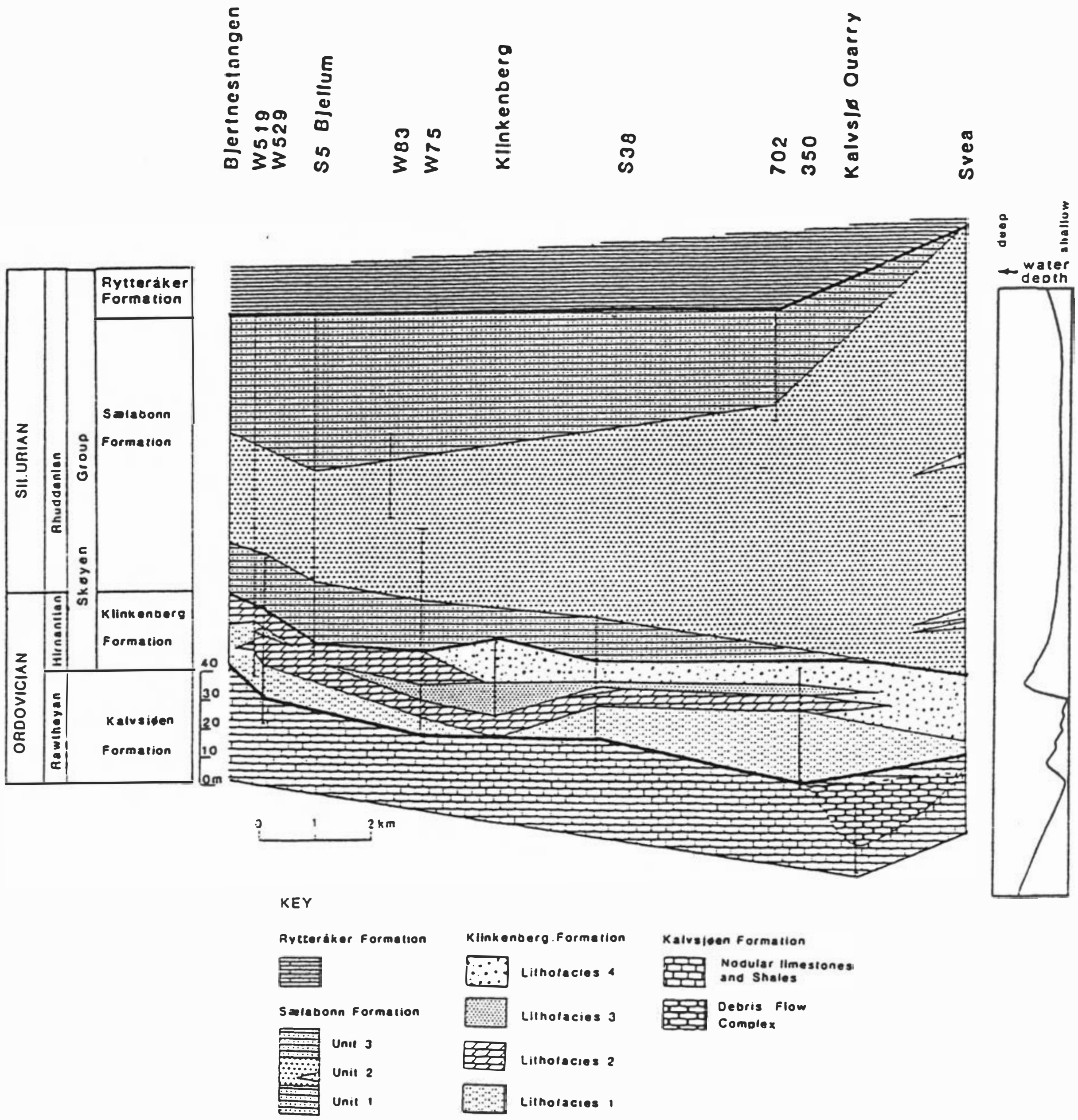



*Fig. 2.* Composite west–east stratigraphical section through the uppermost Ordovician and Silurian of Hadeland. Note that Lithofacies 5 and 6 of the Klinkenberg Formation are thin and localised and thus cannot be shown at this scale.

ritised fragments of algae, crinoids, gastropods, brachiopods and bryozoans. Algae are present in all of the nodule morphologies and are commonly the most abundant bioclasts within fine-grained horizons. Bioclasts are randomly orientated and although best preserved in the nodules, they are not restricted to them. The bioclasts are commonly graded, giving coarser bases and finer tops.

Three nodule morphologies are recognised (Fig. 4): (1) Large ellipsoidal nodules, 3–20 cm long and 5–10 cm thick. These constitute approximately 20% of all nodules. They are aligned parallel to bedding and are spaced laterally at 5–15 cm intervals separated by compacted, burrowed, shales and siltstones which thus thicken in internodule areas. (2) Irregular nodules 1–10 cm thick forming about 60% of all nodules and arranged in discontinuous layers up to several metres in lateral extent. (3) Laterally and vertically coalescing nodules which form about 20% of all nodules. Intervening material consists of siltstones and shales which commonly appear to be a concentration from pressure dissolution.

### *Depositional environment and biota of the nodular limestones*

The nodular limestones are thought to have originated as a sequence of hemipelagic deposits intercalated with layers of shelly debris derived from a shallower shelf or slope. The nodules are interpreted as early diagenetic features; a mode of formation similar to that postulated by Möller & Kvingan (1988) for nodules elsewhere in the Oslo Region succession.

Fossils are most common in the nodules and commonly show signs of abrasion and fragmentation. Representative fossils from the formation are shown in Fig. 5 and the whole biota encountered in the present study is shown on the range chart of fossils across the Ordovician–Silurian boundary in Hadeland (Fig. 6). Bryozoans are uncommon in the limestones but include the cryptostomes *Rhabdostomata* and *Pachydictia* and the trepostome *Trematopora.* Solitary streptelasmatid and colonial corals are poorly preserved and occur throughout the formation. Gastropods, present in both the nodules and the intervening shales, include large specimens of *Trochonema* (up to 6 cm in height) and species of *Cyclonema*, *Liospira* and *Lophospira.* Algae occur locally throughout the formation and are generally fragmented. The dasycladacean *Vermiporella*, the udoteacean *Dimorphosiphon* and the codiacean *Palaeoporella* are all known from the nodular limestones although the last of these is much less common than in Oslo–Asker, where in situ thickets occur (Brenchley & Newall 1975).

Although identifiable fossils are generally rare in the shales, Bockelie (1984) has recorded thecae of the rhombiferan cystoid *Hemicosmites variabilis* and species of the brachiopods *Sampo*, *Glyptorthis*, *Leptaena*, *Dolerorthis*, *Eospirigerina* and *Lingulella.* Crinoid ossicles have been described by Briskeby in an unpublished thesis (1980).

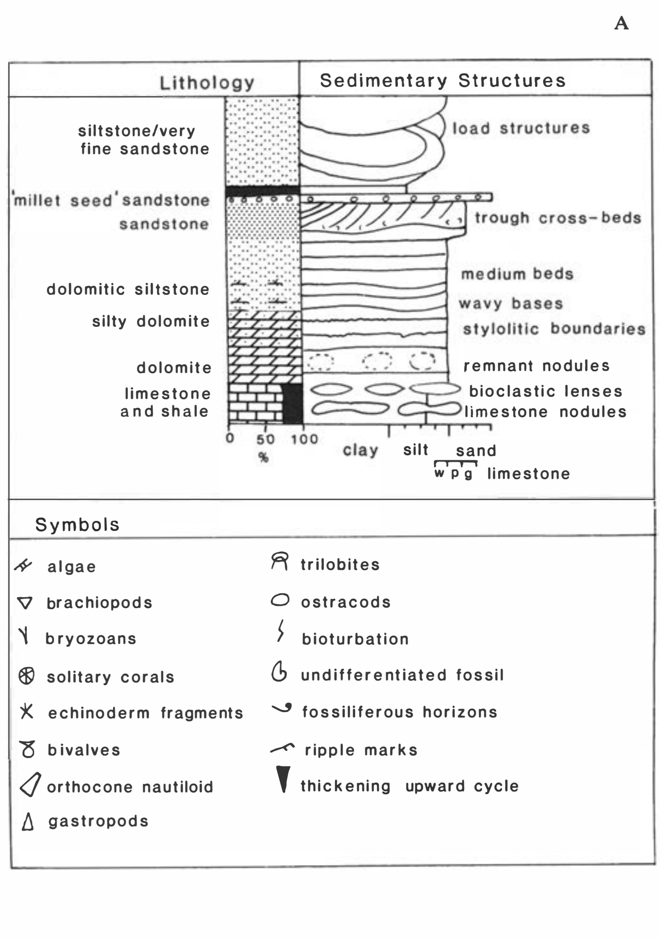
An unusually abundant and diverse biota was recorded from shales north of Sverigetjern (NM 80908620) by Owen & Heath (1990). These yielded species of the trilobites *Erratencrinurus*, *Brachyaspis*, *Stygina*, *Prionocheilus*, *Toxochasmops* and a lichid. Brachiopods are similarly diverse and include *Eoplectodonta* cf. *oscitanda* Cocks (also known from the Langåra Fm. in Oslo–Asker, see Cocks 1982), *Plectatrypa tripartita* Sowerby and *Platystrophia* aff. *anomala* Hiller, together with species of *Leptaena*, *Nicolella*, *Dolerorthis*, *Eostropheodonta*, *Eospirigerina* and *Dalmanella.* Other fossils include the solitary coral *Grewinkia*, stick bryozoans and the alga *Cyclocrinites.* Although the very shaly development of the Kalvsjøen Fm. and the generic composition of its fauna here are very similar to the underlying Kjørrven Fm., the encrinurine species *Erratenrinurus (E.) inopinatus* is different from that in the underlying unit (see Owen & Heath 1990). Moreover, the occurrence of *Brachyaspis* is the only record of the genus from Hadeland although it is common elsewhere in the Ashgill of the Oslo Region. The Kjørrven Fm. is demonstrably Rawtheyan in age (Owen 1978, 1981) and the fairly high diversity of the Kalvsjøen Fm. faunas suggests it too belongs in this stage. The base of the Hirnantian in many sections throughout the world is commonly marked by a decrease in faunal diversity consequent on the end Rawtheyan extinction event (Owen et al. in press).

### *The debris flow complexes*

These contrast markedly with the enclosing nodular limestones as they comprise a chaotic arrangement of carbonate blocks within a wackestone matrix. Grainstones and bedded wackestones are also present. The complexes crop out at five localities (Fig. 1): (1) east of Kalvsjø lake (NM 870850), (2) north of Kalvsjø lake (NM 866854), (3) the quarry 2 km SW of Roa (NMA 885850), (4) the abandoned marble quarry east of Buhammaren (NM 834903) and (5) Kalvsjø Quarry (NM 874852). It is likely that all these deposits are at or very near the top of the Kalvsjøen Fm. Fissures and cavities within the deposits at Kalvsjø Quarry represent karst development in response to a low stand in sea level. The detailed sedimentology of the debris flow complexes will be described elsewhere.

### *Biota of the debris flow complexes*

Much of the biota of these deposits is similar to that of the nodular limestones but corals and bryozoans are more abundant. The former include species of the colonial forms *Catenipora* and *Palaeophyllum* together with the solitary *Leolasma*, *Streptelasma* and *Ullernelasma.* The first of these solitary genera is known from the Upper Ordovician of Estonia (Neumann 1975), Middle to Upper Ordovician of China (Yu 1960) and Lower Llandovery of Venezuela (Scrutton 1971). *Streptelasma* is known



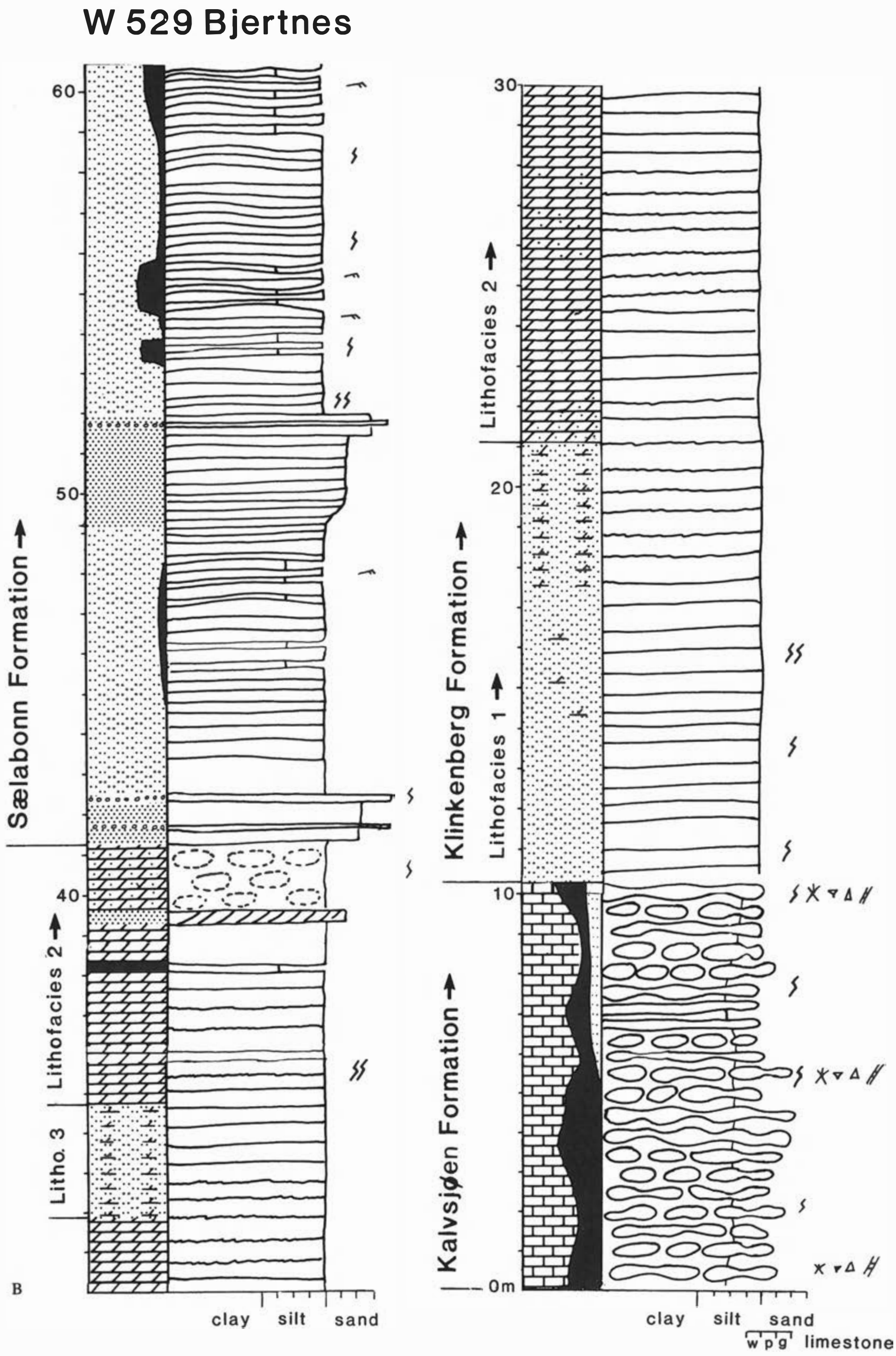



*Fig. 3.* A. Key to graphic logs used in this paper. B. Unit stratotype for the Klinkenberg Formation and the basal boundary stratotype for the overlying Sælabonn Formation. See Fig. 1 for location.

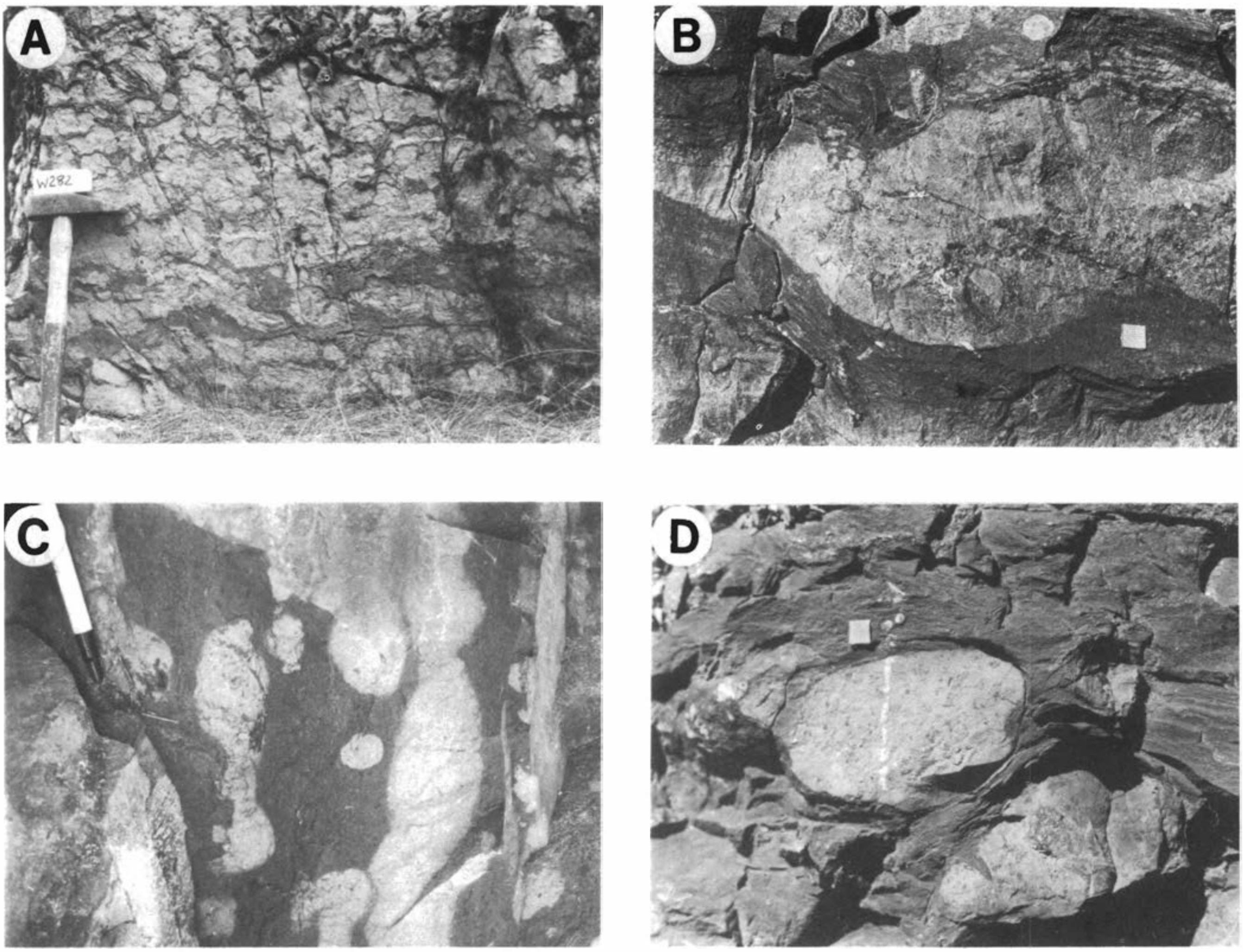



*Fig. 4.* Nodule morphologies in the Kalvsjøen Formation. A. Laterally and vertically coalescing nodules with 'stringers' pinched between nodules. The stringers are a combination of primary depositional fabric and residues from pressure dissolution. Location: road between Lunner and Sløvika (NM 808861). Hammer shaft 40 cm long. B. Irregular nodule. Clay linings to burrows have formed foci for dissolution. The bioclastic material in the nodule is graded. Location: Bjertnes (loc. W529, NM 767869). Scale square 1 cm. C. Irregular nodules forming extensive discontinuous layers. Locality: Bjertnestangen shore section (NM 761871). Hammer shaft 40 cm long. D. Large isolated nodule with host sediment deflected around it. Location: Bjertnes (loc. W529, NM 767869). Scale square 1 cm.

from the Upper Ordovician and Lower Llandovery in Sweden and *Ullernelasma* from the uppermost Ordovician of Ringerike (Neumann 1975).

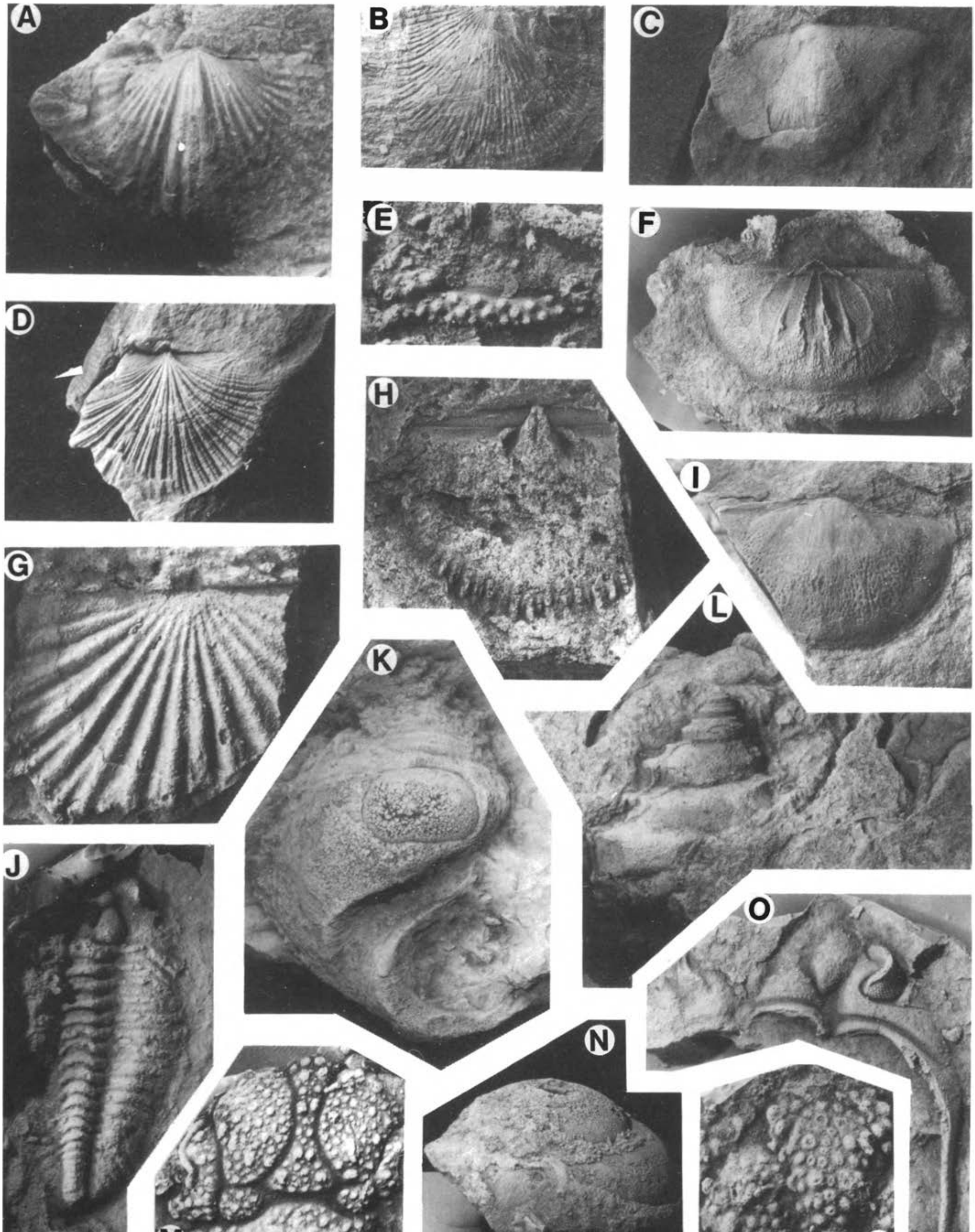
## The Skøyen Group

(redefined herein)

*Basal boundary stratotype.* The road section at Bjertnes (NM 767869) (Fig. 3B). The base of the formation is defined at the appearance of the first thick (>0.5 m) sandstone above the nodular limestones of the Kalvsjøen Fm. The increase in siliciclastic content is gradual and thus the boundary in other sections can be difficult to define. The name Skøyen is taken from a hamlet north of Kalvsjø Lake (NM 865854).

The Skøyen Group consists of the Klinkenberg Fm. and the Sælabonn Fm. It includes all the strata referred to as the Skøyen Sandstone by Owen (1978) together with the uppermost parts of his 'Kalvsjø Fm'. The thickness of the group (largely calculated from unpublished maps by A.W.O.) increases towards the northeast from about 120 m to about 194 m (Fig. 10). The Skøyen Group spans the Ordovician–Silurian boundary, which probably lies close to the base of the Sælabonn Fm.

*Fig. 5.* Representative fossils from the Kalvsjøen Formation. All specimens housed in the Paleontologisk Museum, University of Oslo. A, C, E, F, H, I, J, K, O, P are from the upper part of the Kalvsjøen Formation (loc. W273), on the road section between Sløvika and Lunner (NM 809862). A. *Platystrophia* cf. *anomala* Hiller. Brachial valve exterior, PMO 121.067, loc. W273, ×2. B. *Strophomena?* sp. Brachial valve exterior, PMO 121.068, upper part of the Kalvsjøen Formation from the road cutting south of Jørvik, ×2. C. *Eoplectodonta* sp. Brachial valve exterior, PMO 121.069, loc. W273, ×2. D. *Eostropheodonta* sp. Pedicle valve exterior, PMO 121.070, W of Grimsrud (NM 814888), ×2. E. *Erratencrinurus (E.) inopinatus* Owen & Heath. Latex cast of paratype free cheek, PMO 118.556, loc. W273, ×3.5 (original of Owen & Heath 1990, Fig. 3B). F. *Eoplectodonta* cf. *oscitanda* Cocks. Latex cast of brachial valve interior, PMO 121.071, loc. W273, ×2.1. G. *Nicolella* sp. Brachial valve exterior, PMO 121.072. Railway cutting NE of Bjellum (NM 814888), ×3.1. H. *Dolerorthis* sp. Internal mould of brachial valve, PMO 121.073, loc. W273, ×1.5. I. *Eoplectodonta* sp. Internal mould of pedicle valve, PMO 121.074, loc. W273, ×2.5. J. *Prinocheilus* sp. Dorsal view of latex cast of complete specimen, PMO 121.075, loc. W273, ×2.5. K. *Cyclonema* sp. Internal mould, PMO 121.076, Kalvsjø Quarry (NM 874852), ×2. L. *Lophospira* sp., PMO 121.077.




Upper part of the Kalvsjøen Formation near Kalvsjø Lake (NM 886849), ×1.5. M. *Autoloxolichas* sp. Dorsal view, latex cast of external mould of cranidium, PMO 121.078. Railway cutting NE of Kalvsjø Quarry (NM 87108535), ×1.5. N. *Liospira* sp. Internal mould, PMO 121.079, Kalvsjø Quarry (NM 874852), ×1.8. O. *Toxochasmops* sp. Dorsal view, latex cast of cephalon, PMO 121.080, loc. W273, ×2.3. P. *Erratencrinurus (E.) ionopinatus* Owen & Heath. Latex cast of holotype cephalon, PMO 118.555, loc. W273, ×2.5 (original of Owen & Heath 1990, Fig. 3A).

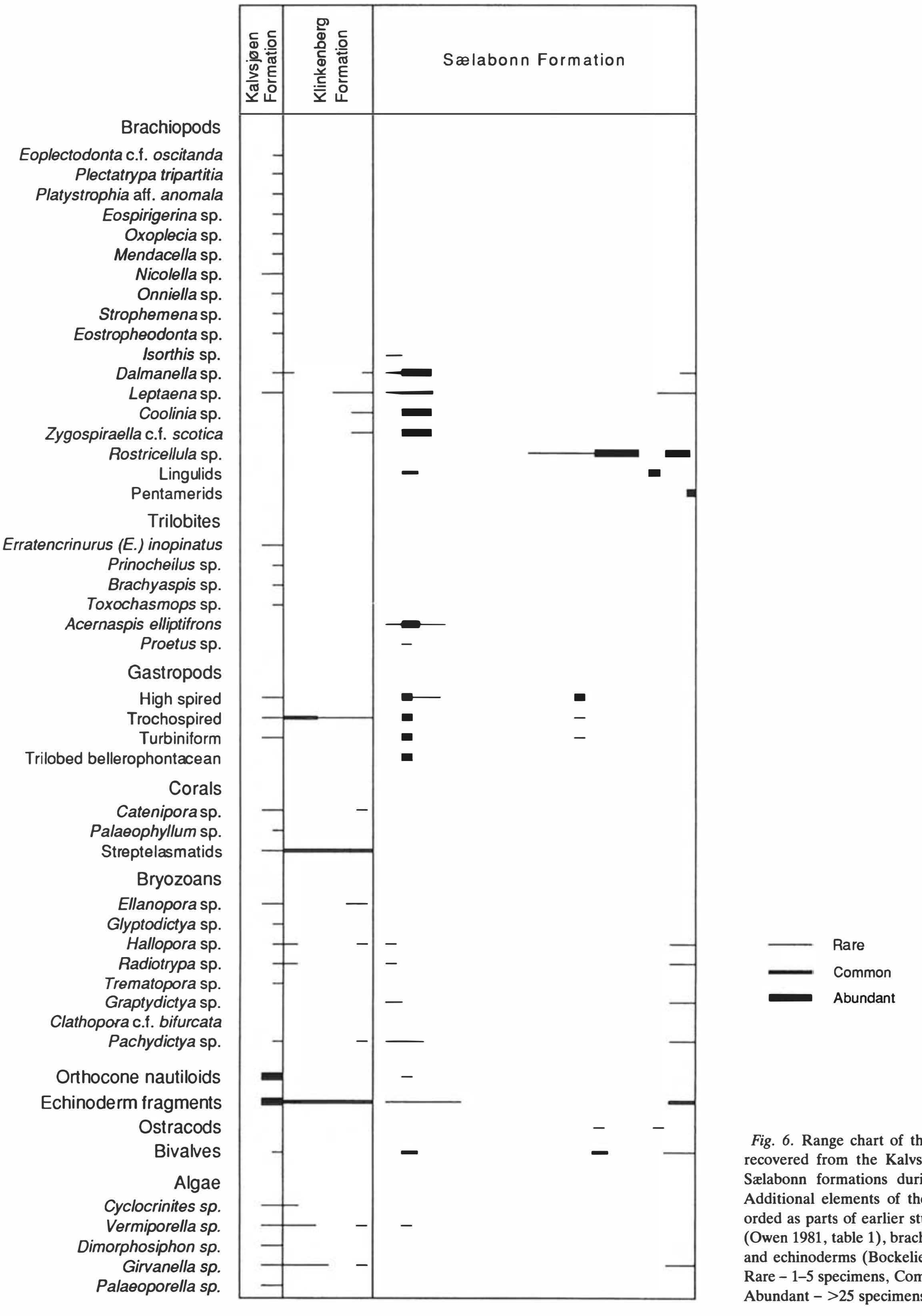



*Fig. 6.* Range chart of the fauna and algal flora recovered from the Kalvsjøen, Klinkenberg and Sælabonn formations during the present study. Additional elements of the biota have been recorded as parts of earlier studies; notably trilobites (Owen 1981, table 1), brachiopods (Bockelie 1984) and echinoderms (Bockelie 1984; Briskeby 1980). Rare – 1–5 specimens, Common – 6–25 specimens, Abundant – >25 specimens.

## The Klinkenberg Formation

(new name based on the hamlet of Klinkenberg (NM 811812) where one of the hypostratotypes is defined)

*Basal boundary stratotype.* As for the Skøyen Group as a whole (see above).

*Hypostratotypes.* (1) The section along the shore of the Randsfjord (NM 761872) at Bjertnestangen (Figs. 1, 7 see also Major 1946). This section was used by Owen (1978) as the unit stratotype for his Skøyen Sandstone. It is here maintained as a hypostratotype for the Klinkenberg Fm., the lower formation of the Skøyen Group,

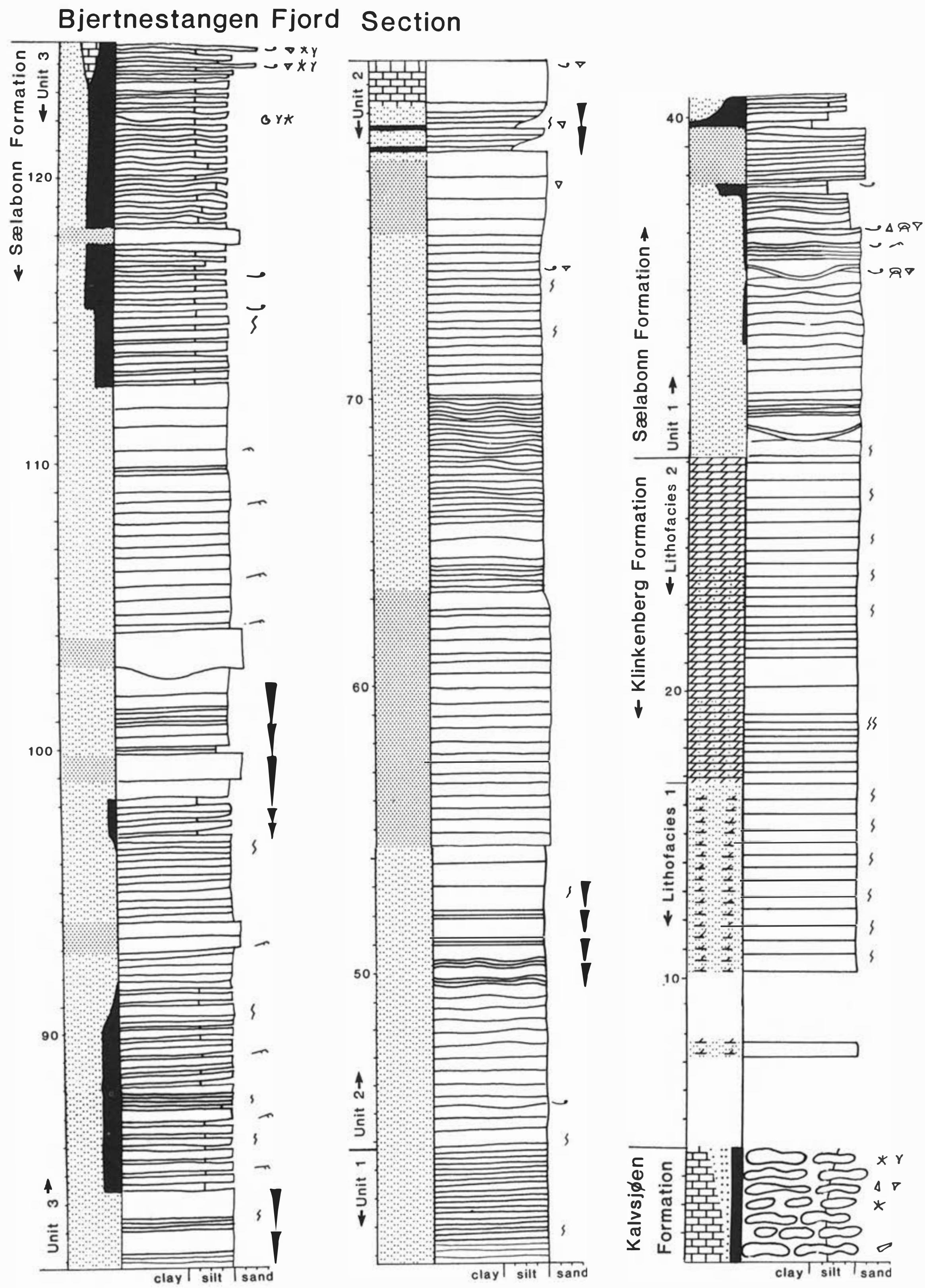
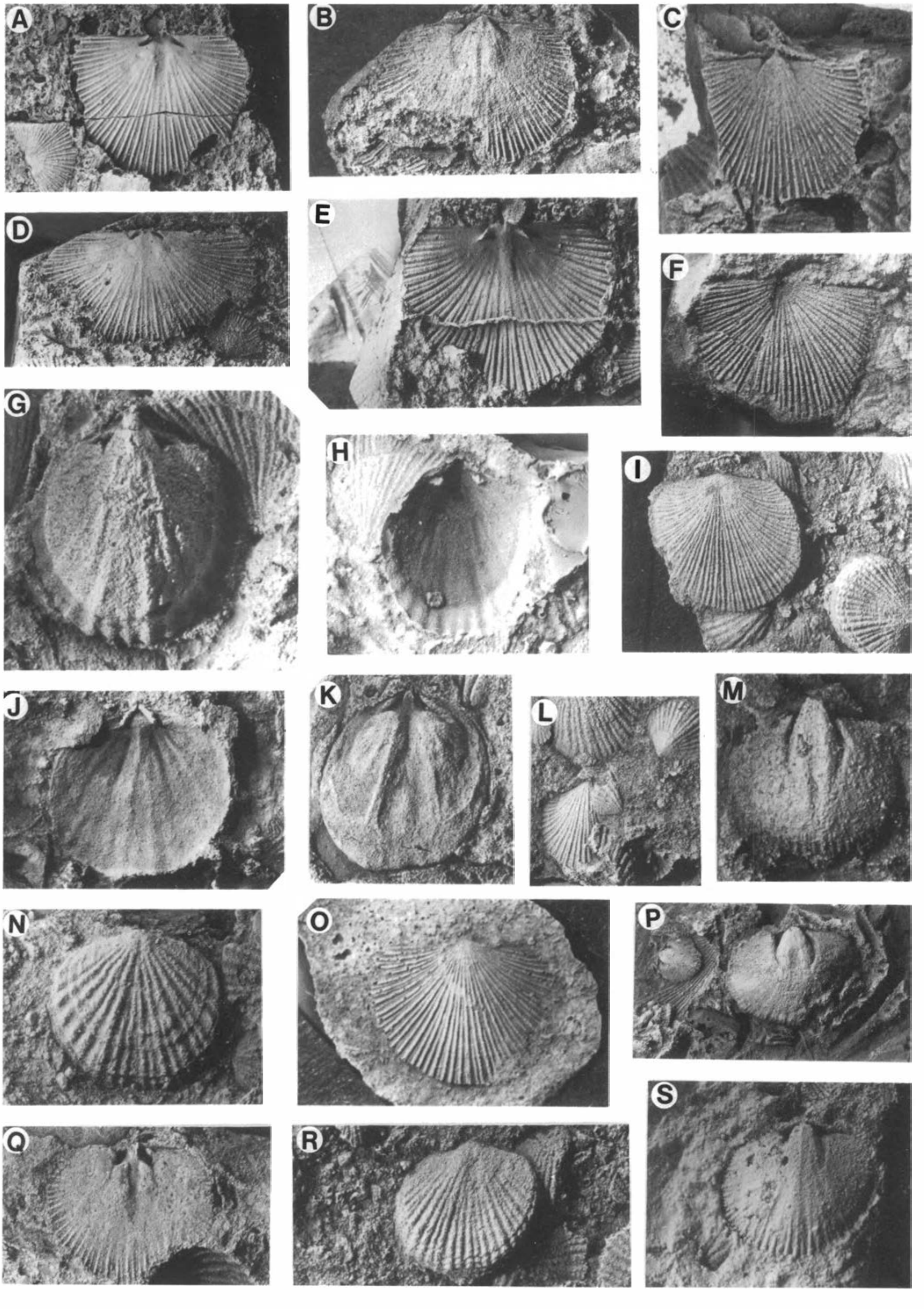



*Fig. 7.* Graphic log of the Kalvsjøen, Klinkenberg and Sælabonn formations along the Bjertnestangen shore (NM 761872). See Figs. 1 and 3A for position of locality and explanation of symbols respectively.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but because the basal few metres are not exposed, another outcrop has been chosen as the basal stratotype. (2) The section at the cross-roads at Klinkenberg (NM 811812) where some 20 m of cross-bedded calcarenites and sandstones crop out (see also Major 1946).

The formation consists of six laterally impersistent lithofacies (Fig. 2). This heterogeneity, together with the abundance of carbonates (including a significant proportion of dolomite) distinguishes the Klinkenberg Fm. from the predominantly siliciclastic Langøyene Fm. in Oslo–Asker. The six lithofacies vary in thickness and the boundaries between them are commonly gradational. The thickness of the formation as a whole varies from greater than 45 m in the east, where exposure is incomplete to at least 24 m in the west in the hypostratotype at Bjertnestangen where the base is not seen.

*Lithofacies 1* consists of coarse bioclastic lenses intercalated with fine quartz sandstones and siltstones with minor shales. It forms 26 m of strata in eastern Hadeland, decreasing to about 14 m in the west (Fig. 2). The fine sandstones and siltstones are typically black and calcareous or dolomitic, forming beds 10–70 cm thick. They are commonly heavily burrowed with *Chondrites* up to 0.5 cm in diameter but lamination is locally preserved. Rare load casts occur and are up to 2 m across and several metres long (e.g. in the railway cutting 2 km NE of Sløvika, NM 797855).

Coarse bioclastic lenses are most abundant in the east of Hadeland, where they are exposed at three localities: Loc. 357 west of Kalvsjø Lake (NM 859845), Loc. 350 at Kalvsjø School (NM 868849) and Loc. 684 east of Grinvoll (NM 887852) (Fig. 1 shows the localities). Bioclastic lenses up to 10 cm thick are interbedded with calcareous siltstone to form units 4–5 m thick.

*Lithofacies 2* consists predominantly of dolostones with siltstones and sandstones. It ranges between 2 and 32 m thick and has a gradational boundary with Lithofacies 1 (Fig. 2). The amount of siltstone and sandstone present varies from 20 to 80%, but this cannot be determined in the field since all three lithologies appear very similar. Fossils are present but unidentifiable owing to extensive dolomitisation.

*Lithofacies 3* is characterised by coarse siltstones and fine quartz sandstones and is 2–11 m thick. It is thickest at Klinkenberg in south central Hadeland (Fig. 1), where it comprises 11 m of regularly bedded pale quartz sandstone with low angle internal cross-lamination. The base is not seen here but the unit is overlain by the calcarenites of Lithofacies 4. In western areas, sandstones interfinger with lithofacies 2 and 4.

The sediments of Lithofacies 3 are diffusely laminated on a millimetre scale and beds are 5–30 cm thick. Bedding surfaces are planar and commonly capped by burrowed clays. Wedges of bioclastic material occur locally and consist of fragmented pelmatozoans, brachiopods and corals.

*Lithofacies 4* consists of cross-bedded grainstones and sandstones which occur in the eastern and central part of Hadeland. Outcrops occur in the hypostratotype at Klinkenberg (NM 811812), east of Klinkenberg (NM 819823), south of Kalvsjø Lake (NM 868849), north of Olum (NM 830835), Bjerke (NM 883837) and Svea (NM 892818). It overlies Lithofacies 3 at Klinkenberg and Lithofacies 2 north of Olum. The unit reaches a maximum thickness of 16 m at Klinkenberg where fine sandstones and bioclastic limestones are interbedded, forming sets of low-angled cross-beds alternating with trough cross-bedded sets and ripples with low angle cross-lamination.

The bioclastic limestones are laterally confined and fossil fragments within them are wave reworked. The absence of an in situ fauna precludes any detailed biostratigraphy but the low density, allochthonous, fauna must have been derived from a similarly low diversity source. Fragments include crinoids, streptelasmatid corals and the following brachiopods: *Zygospiraella* cf. *scotica* (M'Coy), *Dalmanella* sp. and rare *Leptaena* (Figs. 6, 8, 9). Bryozoans include the thin stick forms *Pachydictya* and *Radiotrypa* and ramose fragments of *Hallopora* sp.

*Lithofacies 5* consists of about 1 m of nodular limestones which are found in most localities at the top of the formation. In central and eastern Hadeland it overlies bioclastic limestones of Lithofacies 4 and is in turn overlain by shales and sandstones of the Sælabonn Fm. It is very similar to the nodular limestones of the Kalvsjøen Fm. Layers of flat, ellipsoidal nodules, commonly up to 15 cm in diameter and up to 7 cm thick, consist of wackestone with bioclasts of algae, fragments of brachiopods and echinoderms. These are separated by shales up to 3 cm thick. In western Hadeland Lithofacies 5 is partly

*Fig. 8.* Representative fossils from the Klinkenberg and Sælabonn formations. All specimens housed in the Paleontologisk Museum, University of Oslo. A–F. *Coolinia* sp. A, E. Internal mould and latex cast of brachial valve, PMO 121.082, Klinkenberg Formation, Bjerke (NM 883837). A. ×2.2, E. ×2.6. B. Internal mould of pedicle valve, PMO 121.083 (same block as specimen 9H). Lower Sælabonn Formation, N of Olum (NM 830835), ×3.7. C. Internal mould of pedicle valve, PMO 121.084. Lower Sælabonn Formation, railway cutting near Bjellum (NM 782833), ×2.7. D. Internal mould of brachial valve, PMO 121.085, Klinkenberg Formation, Bjerke (NM 883837), ×2.1. F. Brachial valve exterior, PMO 121.086. Road cutting near Tønnerud (NM 782922), ×2.4. G, H, J, K, N, R. *Zygospiraella* cf. *scotica* (M'Coy). Lower part of the Sælabonn Formation. G, H. Internal mould and latex cast of pedicle valve, PMO 121.087, G. ×5.1, H. ×4. J, K. Latex cast and internal mould of brachial valve, PMO 121.086, Bjellum Road section (NM 781829), ×3.8. N. Latex cast of pedicle valve exterior, PMO 121.093, N of Olum (NM 830835), ×1.8. R. Latex cast of brachial valve exterior, PMO 121.090, N of Olum (NM 830835), ×3.8. I, L, O, P, S. *Dalmanella* sp. from the lower part of the Sælabonn Formation. I. Latex cast of brachial valve exterior, PMO 121.089, N of Olum (NM 830835), ×3. L. Latex cast of *Dalmanella* sp. valves, PMO 121.191, N of Olum (NM 830835), ×2. O. Latex cast of external mould of pedicle valve PMO 121.094, Bjernestangen shore section (NM 761872), ×3.5. P. Internal mould of pedicle valve, PMO 121.095, W of Skøyen (NM 858855), ×2.5. S. Internal mould of pedicle valve, PMO 121.097, ×3.5. M, Q. *Isorthis prima* Walmsley & Boucot. Lower part of the Sælabonn Formation. M. Internal mould of pedicle valve, PMO 121.092, N of Olum (NM 830835), ×4.1. Q. Internal mould of brachial valve PMO 121.096, Bjellum Road section (NM 781829), ×3.3.

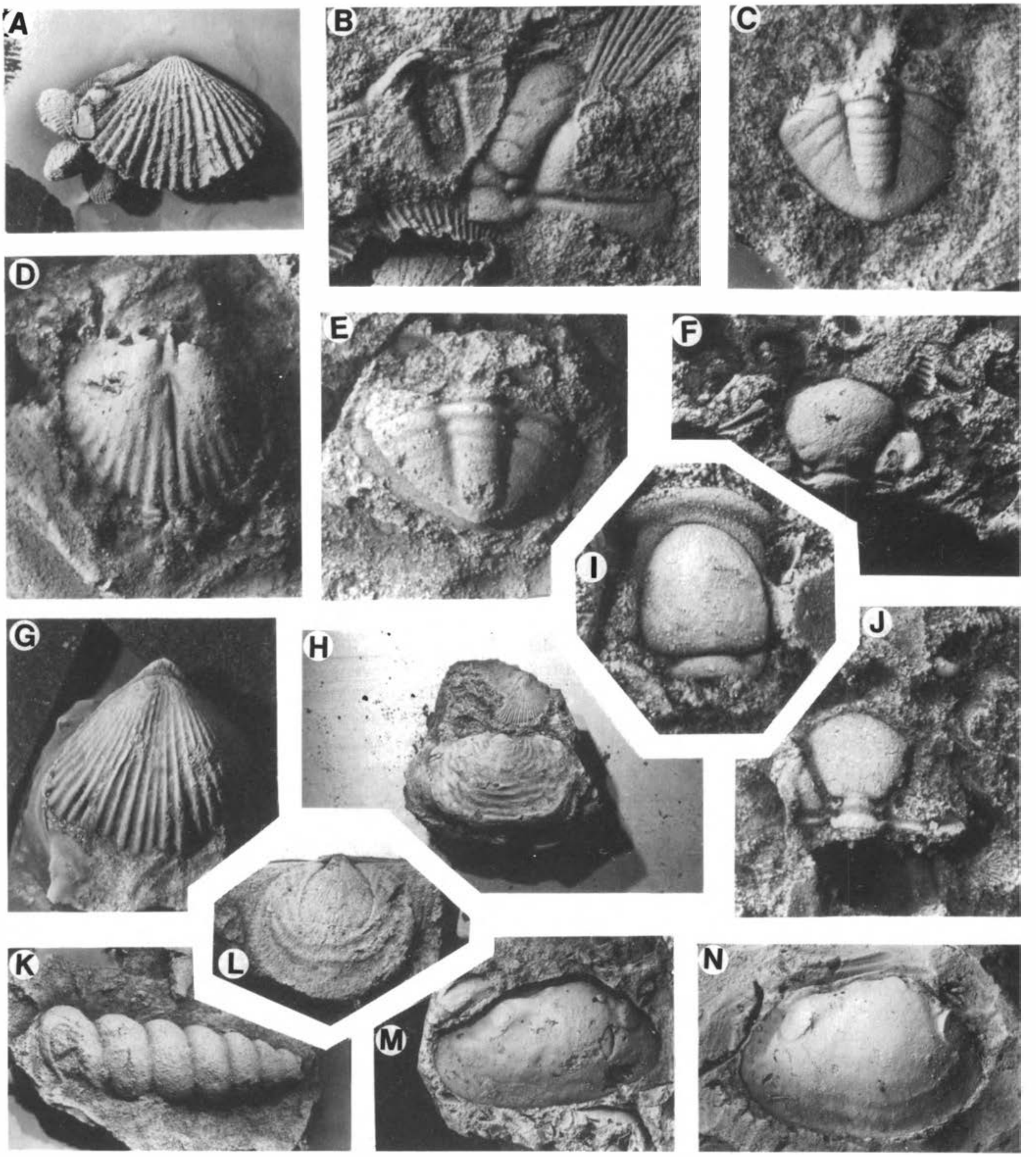


*Fig. 9.* Representative fossils from the Sælabonn Formation. A, D, G, *Rostricellula* sp. A. Latex cast of pedicle valve exterior, PMO 121.098, Bjellum Road section (NM 781829), ×3. D. Internal mould of brachial valve, PMO 121.101, Bjertnes Road section, loc. W519 (NM 768875), ×4.5. G. Brachial valve exterior, PMO 121.105, Ragnhildrud (NM 816825), ×3.8. B, C, E, F, J. *Acernaspis elliptifrons* (Esmark) from the lowest Sælabonn Formation at Bjertnestangen shore section (NM 761872). B. Dorsal view, latex cast of cranidium, PMO 121.099, ×6. C. Dorsal view, latex cast of cranidium, PMO 121.100, ×6.5. E. Dorsal view, internal mould of pygidium, PMO 121.102, ×5.5. F. Dorsal view, internal mould of cranidium, PMO 121.108, ×6.5. H. *Leptaena* sp. Brachial valve exterior, PMO 121.104, N of Olum (NM 830835), ×1. I. *Proetus* sp. Dorsal view, latex cast of cranidium, PMO 121.107, lowermost Sælabonn Formation, Bjertnestangen shore section (NM 761872). K. *Lophospira* sp. Internal mould, PMO 121.109, Bjertnes loc. W519 (NM 768875). L. *Leptaena* sp. Internal mould of pedicle valve, PMO 121.110, N of Olum (NM 830835), ×1.5. M. Indet. bivalve. Internal mould of right valve, PMO 121.111, Bjertnes (NM 768875), ×2. N. Indet. bivalve. Internal mould of right valve, PMO 121.112, Bjertnes (NM 768875), ×2.1.

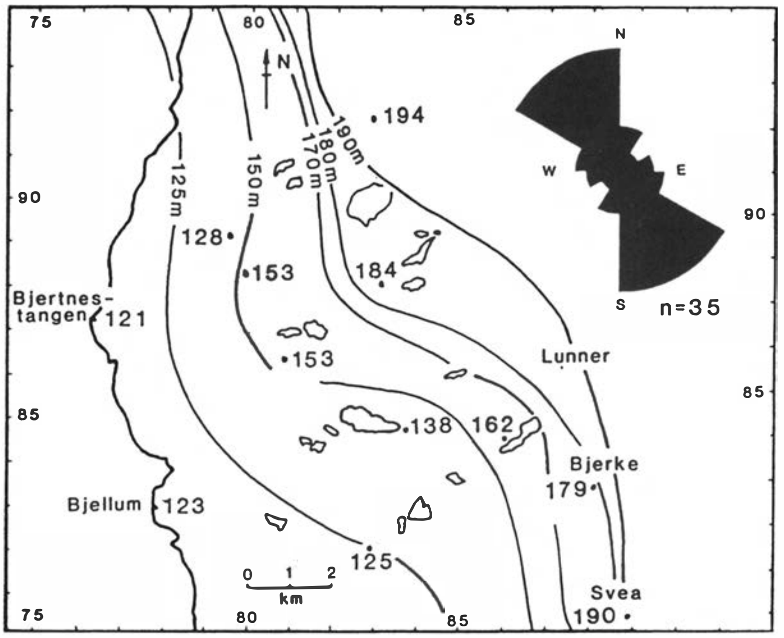


*Fig. 10.* Isopachyte map of the Skøyen Group. The rose diagram shows current directions recorded by wave ripple orientations.

dolomitised, less well defined and overlies dolomite and siltstone of Lithofacies 2.

*Lithofacies 6.* Nearly spherical quartz grains are most abundant in the upper part of the Klinkenberg Fm. but also occur in the Lower Sælabonn Fm. These 'millet seed' grains are typically well rounded, generally mono- or sometimes polycrystalline and up to 2 mm in maximum diameter. They occur as individual grains dispersed in fine sandstone and dolomite, as aggregates in thin discontinuous beds, or as distinct beds 30–50 cm thick overlying Lithofacies 5. In the NE of Hadeland, they fill fissures within dolotomised limestone. Similar grains also fill fissures in erosion surfaces at the top of the Ordovician in the Mjøsa districts (own observations) and in Ringerike (Thomsen 1982).

*Biota of the Klinkenberg Fm.*

The main taxa documented from the uppermost Ordovician (Hirnantian) of Oslo–Asker by Brenchley & Cocks (1982) are not present in Hadeland. The only brachiopod in the Klinkenberg Fm. in common with the *Hirnantia* Fauna (*sensu* Rong & Harper 1988) is *Dalmanella*. Components of this fauna are thought to have occupied niches in a range of water depths ranging from those of Benthic Assemblage 2–3 of Boucot (1975) to BA 4 or even 5 (Rong & Harper 1988). The Hadeland area was probably shallower than the inner shelf environments in Oslo–Asker (Heath in prep.) from which Brenchley & Cocks (1982) described their *Hirnantia* Faunas. Shallower faunas in Oslo–Asker contain the *Thebesia* and *Brevilamnulella* associations which contain elements of the low latitude, North American Edgewood Fauna (Brenchley & Cocks 1982). Rong & Harper discussed the similarity between these faunas and suggested that they inhabited similar shallow water tropical environments. Broadly comparable environments probably existed in Hadeland where three of the Edgewood Fauna elements, *Dalmanella*, *Coolinia* and *Leptaena* (Figs. 6, 8, 9), are present in the Klinkenberg Fm.

The precise age of the Klinkenberg Fm. is not known. Its base marks a major sedimentological change and elsewhere in the Oslo Region together with many other parts of the world such a change occurs at the base of the Hirnantian Stage (e.g. Brenchley 1988). Detailed biostratigraphical data to support such a correlation in Hadeland are not available but the underlying Kalvsjøen Fm. is probably Rawtheyan and the base of the overlying Sælabonn Fm. is probably close to the base of the Llandovery. There is therefore at least circumstantial sedimentological and biostratigraphical evidence for a broadly Hirnantian age for the Klinkenberg Fm.

## The Sælabonn Formation

(Worsley et al. 1983)

*Hypostratotype.* The road section at Bjertnes (Loc. W529; NM 767869) (Figs. 1 & 3). This formation was originally defined in Ringerike (Worsley et al. 1983, pp. 16–17). Its base in Hadeland is marked by thinly bedded sandstones which commonly overlie a nodular limestone or dolomitic unit at the top of the Klinkenberg Fm. The upper boundary is the base of the Rytteråker Fm. which was also originally defined in Ringerike (Worsley et al. 1983, p. 20). This boundary lies in a gradual transition over several metres from a dominantly siliciclastic to a dominantly calcareous succession. In Ringerike, Möller defined the base of the Rytteråker Fm. at the last (5.5 cm) planar laminated limestone bed below the base of the massive coarse bioclastic unit of her facies B (1987, p. 217). This is inappropriate in Hadeland owing to the gradual increase of coarse bioclastic beds at the top of the Sælabonn Fm.

The sediments of the Sælabonn Fm. contrast markedly with those of the underlying Klinkenberg Fm. Other areas in the Oslo Region also show a distinct lithological change at about this level. In Ringerike, the Sælabonn Fm. fills runnels in the eroded top of the Ordovician (Thomsen 1982) and in Oslo–Asker the shaly Solvik Fm. overlies oolitic limestone of the uppermost Ordovician (Baarli 1985).

Three lithological divisions are recognised in the Sælabonn Fm. in Hadeland (Fig. 2) and these are similar to those described by Thomsen (1982) in Ringerike where the succession is not as thick and contains more carbonate material. All three units in Hadeland contain the ichnofossils *Scolithos* and *Palaeophycus*.

### *Unit 1*

This unit forms 15–25 m of strata at the base of the formation overlying nodular limestones or dolomites of the Klinkenberg Fm. The basal sandstones total 0.5–9 m in thickness. Millet seed grains are present either as scattered grains or as diffuse, discontinuous beds but they are not as common as in the underlying formation. The rest of Unit 1 comprises thinly bedded sandstones and shales (bed thickness terminology following Ingram 1954), the latter forming about 15% of the total succession but increasing to 25% near the top of the unit.

The sandstones are very fine grained and form beds 1–25 cm thick. Thinning and thickening cycles are common and fossils are commonly concentrated in the bases of the thicker beds. Bed bases are generally sharp and planar. Upper surfaces are either rippled or planar and internally, beds are commonly laminated parallel to their surface. At some localities, sandstones up to 0.5 m thick form load structures which protrude downwards into the underlying sandstones. They are comparable but on a smaller scale to those described from Lithofacies 1 of the Klinkenberg Fm and are well developed in the road sections at Bjellum (NM 781829) and Bjertnestangen (NM 767867) and in the shore section at Bjernestangen (NM 761872).

*Biota.* A high density, low diversity biota occurs in all of the lower Sælabonn Fm. sections in 2–5 fossiliferous horizons between 4 and 13 m above the base of Unit 1 (Figs. 6, 8, 9). Brachiopods include species of *Dalmanella*, *Coolinia* and *Zygospaerella*; the trilobites, *Acernaspis elliptifrons* (Esmark) and *Proetus* sp., and the gastropods include *Trochonema* sp., murchisoniaceans, indeterminate turbiniform species and trilobed bellerophontaceans. Other fossils include bryozoans, solitary corals, bivalves, orthocones, tentaculites and algae.

### *Unit 2*

This unit consists of regularly bedded sandstones (more than 90% of the total thickness) with minor shales. The thickness is generally between 30 and 38 m but increases eastwards and at Svea (Fig. 1) the unit is 142 m thick and constitutes the whole of the Sælabonn Fm. Thinning and thickening upward cycles are common and there are some coarsening upward units. Bed bases are mostly sharp and bed tops are wave rippled; recording NNW/SSE oscillations. Fossils are concentrated in the bases of thicker beds but are not as abundant as in units 1 and 3. They include the brachiopods *Rostricellula*, gastropods and bivalves (Fig. 9).

### *Unit 3*

This unit comprises three lithological divisions: a lower sandstone and shale, a middle thinly bedded sandstone and an upper sandstone and shale with limestone increasing towards the overlying Rytteråker Fm. Unit 3 is thickest in the Bjellum road section (Loc. S5, Fig. 1) and thins westward. It differs from the underlying units in containing abundant shale and limestone interbeds. However, the structures within siliciclastic beds are similar to those in the other two units in having clay-draped surfaces with burrow and surface traces.

Fossils occur in abundance both in the upper and lower of the three divisions of Unit 3 and include bivalves, leperditiid ostracods and gastropods. The brachiopod *Rostricellula* (Fig. 9) occurs sporadically throughout the unit.

### *Biostratigraphy*

The presence of the trilobite *Acernaspis elliptifrons* between 4 and 11 m above the base (Fig. 6) indicates a Silurian age for most if not all of the Sælabonn Fm. as it suggests that the base of the System lies close to that of the formation. Lespérance (1988) inferred that the appearance of *Acernaspis* may coincide with the base of the *Parakidograptus acuminatus* Zone (the basal Silurian graptolite zone) in the Oslo Region and parts of the USSR. However, Barnes & Bergström (1988, p. 331) have pointed out that the first appearance of *Acernaspis* in Oslo–Asker is in the overlying *Monograptus atavus* Zone in the middle of the Solvik Fm.

The base of the Sælabonn Fm. in Hadeland represents a major transgression across a karstic surface comparable to other transgressions at the end of the Hirnantian (e.g. Brenchley 1988). This too would provide circumstantial evidence for the Ordovician–Silurian boundary being close to the base of the Sælabonn Fm. but without graptolite faunas this cannot be determined precisely.

### *Depositional environment of the Sælabonn Fm.*

The variation in relative amount of sandstone across the area is unsystematic and abrupt. This is consistent with the distribution of sand along distinct pathways rather than regularly across a gradual incline. Planar laminated beds with a few load structures point to an environment of rapid deposition. These alternate with sediments of lower energy regimes. During the quieter periods, the sediments were colonised by a prolific infaunal community.

The sandstones of the Sælabonn Fm. are similar to storm deposits described by Aigner (1985) from offshore areas in the North Sea. They are interpreted as resulting from storms on low-angled slopes and regarded as tempestites. Coarse shelly bases are common in the Sælabonn Fm. and similar features have been described and interpreted by Brenner & Davies (1973) as storm deposits associated with flushing of surge channels. Such channels may have been responsible for transporting sand in Hadeland as lobes off the platform margin. The lobes were initially confined during the early stages of deposition of the Sælabonn Fm., allowing the accumulation of fines in the interdistributary areas.

## The Rytteråker Formation

This unit has been examined in Hadeland by Möller (1989) as part of a wider study of the formation in the Oslo Region. She noted that the basal 9.7 m is characterised by bioclastic limestone associated with siliciclastic material. This is overlain by 11 m of bioclastic limestone, the basal few metres of which contain abundant valves of the pentamerid *Borealis borealis osloensis* Mørk as well as valves of *Pentamerus oblongus* (J. de C. Sowerby). Mørk (1981) suggested that the transition between *B. borealis* and *P. oblongus* occurred in the Aeronian (see also Baarli & Johnson 1982, 1988; Möller 1989).

## Discussion

During the late Ordovician the Hadeland area was dominated by carbonate deposition and was subjected to two major events of sea level lowering. The first of these caused the deposition of carbonate debris flows, five of which are recognised in the Kalvsjøen Fm. and contrast markedly with the host nodular limestones and shales. The debris flow material was derived from a lithified shelf to the east of Hadeland and was transported via westward trending channels. This first low stand of sea level was probably at or near the beginning of the Hirnantian and culminated in the emergence of the channel fills and the development of karst (Braithwaite & Heath in prep).

The overlying Klinkenberg Fm. of probable Hirnantian age comprises six lithofacies, some of which are laterally discontinuous. This variation was primarily the result of the presence of a carbonate barrier to the east of Hadeland which confined sediment transport to distinct pathways. Deposition of material was rapid with the development of load structures and planar beds. It was also sporadic and wave activity reworked and mixed siliciclastic and bioclastic material. The oscillatory nature of the sea level changes is recorded in the calcite cement sequences which show that pore waters were incompletely mixed in a shallow burial environment. Platform draining during the second major sea level lowering probably at the end of the Ordovician resulted in extensive dolomitisation of limestones and ultimately the development of fissures within the dolomite. These fissures were filled with millet seed sand grains derived from a mature landscape.

With the sea level rise at the beginning of the Silurian, the carbonates characteristic of the uppermost Ordovician were diluted by rapidly deposited siliciclastic material. The presence of the trilobite *Acernaspis* low in the Sælabonn Fm. suggests that the systemic boundary lies close to the base of the formation.

In parallel with the sedimentological changes, there are changes in biotic composition across the Ordovician–Silurian boundary. The latest Ordovician faunas of the Klinkenberg Fm. are essentially of low density and diversity whereas those in the lowest Silurian Sælabonn Fm. are high density, low diversity assemblages. The environment was probably shallower than in more southerly areas of the Oslo Region (including Oslo–Asker) where early Silurian faunas are of higher diversity.

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## References

Aigner, T. 1985: *Storm Depositional Systems. Lecture Notes in Earth Sciences 3*, 174 pp. Springer Verlag, Berlin.

Baarli, B. G. 1985: The stratigraphy and sedimentology of the early Llandovery Solvik Formation, Central Oslo Region, Norway. *Norsk Geologisk Tidsskrift 65*, 229–249.

Baarli, B. G. & Johnson, M. E. 1982: Lower Silurian biostratigraphy of strictlandiid and pentamerid lineages in the Central Oslo Region, Norway: *In* Worsley, D. (ed.): *IUGS Subcommission on Silurian Stratigraphy. Field Meeting Oslo Region 1982. Paleontological Contributions from the University of Oslo 278*, 91–93.

Baarli, B. G. & Johnson M. E. 1988: Biostratigraphy of key brachiopod lineages from the Llandovery Series (Lower Silurian) of the Oslo Region. *Norsk Geologisk Tidsskrift 68*, 259–274.

Barnes, C. R. & Bergström, S. M. 1988: Conodont biostratigraphy of the upper Ordovician and lowermost Silurian. *Bulletin of the British Museum Natural History (Geology) 43*, 325–343.

Bockelie, J. F. 1984: The Diploporita of the Oslo Region, Norway. *Palaeontology 27*, 1–68.

Boucot, A. J. 1975: *Evolution and Extinction Rate Controls.* 427 pp. Elsevier, Amsterdam.

Brenchley, P. J. 1985: Storm influenced sandstone beds. *Modern Geology 9*, 369–396.

Brenchley, P. J. 1988: Environmental changes close to the Ordovician/Silurian boundary. *Bulletin of the British Museum Natural History (Geology) 43*, 377–385.

Brenchley, P. J. & Cocks, L. R. M. 1982: Ecological associations in a regressive sequence; the latest Ordovician of the Oslo–Asker District, Norway. *Palaeontology 25*, 783–815.

Brenchley, P. J. & Cullen, B. 1984: The environmental distribution of associations belonging to the *Hirnantia* fauna. *In* Bruton, D. L. (ed.): *Aspects of the Ordovician System*, 113–125. Universitetsforlaget, Oslo.

Brenchley, P. J. & Newall, G. 1975: The stratigraphy of the Upper Ordovician Stage 5 in the Oslo–Asker District, Norway. *Norsk Geologisk Tidsskrift 55*, 243–275.

Brenchley, P. J. & Newall, G. 1977: The significance of contorted bedding in the Upper Ordovician sediments of the Oslo Region, Norway. *Journal of Sedimentary Petrology 47*, 819–833.

Brenchley, P. J. & Newall, G. 1980: A facies analysis of Upper Ordovician regressive sequences in the Oslo Region, Norway – A record of glacio-eustatic changes. *Palaeogeography, Palaeoclimatology, Palaeoecology 31*, 1–38.

Brenchley, P. J. & Newall, G. 1984: Late Ordovician environmental changes and their effects on faunas. *In* Bruton, D. L. (ed.): *Aspects of the Ordovician System*, 65–79. Universitetsforlaget, Oslo.

Brenchley, P. J., Newell, G. & Stanistreet, I. G. 1979: A storm surge origin for sandstone beds in an epicontinental platform sequence, Ordovician, Norway. *Sedimentary Geology 22*, 185–217.

Brenner, R. L. & Davies, D. K. 1973: Storm generated coquinoid sandstones: genesis of high energy marine sequences from the Upper Jurassic of Wyoming and Montana. *Geological Society of America Bulletin 84*, 1685–1698.

Briskeby, P. I. 1980: Klassification av krinoidstilker fra den over-ordoviciske Kalvsjøformasjon på Hadeland. Unpublished Cand. Real. thesis, University of Oslo. 170 pp.

Cocks, L. R. M. 1982: The commoner brachiopods of the latest Ordovician of the Oslo–Asker district, Norway. *Palaeontology 25*, 755–787.

Cocks, L. R. M. & Rickards, R. B. (eds) 1988: A global analysis of the Ordovician–Silurian boundary. *Bulletin of the British Museum Natural History (Geology) 43*, 1–394.

Hagemann, F. 1957: On the petrology of the Silurian shales from Hadeland, Norway. *Norsk Geologisk Tidsskrift 37*, 229–246.

Hagemann, F. 1966: Silurian bentonites in the Oslo Region. *Norges geologiske undersøkelse Bulletin 244*, 44–61.

Holtedahl, O. & Schetelig, J. 1923: Kartbladet Gran. *Norges geologiske undersøkelse 97*, 1–46.

Ingram, R. L. 1954: Terminology for the thickness of stratification and parting units in sedimentary rocks. *Geological Society of America Bulletin 65*, 937–938.

Kiær, J. 1908 (for 1906): Das Obersilur in Kristianiagebeite. Eine stratigrafische-faunistische Untersuchung. *Videnskabs-Selskabets Skrifter. I. Matematisk-Naturvidenskapelig Klasse 1906, No. 2*, 1–595.

Lespérance, P. J. 1988: Trilobites. *Bulletin of the British Museum Natural History (Geology) 43*, 359–376.

Major, H. 1945: A Silurian 'Pipe-rock' at Hadeland. *Norsk Geologisk Tidsskrift 25*, 225–229.

Major, H. 1946: Noen profiler fra eldste Silur i Oslofeltets nordlige del. *Norsk Geologisk Tidsskrift 26*, 59–141.

Möller, N. K. 1987: A lower Silurian transgressive carbonate succession in Ringerike (Oslo Region, Norway). *Sedimentary Geology 51*, 215–247.

Möller, N. K. 1989: Facies analysis and palaeogeography of the Rytteråker Formation (Lower Silurian, Oslo Region, Norway). *Palaeogeography, Palaeoclimatology, Palaeoecology 69*, 167–192.

Möller, N. K. & Kvingan, K. 1988: The genesis of nodular limestones in the Ordovician and Silurian of the Oslo Region (Norway). *Sedimentology 35*, 405–420.

Mørk, A. 1981: A reappraisal of the lower Silurian brachiopods *Borealis* and *Pentamerus*. *Palaeontology 24*, 537–553.

Neumann, B. 1975: New Lower Palaeozoic streptelasmatid corals from Scandinavia. *Norsk Geologisk Tidsskrift 55*, 335–359.

Owen, A. W. 1978: The Ordovician and Silurian Stratigraphy of Central Hadeland, South Norway. *Norges geologiske undersøkelse 338*, 1–23.

Owen, A. W. 1979 (for 1978): The upper Ordovician succession at Norderhov and on Frognøya in Ringerike. *Norsk GeologiskTidsskrift 58*, 245–258.

Owen, A. W. 1981: The Ashgill trilobites of the Oslo Region, Norway. *Palaeontographica Abteilung (A)* 175, 1–88.

Owen, A. W., Bruton, D. L., Bockelie, J. F. & Bockelie, T. G. (1990): The Ordovician successions of the Oslo Region, Norway. *Norges geologiske undersøkelse Special Publication 4*, 1–54.

Owen, A. W., Harper, D. A. T. & Rong Jia-yu (in press). Hirnantian trilobites and brachiopods in space and time. *In* Barnes, C. R. & Williams, S. H. (eds): Advances in Ordovician Geology. Proceedings of the Fifth International Symposium on the Ordovician System. *Geological Survey of Canada Papers.*

Owen, A. W. & Heath, R. A. 1990 (for 1989): A review of the upper Ordovician trilobite genus *Erratencrinurus* with a description of a new species from Hadeland. *Norsk Geologisk Tidsskrift 69*, 225–233.

Robertson, D. B. R., Brenchley, P. J. & Owen, A. W. (in press): Ecological disruption close to the Ordovician–Silurian boundary. *Historical Biology.*

Rong, Jia-yu & Harper, D. A. T. 1988: A global analysis of the latest Ordovician Hirnantian brachiopod faunas. *Transactions of the Royal Society of Edinburgh: Earth Sciences 79*, 383–402.

Scrutton, C. T. 1971: Palaeozoic coral faunas from Venezuela 1. Silurian and Permo-Carboniferous corals from the Merida Andes. *Bulletin of the British Museum Natural History (Geology) 20*, 185–227.

Størmer, L. 1945: Remarks on the Tretaspis (Trinucleus) Shales of Hadeland with descriptions of the trilobite faunas. *Norsk Geologisk Tidsskrift 25*, 379–425.

Thomsen, E. 1982: Sælabonn Formationen (nedre Silur) i Ringerike, Norge. *Dansk Geologisk Forening Årskrift for 1981 104*, 1–11.

Worsley, D., Aarhus, N., Bassett, M. G., Howe, M. P. A. & Olaussen, S. 1983: The Silurian succession of the Oslo Region. *Norges geologiske undersøkelse 384*, 1–57.

Yu, C. M. 1960: Upper Ordovician corals from China. *Acta Palaeontolgoca Sinica 5*, 307–324.