Upper Ordovician–Lower Silurian strata and biota from offshore South Norway

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The shallow stratigraphic core 13/2-U-2 drilled northeast of the Farsund Basin penetrated 76.5 m of clastics and limestones of Late Ordovician and Early Silurian age. The well represents the first record of Lower Palaeozoic rocks offshore south Norway and is the westernmost known extension of the Lower Palaeozoic Scandian foreland deposition area. Lithologically, the core can be subdivided into four units. The lower Unit A (Late Ashgill, Rawtheyan) comprises nodular limestones and shales. The overlying Upper Ordovician Units B (Rawtheyan) and C (Hirnantian) are predominantly of siltstones but also contain shale and limestones. The boundary between Unit B and Unit C seems to correlate with a locally defined reflector P marked on the digital seismic. Chronostratigraphically, the Ordovician–Silurian boundary coincides with the boundary between Unit C and the overlying Unit D, although basal Llandovery strata have not been identified. Unit D, of early Silurian (Llandovery, Rhuddanian) age, comprises shales with some siltstone and limestone beds. All the units were deposited in shelf environments. The core displays a regression for the lower three late Ashgill units (A, B and C). This is transgressively overlain by Llandovery sediments deposited in slightly deeper water (Unit D). This development is comparable to what is observed in the contemporaneous successions of the western and northern areas of the Oslo Region.

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Introduction

In the summer of 1989 IKU carried out a shallow drilling project northeast of the Farsund Basin offshore south Norway, using the drillship M/S 'Bucentaur'. This project was part of an industry-financed programme with the objective of carrying out shallow seismic, shallow drilling and laboratory examinations of the subcropping bedrock in the Skagerrak area (Fig. 1). One of the cores drilled on the seismic line IKU-0822SK-88 at site 13/2-U-2, ca. 30 km offshore Kristiansand (57°59′40.76″N, 8°22′0.62″E), penetrated 76.5 m of Late Ordovician–Early Silurian carbonates and clastics (Figs. 2, 3). Although contemporaneous deposits are well known from the Oslo Region, and also from the allochthonous Caledonides in the Bergen Region (Stord, Karmøy, Ulven–Heggeland areas); the present article presents the first published documentation of the Lower Palaeozoic succession in offshore south Norway. The core site represents the westernmost known extension of the Lower Palaeozoic foreland depositional area, and provides an important link between the well-documented Upper Ordovician–Lower Silurian succession in the Oslo Region and the contemporaneous deposits drilled in Denmark (Fig. 1).

Core description and depositional environments

Core 13/2-U-2 consists of fine-grained clastics and limestones and is subdivided into four informal lithostratigraphic units (Fig. 3).

Unit A, 104.25 (TD)–90.4 m (Upper Ashgill, Rawtheyan)

Unit A consists of nodular limestones in a shaley matrix. Towards the top of the unit abundant limestone nodules are replaced by limestone beds and some siltstone beds occur. In the lower half of the unit limestone nodules are a few centimetres and larger in size. The nodules consist of lime mud or wackestone. The boundaries between the nodules are often gradational and show interfingering of shale and limestone laminae. In the upper part of the unit, thin beds of calcareous siltstone occur; these beds often have sharp bases and gradational transition into the overlying shale. Some beds consist of fossil debris at their base, grading through pack- to wackestone and siltstone, often laminated; the whole 'couplet' being only a few centimetres thick. Bioturbation often occurs in the upper part of such beds. Brachiopods, echinoderm debris and rugose corals are common throughout the interval, and tabulate corals, bivalves, gastropods and trilobites also occur. In thin-sections there are also ostracods, trilobite and bryozoan fragments, as well as the alga *Girvanella*.

Bioturbation is sparse in the limestones, but the shale displays well-preserved ichnofabrics, with low ichnodiversity; the traces are deformed by compaction around the nodules. Whereas the limestone nodules in the lower part of the unit show no signs of precursor burrow fill, ghosts of larger biogenic structures are present in the upper part of the unit. Pressure solution structures are common, especially at the transition between the lime-

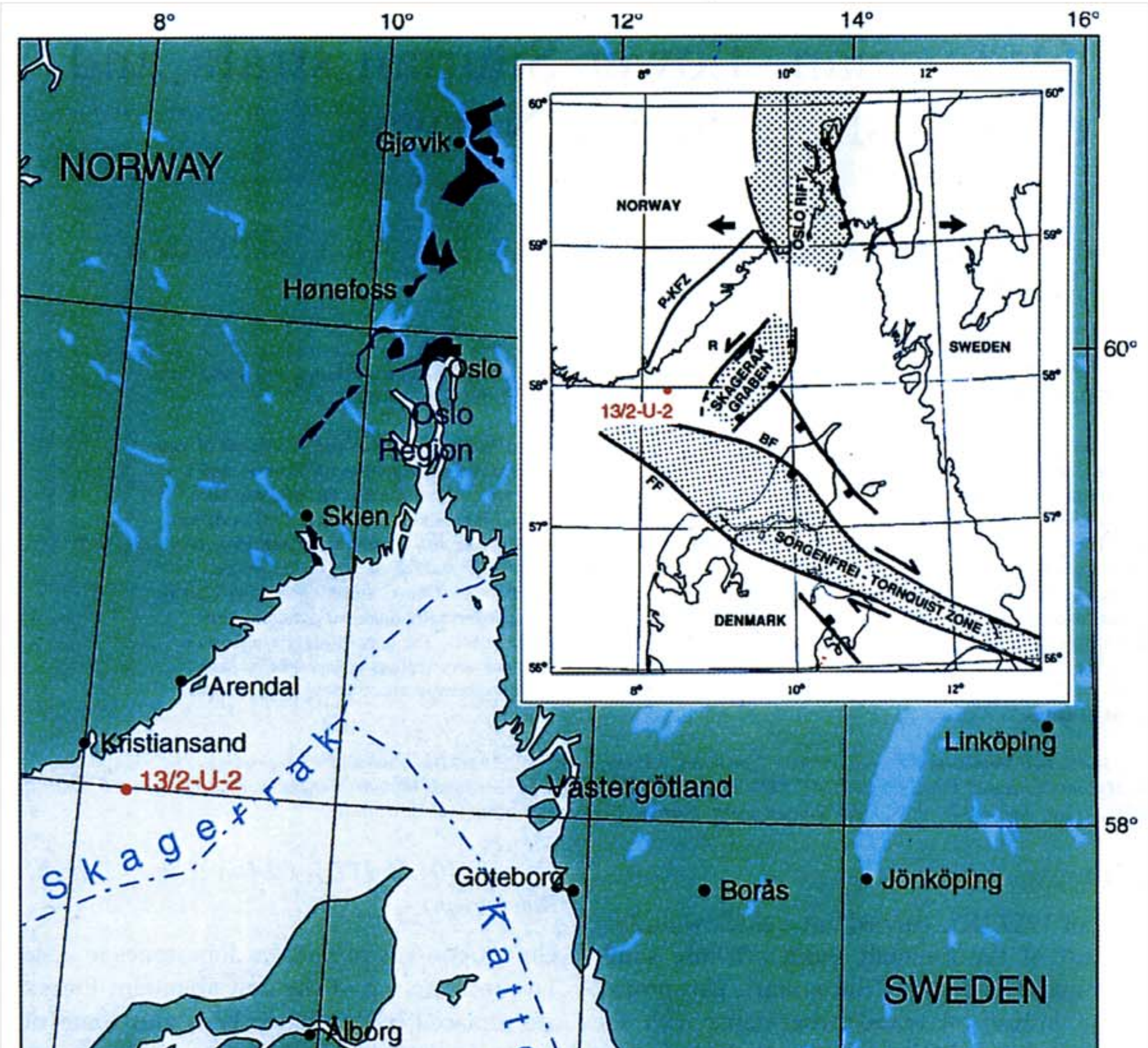


Fig. 1. Location map showing the main structural elements and the position of borehole 13/2-U-2 off southern Norway, and the position of Danish wells which have penetrated Lower Palaeozoic strata. (Fault map from Fanavoll & Lippard 1994).

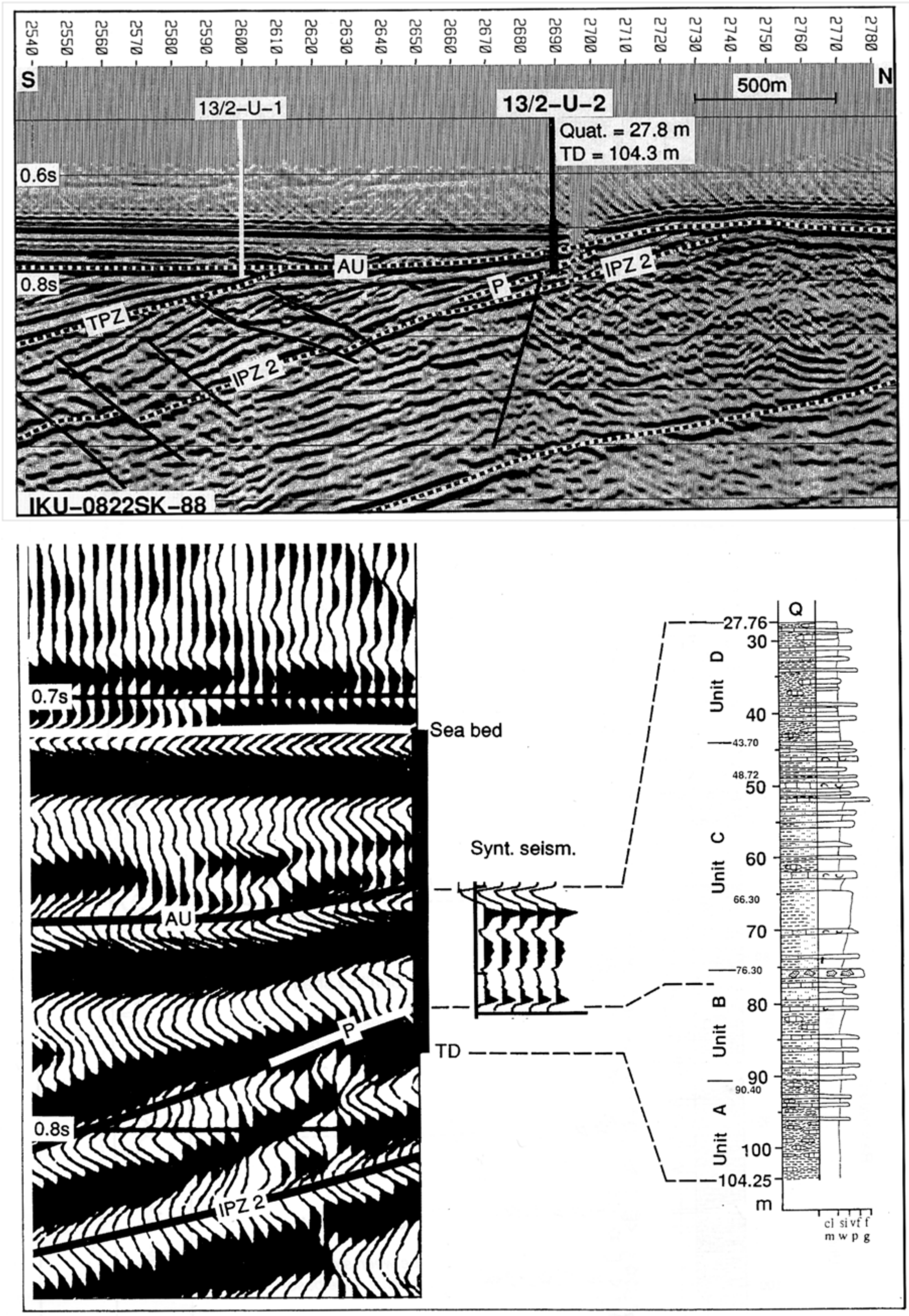


Fig. 2. Shallow seismic section of core-site 13/2-U-2. The synthetic seismogram indicates a reflection slightly below the boundary between Units B and C (i.e. at approximately 77 m). This reflection seems to fit with the reflector P marked on the digital seismic. AU: Base Quaternary Reflector; P: Reflector P; TPZ: Top Palaeozoic Reflector; IPZ2: Intra Palaeozoic Reflector 2.

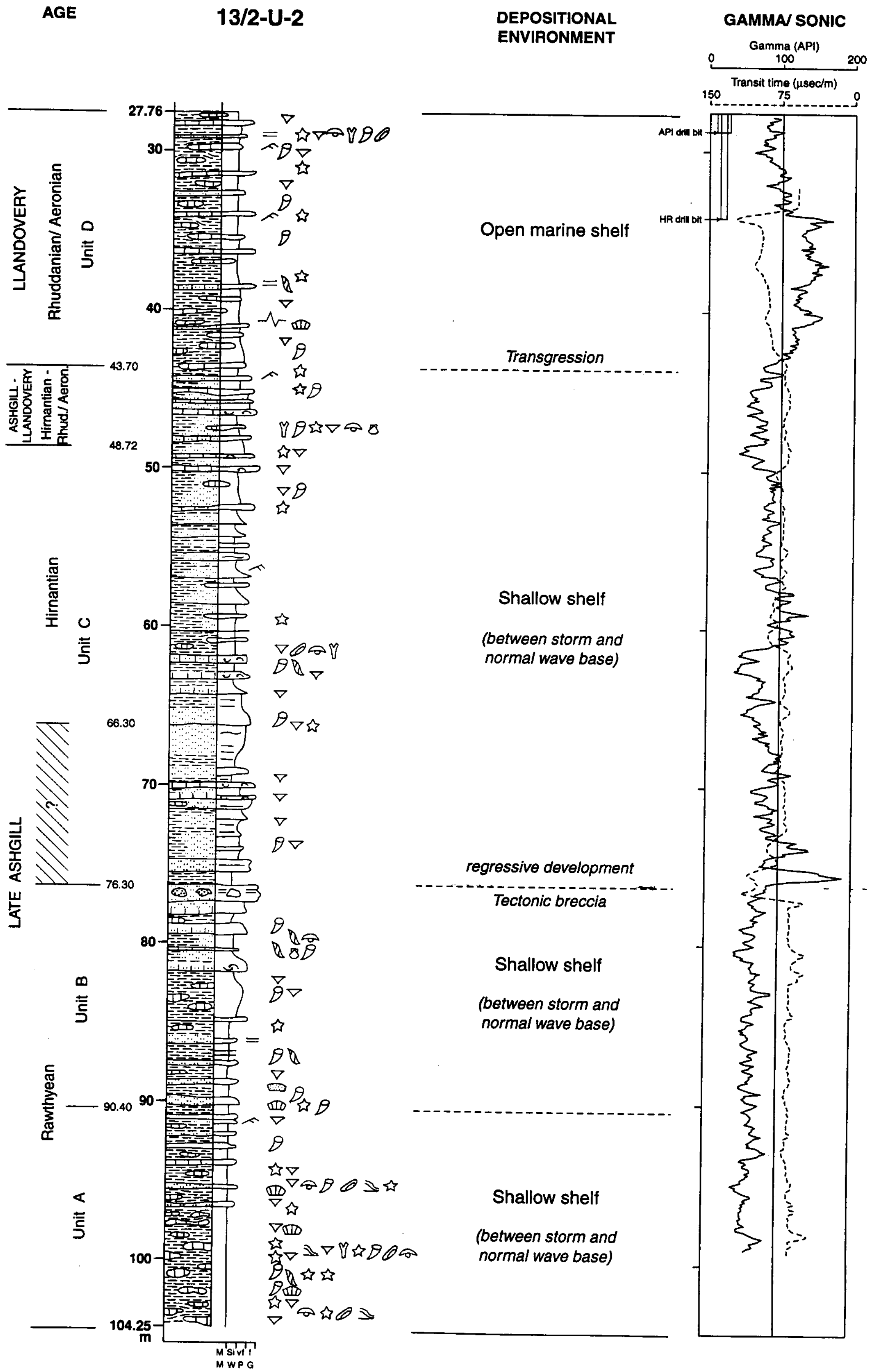


Fig. 3. Lithology and depositional environment of core 13/2-U-2. Legend in Fig. 4.

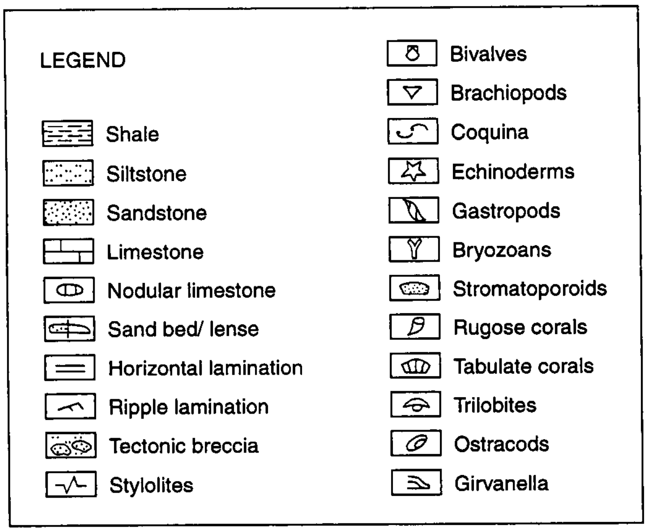


Fig. 4. Legend to the sedimentological core log.

stone nodules and the shale. These solution seams are often enriched with heavy minerals.

In Unit A the diverse marine fauna indicates open marine conditions, and the high abundance of the ?blue-green alga *Girvanella* shows that the deposition took place in the photic zone (Mørk & Worsley 1980). The dominating wackestone indicates calm environments, while packstone and lamination in the upper part of the unit indicate some current activity. The limestone nodules often show water escape and compaction structures (Fig. 5a, b, c). Calcite veins often occur on top of nodules as infilling of cracks and shale laminae bend down into the surface of such cracks (Fig. 5c). Some nodules have the shape of trace fossil infillings (Fig. 5c). All these features have contributed in the formation of the nodular limestone (cf. Wanless 1979). The decrease in nodule content towards the top of the unit and the increase in siltstone content may be due to both increasing energy levels and rates of deposition. Deposition below fair weather wave base but in the photic zone is suggested, in a moderately deep shelf environment and with moderate to low energy levels. Progressive regression may explain these features.

Unit B, 90.4–76.3 m (Upper Ashgill, Rawtheyan)

Unit B is dominated by thinly bedded siltstones although sandy/silty limestone beds and some limestone nodules occur throughout the unit. Beds grading from packstone/wackestone in their lower parts to siltstone are also present throughout the unit. Several of the packstone–siltstone beds consist of couplets with shell debris at their bases, grading upwards to siltstone. The most common sedimentary structures are parallel lamination or very low-angle cross-lamination. Bioturbation is common, mostly as minor burrowing in the upper part of the siltstone beds and showing a distinct tiering profile. Abundant fossils are brachiopods and rugose corals, together with occasional gastropods, stromatoporoids, trilobites, bryozoans and ostracods. The breccia at the top of the unit (Fig. 5j) consists of different-sized and crushed fragments of sandstone with clay infill. The fragments are undoubtedly derived from the surrounding rocks, but are today reddened due to abundant hematite dispersed in the sediments. The siltstones, although quite similar on both sides of the breccia, change colour as the beds are darker below the breccia.

The very good sorting of the siliciclastic sediment, with dominating grain size in the range of coarse silt to very fine sand, indicates that the sediment was transported to the depositional area in suspension, possibly by storms. Graded bedding is abundant, as the lower part of beds often consists of packstones or grainstones overlain by the finer siliciclastics. The grading probably reflects episodic storms that have stirred up and remobilized the sediment. Planar laminated beds with ripples at their tops is consistent with this model.

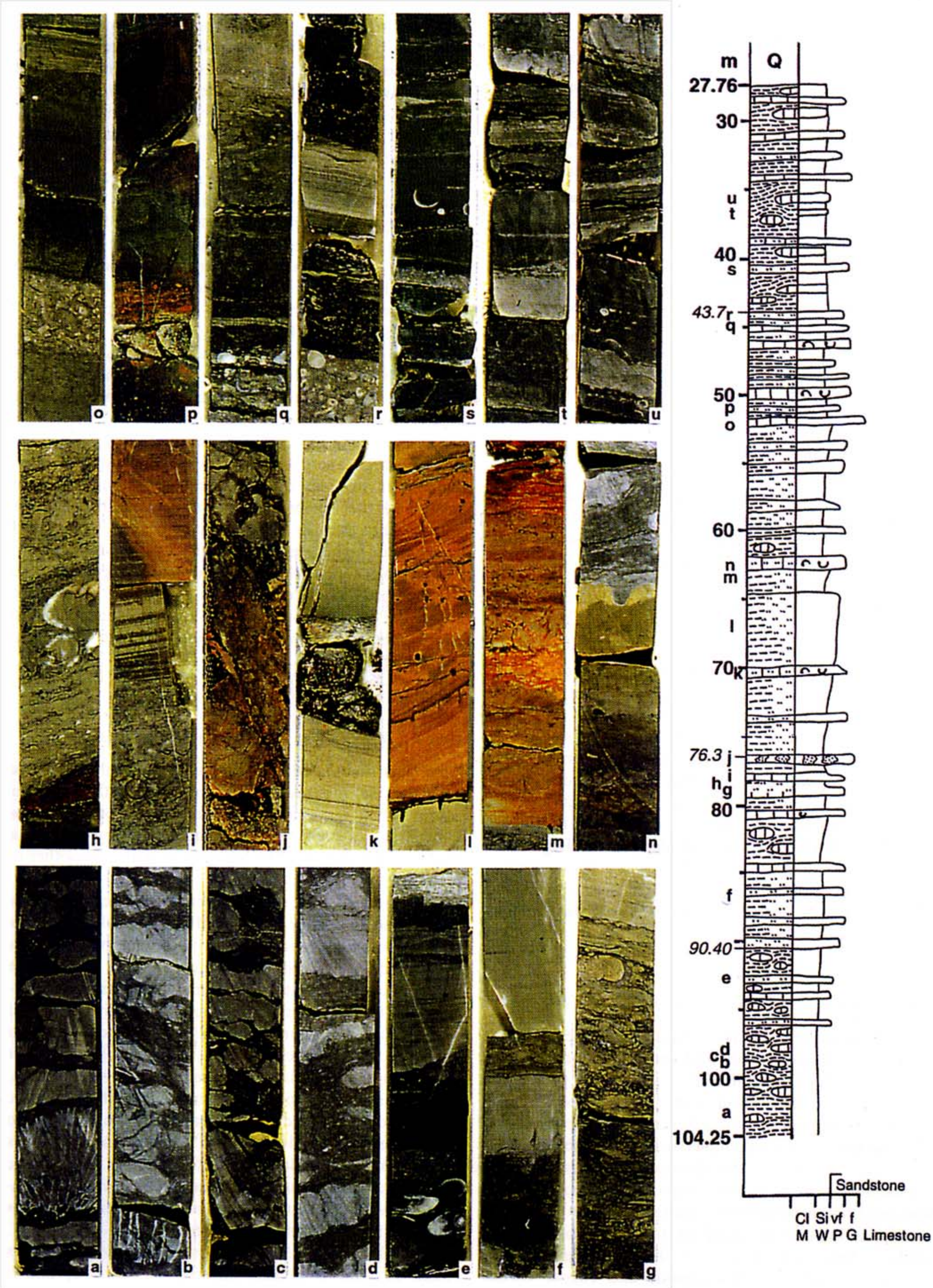
The high fossil diversity dominated by forms tolerating sporadic high energy demonstrates deposition in open marine environments. The weak coarsening-upward trend and the higher content of coquina beds in the upper rather than in the lower part of the unit suggest exposure to higher energy conditions. The ?storm generated couplets, possibly micritized fossil fragments, and coquina beds all show that the deposition took place above the storm wave base. No change in depositional environment is apparent across the tectonic breccia in the top of Unit B.

Unit C, 76.3–43.7 m (Upper Ashgill, Hirnantian)

Unit C is dominated by siltstone beds similar to those occurring in the underlying unit, but with a lighter colour. There is a change in log response from below, as Unit B shows higher sound velocity and lower gamma readings than Unit C. The log pattern is also smoother in Unit B than in Unit C.

Siltstone beds up to two metres in thickness show planar and low-angle cross-bedding. Several beds show couplets of packstone, often with brachiopod coquina beds grading upwards to siltstones. Such beds often contain sandy limestones. Dominant fossils are brachiopods (many fragmentary), both as coquina beds and as individual fossils, and crinoidal debris which may form pack- and grainstones. Rugose corals are present, but they are not as abundant as in the units below and above. Bryozoans and gastropods are minor constituents, while trilobite, ostracod and bivalve fragments are observed in thin-sections. Towards the top of the unit, limestone beds become more abundant while the number of siltstone beds decreases. Bioturbation, chiefly *Chondrites*, is abundant in the shales. In the siltstones, bioturbation increases towards the top of individual beds.

A similar shallow shelf depositional environment as found in Unit B is also inferred for Unit C, and a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continuous regressive development from Unit A through Units B and C is suggested.

Unit D, 43.7–27.76 m (Llandovery, Rhuddanian–Aeronian)

Unit D is dominated by shale with some thin limestone and siltstone beds. Planar lamination dominates, with occasional ripple drift lamination. The limestone beds and lenses are often rich in fossil debris. Rugose corals and brachiopods are the dominant fossils, although crinoid debris may dominate in individual beds. One bed with abundant gastropods is present, and a few tabulate corals occur. In thin-sections, trilobite, ostracod and bryozoan fragments are also observed. Bioturbation is sparse.

This shale-dominated unit contains thin beds of limestone often enriched with fossil debris. The fauna is dominated by brachiopods, particularly *Stricklandia lens*, a brachiopod that is the key fossil of the *Stricklandia* community of moderately deep shelf in Lower Silurian clastic sediments as defined by Ziegler (1965) and Ziegler et al. (1968a). Both the fossil content and the lithology are very similar to the age-equivalent Solvik Formation of the Oslo Region (Worsley et al. 1983). At the transition from Unit C to Unit D, the silt/sandstones mostly disappear and the limestones are mostly wackestones, indicating a transgression.

Biostratigraphy

Core 13/2-U-2 was analysed for brachiopods (L. R. M. Cocks), corals (B. E. E. Neuman), conodonts (H. A. Nakrem) and palynomorphs, i.e. acritarchs, chitinozoans and spore-like microfossils (M. Smelror). Brachiopods and corals occur at various levels throughout the core, while conodonts have only been recovered from the upper part (upper Unit C and Unit D). Acritarchs and chitinozoans are found through the whole core, but fairly diverse assemblages are restricted to Units C and D. Range charts of the brachiopods, corals, conodonts and palynomorphs are presented in Figs. 6, 8, 10 and 12, while illustrations of selected species are shown in Figs. 7, 9, 11 and 13. PMO-numbered fossils are housed in the type collection at the Palaeontological Museum, University of Oslo. Core sections are housed in the IKU Petroleum Research collection, Trondheim. The macrofaunas and palynomorphs indicate that Unit A and Unit B are of early Late Ashgill age (Rawtheyan), while Unit C is of latest Ashgill age (Hirnantian). For Unit D, both the macrofaunas and the microfossils definitely indicate an early Llandovery (Rhuddanian) age, possibly just extending into the succeeding Aeronian Stage.

104.25 (TD)–90.4 m: Unit A, Upper Ashgill (Rawtheyan)

The presence of the corals *Streptelasma primum* at 99.64 m (Fig. 9d) and *Grewingkia bucceros* at 93.88 m (Fig. 9e) (both widespread guide fossils in Baltoscandia) indicates a Rawtheyan, i.e. early Late Ashgill age. Other characteristic Upper Ordovician species found within this Unit include *Grewingkia anguinea*, *Bodophyllum enthum* (Fig. 9b and c), *Densigrewingkia pyrgoidea* (Fig. 9g) and tabulate corals of the genera *Plasmoporella* (Fig. 9a) and *Catenipora*. The brachiopods *Rostricellula*? sp., *Eo-*

Fig. 5. Selected core slabs from borehole 13/2-U-2. All core slabs are 50 mm wide. All depths in core represent base of photo. (a) 102.74 m. Sediment draped, partly crushed *Catenipora* sp. coral in life position? Micritic limestone nodules have partly been modified by compaction. Shale laminae bend around nodules. Water escape and compaction structures (↓), calcite filled cracks (⇓) and the breakage of the coral indicates very early diagenetic cementation. (b) 99.00 m. Sediment draped, partly broken *Catenipora* sp. coral in the lower part. Shale laminae (↓) bent around micritic laminae, demonstrating early diagenetic cementation and compaction. (c) 97.62 m. Micritic and biomicritic limestone nodules commonly surrounded by bent shale laminae. Several nodules are trace fossil infillings (↓). Sparitic fracture infillings in the nodules (⇓) terminate against the shale which may be compacted into the fracture surface indicating very early formation. (d) 96.95 m. Micritic limestone nodules in shale matrix. Water escape structures (↓), and bent shale laminae are the results of compaction during early diagenesis. (e) 93.25 m. The rugose corals *Bodophyllum euthum* and *Densigrewingkia pyrgoidea* have been transported before deposition. Above the corals a fossiliferous wackestone contains fragments of echinoderms, corals and brachiopods. *Chondrites* are abundant in this shale (c). A rippled sandstone occurs in the upper part of the photo. Calcite veins penetrate the siltstone, under and overlying, shale and is of young age. (f) 86.96 m. The sandstone bed in the middle of the photo has a gradational, bioturbated base with shell fragments. The upper The upper very fine-grained sandstone bed is planar laminated. (g) 79.00 m. Strongly bioturbated sandstone and shale with many fossil fragments. The circular burrow in the upper part is crowded with *Chondrites*. (h) 78.55 m. At the base the sandstone is totally bioturbated by *Chondrites*. The sandstone is overlain by a packstone/grainstone with crinoid ossicles, brachiopods, gastropods, corals and with a bryozoan debris, and a few large cephalopods, the last of these with geopetal sparite infilling. (i) 77.97 m. A sandy coral-brachiopod packstone is resting with an erosional base on laminated sandstone (boundary close to the letter (i). The packstone is abruptly overlain by (multi-coloured) sandstone. (j) 76.63 m. Sandstone and limestone breccia penetrated by abundant thin calcite veins. (k) 69.97 m. Planar laminated calcareous siltstone–very fine-grained sandstone interrupted by a burrowed shale. The burrows (*Chondrites*) are filled with sandstone. At top, with sharp base, a coquina bed has sandstone matrix. (l) 66.92 m. Laminated calcareous siltstone. Note that the colour variations follow variations in porosity along laminae and fractures. (m) 63.65 m. Colour variations in a calcareous siltstone. Different colours follow lamination, fractures and fossil fragments and display different porosity. (n) 62.69 m. Multi-coloured calcareous siltstone overlain by shale with sand-infilled burrows. At top a packstone shows compaction phenomena forming a nodule. (o) 52.80 m. A crinoidal–brachiopod packstone/grainstone in a moderately bioturbated siltstone. At top a laminated siltstone. (p) 50.93 m. Green and red moderately bioturbated (*Chondrites*) siltstone. A coquina bed of brachiopod and crinoid fragments (reddened) occur on top of the two small core fragments. (q) 44.97 m. Partly dissolved fossils fragments (corals, crinoid(s) form packstone beds in the lower part. The overlying shale grades into fossiliferous wackestone forming a poorly defined nodule. (r) 44.62 m. At base a packstone bed is dominated by crinoid columns and corals. A very fine-grained sandstone bed has horizontal lamination in the lower part and ripples towards the top. The bed is surrounded by shale with *Chondrites*. (s) 40.96 m. Thin packstone beds in a calcareous shale. Dissolved fossils often occur at the top of limestone beds. Note the partly dissolved rugose coral *Rhegmaphyllum* sp. (t) 36.53 m. Wackestone (in the lower part) and packestone (upper part) beds in calcareous shale. Note water escape structures (↓) and compaction phenomena at the boundary between the limestone beds and the shale, giving the limestone a nodular shape. (u) 35.68 m. Several coquina beds with brachiopod and coral fragments in calcareous shale. Several fossil fragments are partly dissolved.

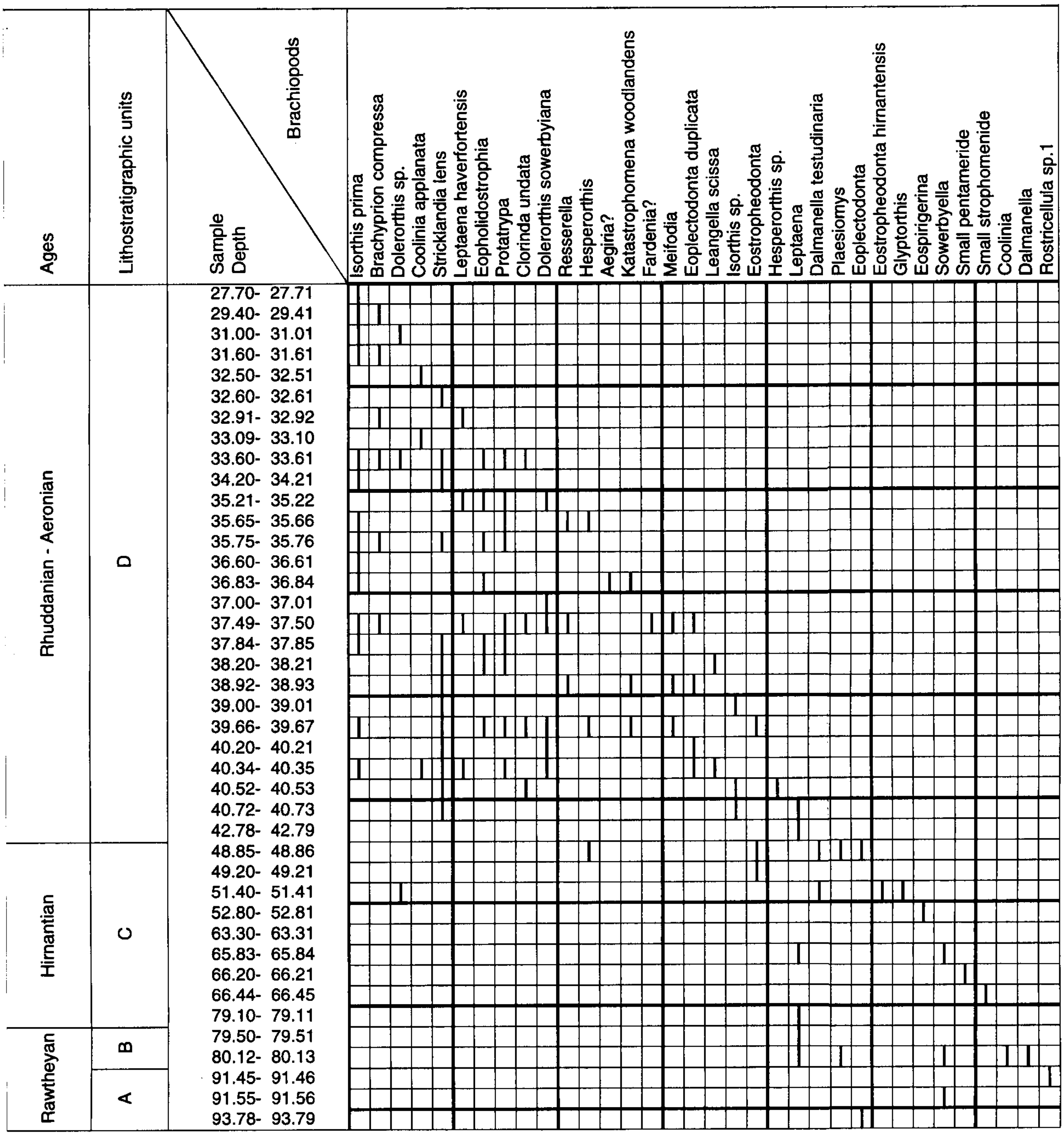


Fig. 6. Distribution chart of brachiopods in core 13/2-U-2.

plectodonta sp. and *Sowerbyella* sp. were recovered from Unit A, but none of them are age-diagnostic forms, except that *Sowerbyella* does not extend upwards into the Silurian.

The low diversity palynomorph assemblages found in Unit A contain acritarchs such as *Baltisphaeridium archaicum*, *Diexallophasis denticulata*, *Goniosphaeridium polygonale*, as well as representatives of the genera *Leiosphaeridia* and *Micrhystridium*. Chitinozoans of the genera *Ancyrochitina* and *Conoclutina* are also present. No conodonts were found in Unit A.

90.4–76.3 m: Unit B, Upper Ashgill (Rawtheyan)

The coral fauna found in Unit B is comparable to that of Unit A, although the Rawtheyan key species *Streptelasma primum* and *Grewingkia buceros* were not present. The brachiopods *Sowerbyella* sp., *Dalmanella* sp., *Leptaena* sp., *Coolinia* sp. and *Plaesiomys*? sp. occur at 80.12 m. The presence of the last-mentioned species supports the Ashgill age as suggested by the corals.

The low-diversity palynomorph assemblages recovered from Unit B contain mainly *Leiosphaeridia* spp., *Lophos-*

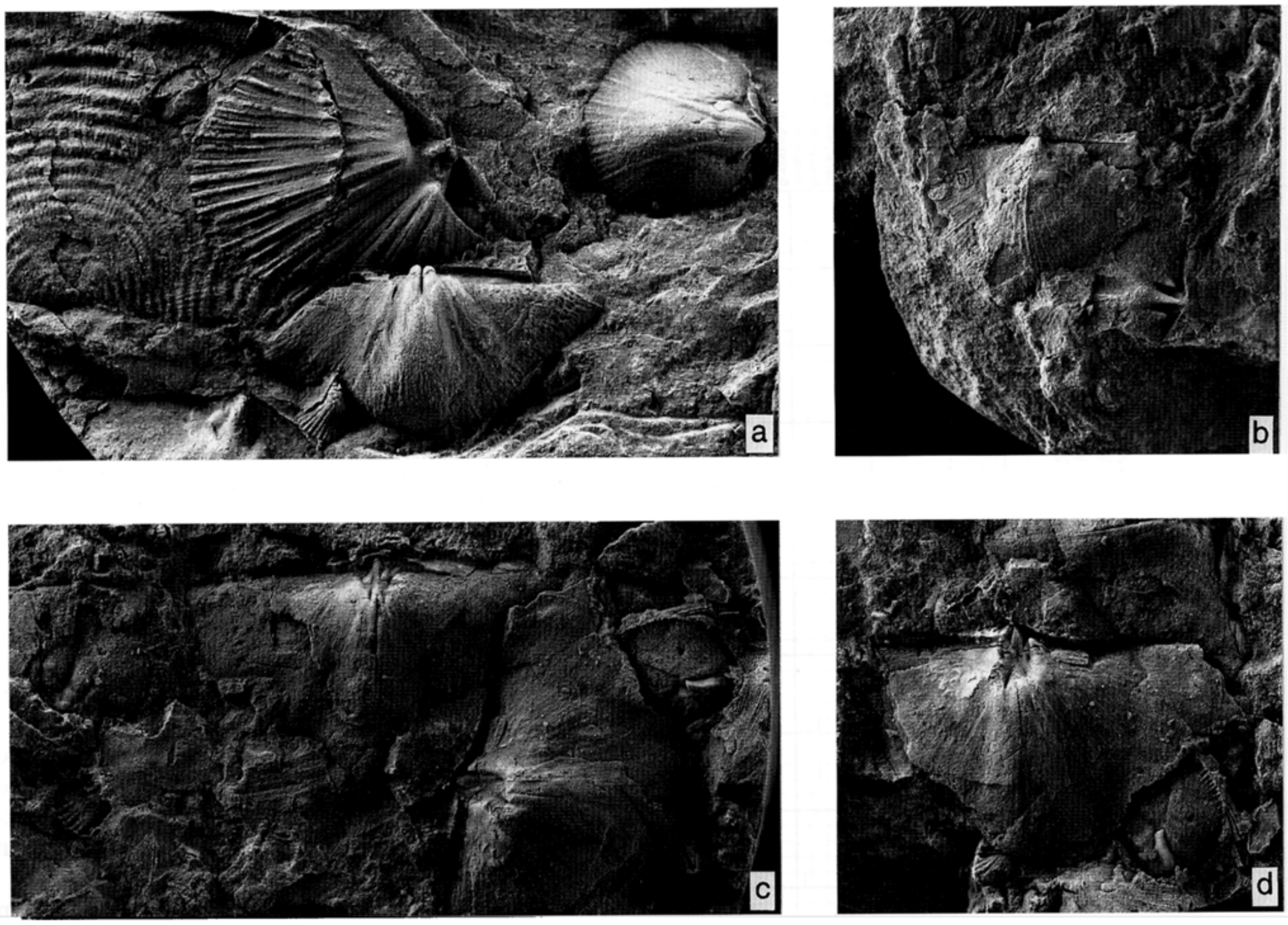


Fig. 7. Early Llandovery (Late Rhuddanian) brachiopods form Unit D: (a) *Eoplectodonta duplicata* ventral internal mould (lower centre), *Dolororthis sowerbyiana* dorsal internal mould (upper centre), *Leptaena haverfordensis* dorsal external mould (left), *Isorthis prima* ventral internal mould (upper right), depth 40.34 m, PMO 139.899, ×3. (b) *Eopholidostrophia sefinensis ellisae* ventral internal mould (upper centre), *Stricklandia lens lens* dorsal internal mould (right), depth 33.60 m, PMO 139.900, ×4. (c, d) *Stricklandia lens lens*, dorsal internal moulds (two views of the same slab), *Isorthis prima*, dorsal internal mould (Fig.c, left), depth 37.75 m, PMO 139.901, ×3.

phaeridium spp., *Micrhystridium* spp., *Goniosphaeridium polygonale* and ?*Ammonidium* sp. A. No conodonts were found in Unit B, but a few pyritic ostracods are present (i.e. at 85.60–86.10 m and 78.10–79.50 m).

76.3–43.7 m: Unit C, Upper Ashgill (Hirnantian)

The coral faunas occurring between 66.30 m and 43.89 m clearly represent a latest Ashgill (Hirnantian) age, characteristic species being: *Bodophyllum duncanae* (Fig. 9h–j), *Ullernelasma svarteoyensis* (Fig. 9k–m), *Densigrewingkia pyrgoidea* and *Helicelasma* sp. A (Fig. 9n–q).

The brachiopod faunas recovered from 48.85 m, 49.20 m and 51.40–51.55 m represent a *Hirnantia* community of latest Ashgill (Hirnantian) age. Characteristic species are *Eostropheodonta hirnantensis*, *Dalmanella* aff. *testudinaria* and *Hesperorthis* sp. *Hirnantia* itself has not been definitely identified, but fragments at 48.90 m may be attributable to that genus.

One bulk sample representing the beds between 48.90 m and 50.30 m yielded the conodonts ?*Distomodus* sp., *Panderodus* sp. and *Phragmodus* sp. *Phragmodus* is a typical Middle to Upper Ordovician genus, and its presence supports the Ashgill age as suggested by the macrofaunas. A significant increase in the abundance and diversity of acritarchs is recognized within Unit C.

Characteristic species restricted to Unit C are aff. *Coryonisphaeridium* sp., *Petaloferidinium* sp., *Ammodinium* sp., *Peteinosphaeridium* cf. *intermedium*, *Peteinosphaeridium velatum*, *Multiplicisphaeridium bifurcatum*, *Rhopaliophora* sp. A, *Acanthodiacrodiunium* sp. I, *Orthosphaeridium insculptum* and *Tunisphaeridium caudatum*, while *Baltisphaeridium archaricum* and *Multiplicisphaeridium irregulare* do not range above this unit. The biostratigraphic significance of these species is poorly documented. However, according to Jacobsen (1987) *M. bifurcatum* and *M. irregulare* are good guide fossils for the Upper Ordovician and support an Ashgill age for Unit C. The presence of Gen et sp. nov. cf. *Rhopaliophora* sp. (*sensu* Martin 1988) at 48.72 m might be of special interest. According to Martin (1988), this species is restricted to Hirnantian strata on Anticosti Island (eastern Canada). Martin also reports that *Orthosphaeridium insculptum* is not known to range above the Hirnantian.

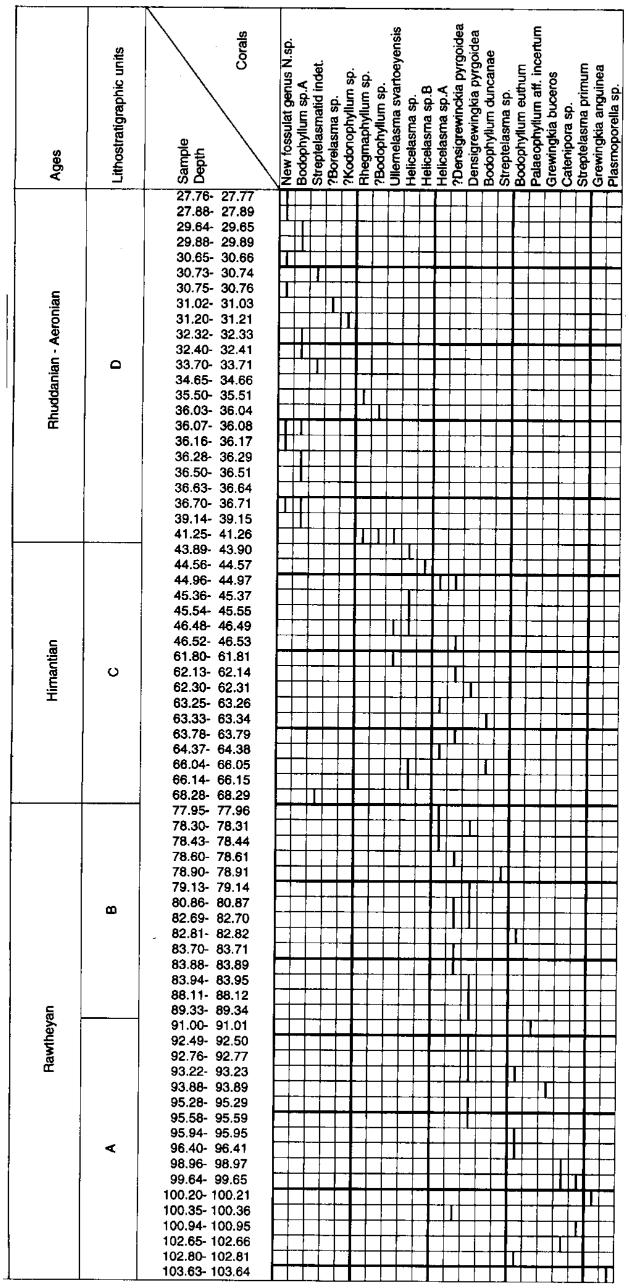


Fig. 8. Distribution chart of corals in core 13/2-U-2.

43.7–27.76 m: Unit D, Llandovery (Rhuddanian–Aeronian)

The corals found from 39.14 m to the top of the core seem to represent the Early Llandovery (i.e. upper Rhuddanian–lowermost Aeronian stages). Characteristic taxa are the new fossulat gen. n. sp. (Fig. 9z–ø) (called *Steptelasma* sp. a by Neuman 1982, p. 34) and *Bodophyllum* sp. a (Fig. 9u–v), which are well known from the Lower Llandovery of the Oslo Region (Neuman 1982).

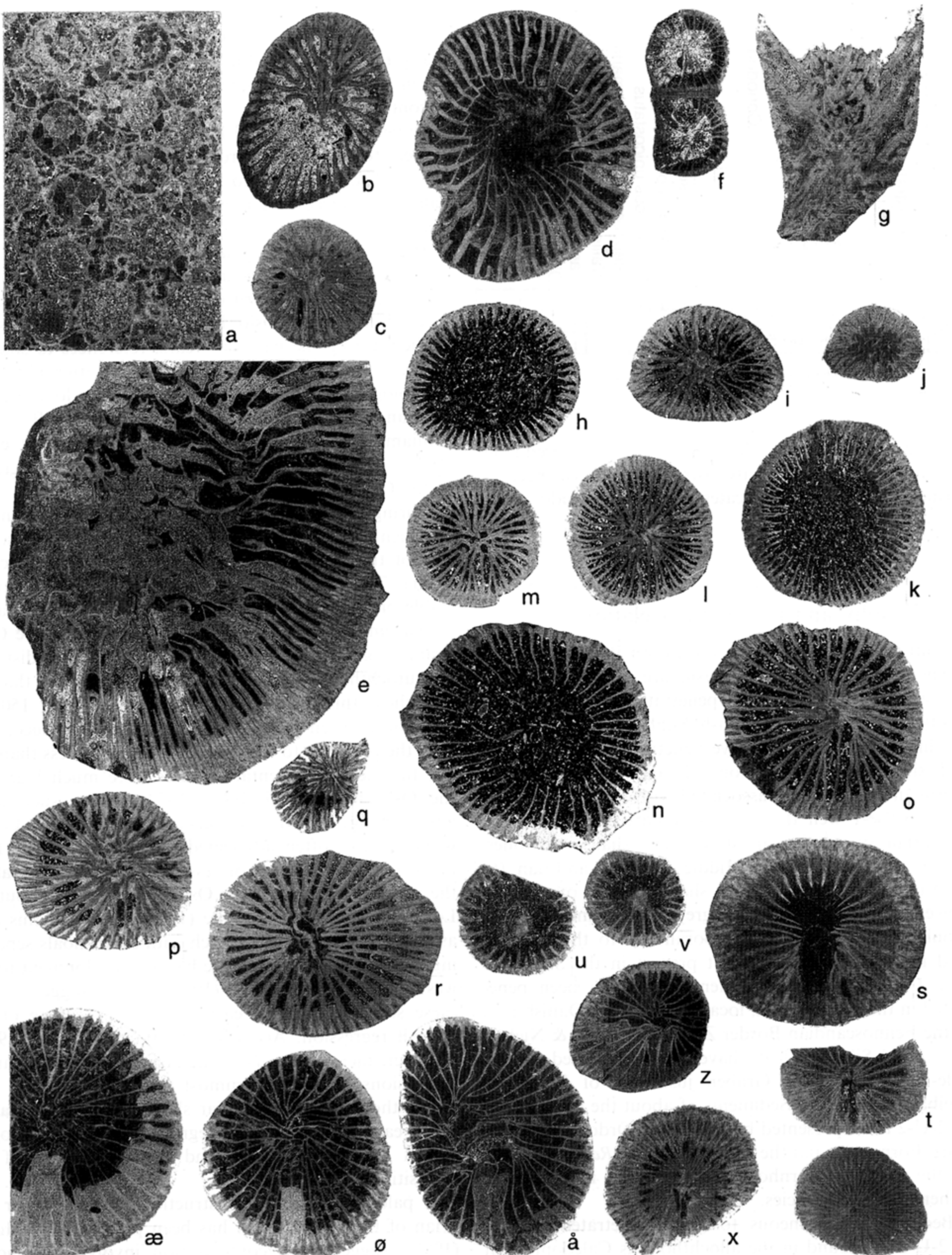
Unit D contains well-preserved and common brachiopods. The species *Stricklandia lens* is recorded from 40.62 m to 33.60 m and is a good Early Llandovery marker (Williams 1951; Cocks 1971; Baarli 1986). The subspecies (Fig. 7) is probably *S. l. lens*, rather than the earlier *S. l. prima* or the later *S. l. intermedia.* Brachiopods from the *Stricklandia–Costistricklandia* lineage are well represented in the Early Silurian of the Oslo Region (Baarli & Johnson 1982), where *Stricklandia lens lens* occurs in the later Rhuddanian and possibly into the earliest Aeronian. Other characteristic Lower Llandovery brachiopods found in Unit D are *Clorinda undata*, *Dolerorthis sowerbyiana*, *Eoplectodonta duplicata*, *Brachyprion compressa* and *Katastrophomena woodlandensis.*

A bulk sample representing the beds between 45.50 m and 42.20 m yielded the condononts *Distomodus kentuckyensis* and *Panderodus unicostatus.* The former species is a faunal element of the Lower Llandovery *Icriodella discreta–I. deflecta* Assemblage Zone defined in the Welsh Borderland (Aldridge 1972). It is also characteristic of the *Distomodus kentuckyensis* Zone recognized in the Lower Llandovery of the Oslo Region (Nakrem 1986).

The bulk sample representing the beds between 38.7 m and 40.0 m yielded the conodonts *Icriodella discreta* and *Ozarkodina oldhamensis.* Both are known to range across the Rhuddanian–Aeronian boundary in the British Isles (Aldridge 1985). The former species defines the *Icriodella discreta–I. defecta* Assemblage Zone of Aldridge (1972). The additional species reported from the sample (*?Oulodus* sp., *Panderodus unicostatus*, *Panderodus* sp., *Pseudooneotodus beckmanni* and *Wallliserodus* sp.) are all previously reported from Lower Silurian sediments of the Oslo Region (Aldridge & Mohamed 1982).

The palynomorph assemblages found in Unit D appear closely related to those reported from the Llandovery of the Oslo Region (Smelror 1987). Common taxa are *Micrhystridium stellatum* group, *Veryhachium wenlockium* and *Leiosphaeridia* spp. Most of the species found in Unit D are known to range through the Lower and Middle Silurian, and none of the biostratigraphic key species used in the acritarch zonation schemes of Hill

Fig. 9. Late Ordovician and Early Silurian rugose and tabulate corals from core 13/2-U-2. All figures, with the exception of 9g, are transverse sections. Fig. 9g is a longitudinal section. All transverse sections of rugose corals are orientated with the cardinal septum downwards. Fig. 9a is enlarged ×6, f, u and v are ×4, and all other figs. are ×3. Corals from Rawtheyan, Unit A: (a) *Plasmoporella* sp., PMO 152.674, depth 103.63. (b–c) *Bodophyllum euthum*, PMO 152.675, depth 102.80 m. (d) *Streptelasma primum*, PMO 152.676, depth 99.64 m. (e) *Grewingkia buceros*, PMO 152.677, depth 93.88 m. (f) *Palaeophyllum* aff. *incertum*, PMO 152.678, 91.00 m. From Rawtheyan Unit B: (g) *Densigrewingkia pyrgoidea*, PMO 152.679, depth 83.94 m. From Hirnantian, Unit C: (h–j) *Bodophyllum duncanane*, PMO 152.680, depth 63.33 m. (k–m) *Ullernelasma svartoeyensis*, PMO 152.681 (k) is sectioned through the calice showing the cardinal septofossula, depth 63.33 m. (n–q) *Helicelasma* sp. A., PMO 152.682 (n) is sectioned through the calice, depth 63.25 m. (r) *Helicelasma* sp. B. PMO 152.683, depth 44.56 m. From Rhuddanian–Aeronian, Unit D: (s–t) *Rhegmaphyllum* sp., (s) PMO 152.684, and (t) PMO 152.685, both specimens from depth 40.78 m. (u–v) *Bodophyllum* sp. A, PMO 152.686, (u) is sectioned through the calice showing the calicular boss, depth 39.14 m. (x–y) *Rhegmaphyllum* sp., PMO 152.687, depth 36.50 m. (z–ø) New fossulate genus, n.sp. (probably two different species are included), (z) PMO 152.688, depth 36.07 m. (æ–ø) PMO 152.689, depth 30.75 m and (å) PMO 152.690, depth 27.76 m.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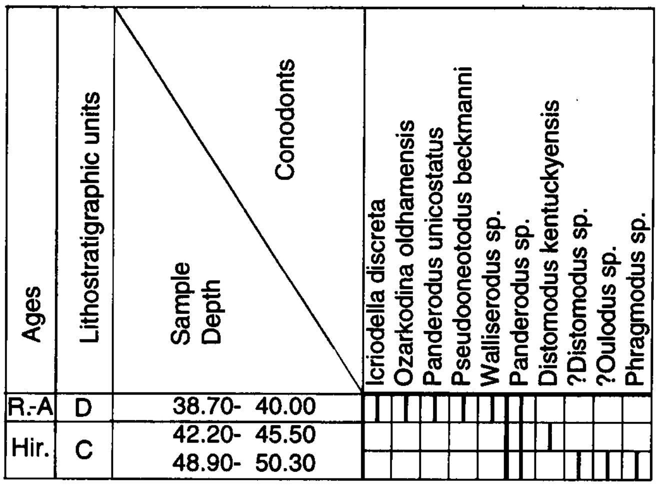

Fig. 10. Distribution chart of conodonts in core 13/2-U-2.

& Dorning (1984) or Smelror (1987) were recovered from this unit. Based on the palynostratigraphic evidence, the acritarch assemblage indicates a general Rhuddanian–Aeronian age for Unit D.

Stratigraphy and regional correlations

The lithology and distribution of Lower Palaeozoic rocks in the Norwegian–Danish Basin are poorly known as few wells in the area have penetrated pre-Triassic deposits. In the onshore Danish Subbas wells, Rønde-1, Nøvling-1 and Slagelse-1 have penetrated Silurian shales and siltstones. In the Rønde-1 and Nøvling-1 wells ?Permian volcanics are associated with the sediments. In the Slagelse-1 well the lowermost part contains Lower Cambrian quartzitic sandstones and shaley siltstones. These are succeeded by Middle–Upper Cambrian (to lowermost Ordovician?) Alum shale, which is overlain by Lower Silurian (Telychian) grey shales and siltstone (Poulsen 1974). Beds contemporaneous to those recovered in core 13/2-U-2 are not present in the Slagelse-1 well. Cambro-Silurian sediments have also been penetrated in the Terne-1 well, located within the Danish part of the Fennoscandian Border Zone (Michelsen & Nielsen 1991), and Silurian strata have been penetrated in Pernille-1 in the Rønne Graben just west of Bornholm (Vejbæk et al. 1994). Sediments of about the same age as 13/2-U-2 are represented by the Upper Ordovician Tommarp Formation and the Lower Silurian '*Rastrites*-shale' on the island of Bornholm, but these are in graptolitic rather than shelly facies.

Beds contemporaneous to those penetrated in core 13/2-U-2 are found in the allochthonous Caledonides at Stord, western Norway. There, the Dyvikvågen Group comprises Ashgill limestones and phyllites of the Limbuvik Formation and graptolitic shales of Early Llandovery age are assigned to the Vikanes Formation and the overlying polymict conglomerates of the Utslettefjell Formation (Thon et al. 1980). According to Thon et al. (1980) the Dypvikvågen Group is resting on the Nonshaug Formation basaltic greenstones; the boundary between these successions represents a major stratigraphic unconformity.

Upper Ordovician and Lower Silurian deposits closely related to those recovered in core 13/2-U-2 are well known from the Oslo Region. There, the Lower Palaeozoic succession is exposed within a NNE–SSW-trending graben which developed mainly during the Carboniferous and Permian. The Lower Palaeozoic sequences are exposed throughout the region between Permian intrusive and extrusive complexes. The Palaeozoic successions of the Oslo Region have been extensively studied during the past 150 years; references to some of the most important contributions on stratigraphy, sedimentology and palaeontology of the Ordovician and Silurian can be found in Owen et al. (1990), Bruton & Williams (1982), Worsley (1982), and Worsley et al. (1983). Latest Ordovician and early Silurian stratigraphy in the Oslo Region is presented in Fig. 14.

During the Lower Palaeozoic the Balto-Scandian epicontinental sea covered an extensive area east and southeast of the Caledonian Front region in western Scandinavia. The Ordovician sedimentation extended from a stable platform in the Balto-Scandian area which passed into a lime mud deposition on the foreland in the Oslo-Scania region and westward for an unknown distance. Parautochthonous sediments along the edge of the fold belt show this distance to have been at least 150 km (Bruton & Owen 1982). While the Ordovician succession over the platform to the east is thin (usually less than 200 m), the mean sedimentation rates were much higher in the Oslo Region (Bjørlykke 1974), where successions approaching 1000 m in thickness are known. Earlier workers have often advocated the presence of a 'Telemark Land' as a more or less permanent feature along the western margins of the Oslo Region throughout the Lower Palaeozoic. Bjørlykke (1974) envisaged this area as consisting of a positive arch with sand shoals separating the Oslo Region from the basinal development to the west. Brenchley & Newall (1977) further suggested that these shoals prograded eastwards in the course of the Ashgill regression. According to Worsley et al. (1983), however, facies patterns in the Ashgill and Rhuddanian successions of the easternmost Oslo District may also reflect the presence of similar shoals over positive areas to the east, with the Ashgill regression producing progradation over both western and eastern margins of the depositional basin.

A paleogeographic reconstruction for the Lower Silurian of the Oslo Region has been presented by Møller (1987), suggesting a configuration involving an active orogenic belt to the north, an open basin to the west, and an intracratonic land area or structural high to the east of the depositional area. Towards the south and southeast, the Oslo basin was probably connected with the large epicontinental sea, in which the Lower Silurian

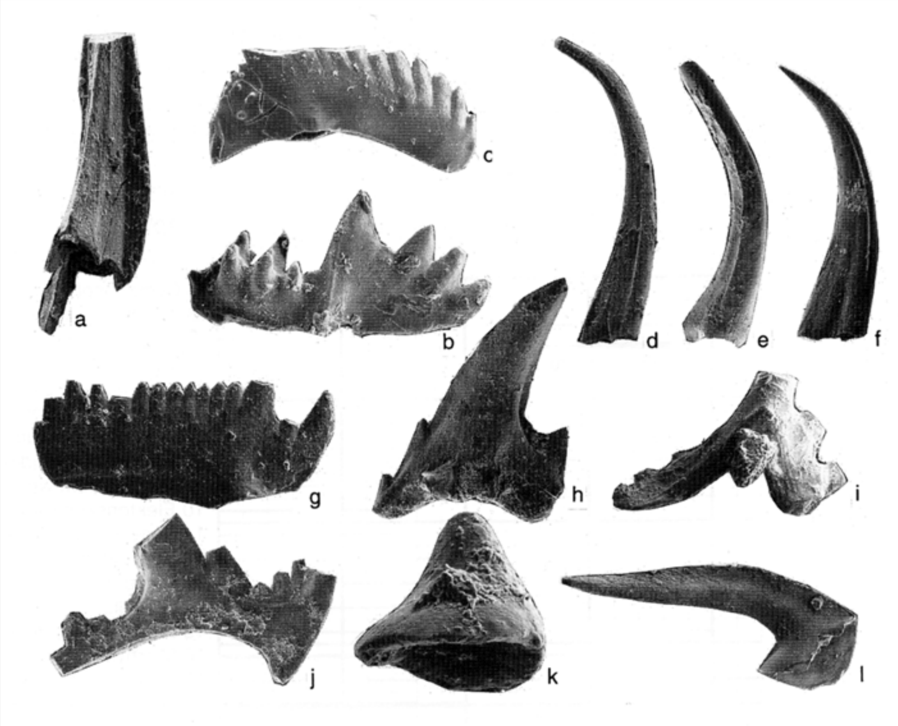

Fig. 11. Early Silurian (1–9, 11) and Late Ordovician (10 and 12) conodonts from core 13/2-U-2. (a) *Walliserodus* sp. depth 38.7–40.0 (m) PMO 142.562/6, ×150. (b) *Icriodella discreta*, Pa-element. Depth 38.7–40.0 m. ×100, PMO 142.562/1. (c) *Ozarkodina oldhamensis*, Pa/Pb-element. Depth 38.7–40.0 m. ×115, PMO 142.562/2. (d) *Panderodus unicostatus*. Depth 38.7–40.0 m. ×100, PMO 142.562/12. (e) Indet simple cone conodont. Depth 38.7–40.0 m. ×70, PMO 142.562/5. (f) Indet simple cone conodont. Depth 38.7–40.0 m. ×100, PMO 142.562/8. (g) *Ozarkodina oldhamensis*, Pa/Pb-element Depth 38.7–40.0 m. ×130, PMO 142.562/3. (h) ?Pb-element, *Distomodus kentuckyensis* or *Icriodella discreta*. Depth 38.7–40.0 m. ×130, PMO 142.562/4. (i) *Ozarkodina oldhamensis*, ?Sa-element. Depth 38.7–40.0 m. ×130. Lost during SEM photography. (j) ?*Oulodus* sp., ?Sc-element. Depth 48.9–50.3 m. ×130, PMO 142.564/10. (k) *Pseudooneotodus beckmanni*. Depth 38.7–40.0 m. ×200, PMO 142.562/11. (l) *Phragmodus* sp. Depth 48.9–50.3 m. ×40, PMO 142.564/2.

succession of Balto-Scandia was deposited. This model was, however, questioned by Baarli (1990) pointing out evidences for open marine environments and contemporaneous deposition of graptolite shales further east in Västergötland. On the basis of detailed bathymetric analyses, Baarli (1990) concluded that the Lower and Middle Llandovery succession of the Oslo Region shows signs of a transitory uplift which advanced from the present north–northwest across a gently east-sloping epicontinental shelf. Baarli suggests that during earliest Rhuddanian until early Telychian times sedimentation was influenced by a foreland basin with a peripheral bulge, developing in the present northwest and moving obliquely down to the epicontinental slope. Its toe reached the central Oslo District by earliest Llandovery time (Baarli 1990).

Llandovery sediments are found in the upper allochthonous units (Vikanes Formation) on Stord and Karmøy (Færseth & Steel 1978). The transport of the Scandian nappes in the southwestern Norwegian Caledonides is assumed to have taken place in the Late Silurian (Bryhni & Sturt 1985), and according to Møller (1987) the presence of the allochthonous transgressive marine earliest Silurian deposits in western Norway indicates that the eastern margin of the advancing continental mass was still more than 300 km to the west of the Oslo Region in Llandovery time.

The location of core 13/2-U-2 is interpreted to be on the foreland area between the developing Caledonide orogenic zone to the west and the cratonic areas further east on the Baltic Shield. Unit A (and possibly lower Unit B) in core 13/2-U-2 corresponds roughly to the Bønsnes Formation in the Ringerike area, the upper part of the Herøy Limestone in Skien–Langesund, the Husbergøya Formation and the lower part of the Langåra Formation in Asker, and to the Kalvsjø Formation in Hadeland. Generally, the Ashgill succession in core 13/2-U-2 resembles that found in the Ringerike area, where the nodular limestones and shales of the Bønsnes Formation pass gradually up into a calcareous sandstone dominated unit, previously known as Etage 5b, now formally assigned to the Langøyene Formation (Owen et al. 1990).

In core 13/2-U-2 there is a comparable change from the nodular limestone and shale Unit A, to the siltstone-dominated Units B and C. Units B and C in 13/2-U-2 may correspond roughly to the Langøyene Formation in Ringerike (see Fig. 14 and Hanken & Owen 1982). According to Owen (1978) this arenaceous unit has broad equivalents in Hadeland (the Skøyen Formation), Oslo (the Langøyene Formation) and in Skien–Langesund. The coral faunas found in Unit C in core 13/2-U-2 are typical of those found in the siliciclastic sediments of the unnamed formation in Ringerike, as well as including taxa from corresponding beds in Asker and Skien–Langesund.

The widespread regression which took place in the latest Ordovician is recognized in the Oslo Region by the development of coarse clastic sediments (Bruton & Owen 1982), and by the regressive sequence of animal communities (Brenchley & Cocks 1982). Brenchley & Newall (1977) argued that these deposits record glacio-eustatic changes. Bockelie (1982), however, suggested that the increase in sedimentation rates throughout the Upper

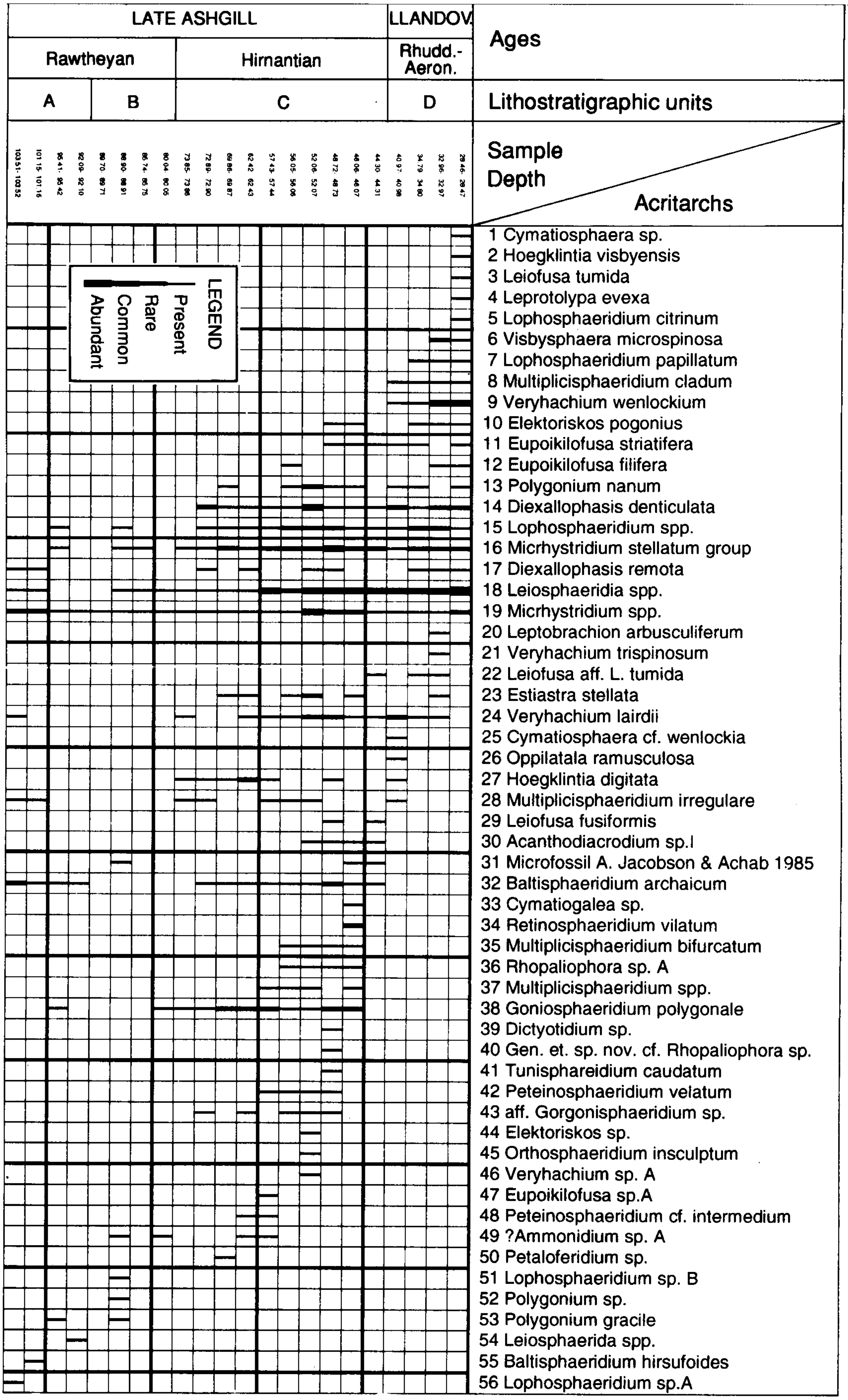

Fig. 12. Distribution chart of acritarchs in core 13/2-U-2.

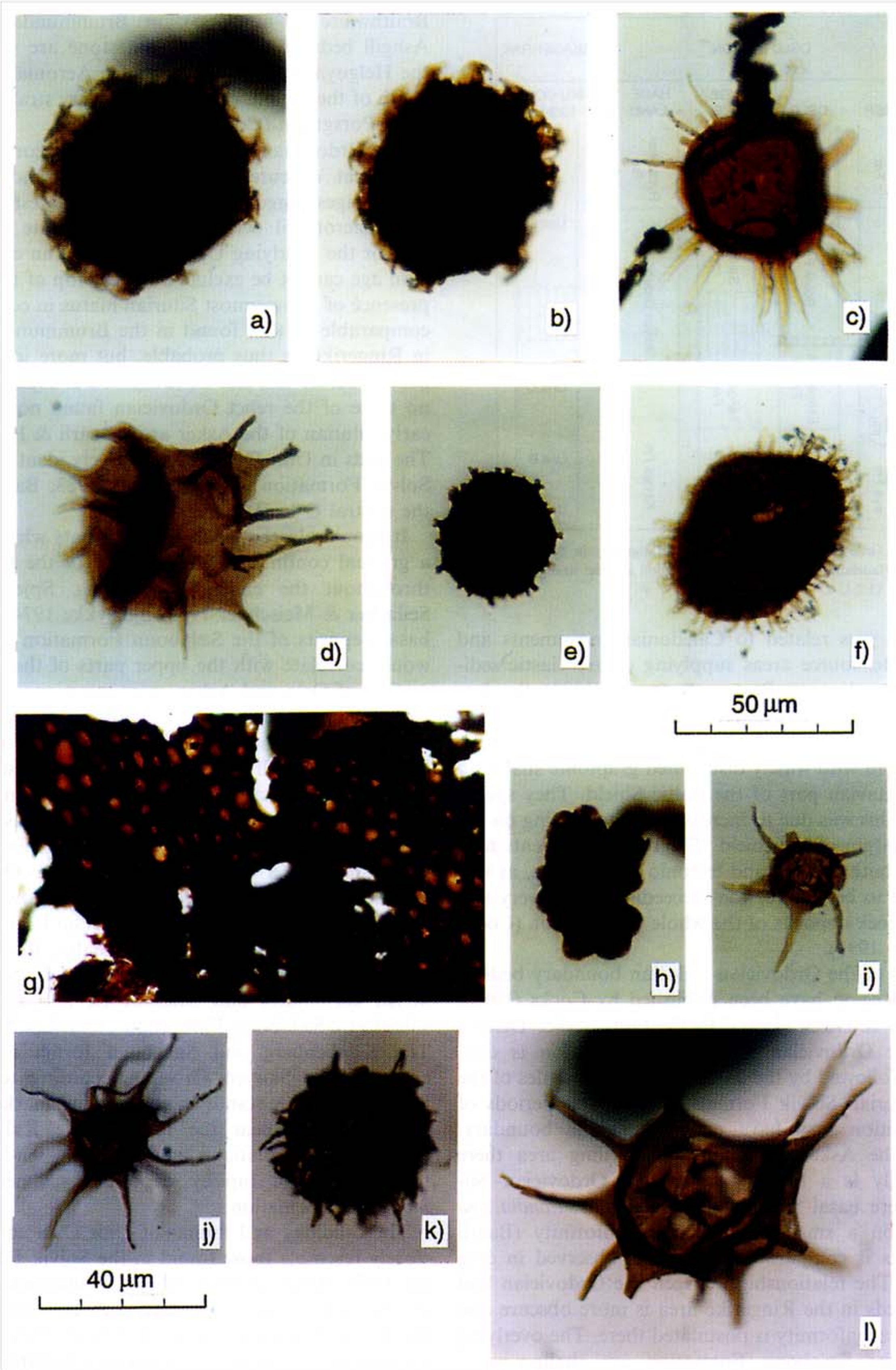

Fig. 13. Early Silurian and Late Ordovician acritarchs from core 13/2-U-2. (a) *Peteinosphaeridium velatum*, 48.72 m, PMO 152.691. (b) *Peteinosphaeridium velatum*, 48.72 m, PMO 152.691. (c) *Baltisphaeridium hirsutoides*, 101.15 m, PMO 152.692. (d) *Goniosphaeridium polygonale*, depth 52.06 m, PMO 152.693. (e) ?*Ammonidium* sp. A, 57.43 m, PMO 152.694. (f) *Rhopaliophora* sp. A, 48.72 m, PMO 152.691. (g) Cuticle-like fragment, 46.06 m, PMO 152.691. (h) ?*Gloecapsamorpha*, 57.43 m, PMO 152.694. (i) *Diexallophasis remota*, 48.72 m, PMO 152.691. (j) *Micrhystridium stellatum* group, 28.46 m, PMO 152.696. (k) *Elektoriskos pogonius*, 28.46 m, PMO 152.696. (l) *Goniosphaeridium polygonale*, 46.06 m, PMO 152.695.

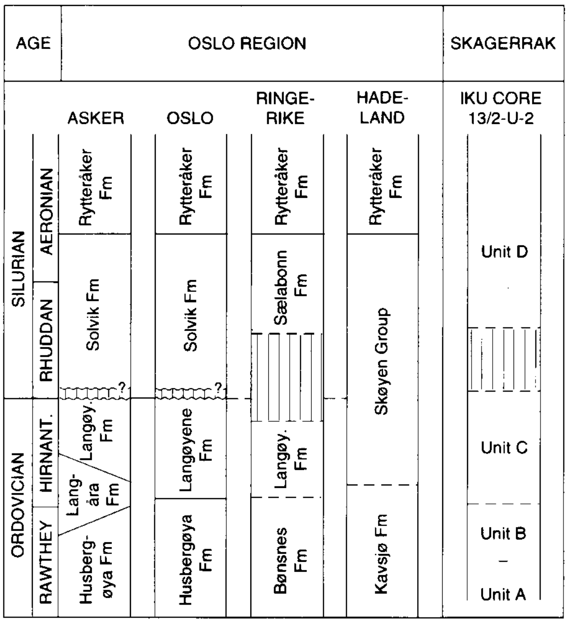

Fig. 14. Latest Ordovician and Early Silurian stratigraphy in the Asker, Oslo, Ringerike and Hadeland districts of the Oslo Region and the stratigraphy of the Skagerrak core 13/2-U-2.

Ordovician was related to Caledonian movements and proximity to source areas supplying coarse clastic sediments. According to Bruton & Owen (1982) the late Ordovician regressive events were separated by phases of sedimentation in relatively deep water, culminating in the early Silurian with widely distributed graptolite shales on the Scandinavian part of the Baltic Shield. They speculated that this was due to increased nappe loading on the western margin of the shield. The regressive events may thus have both eustatic and tectonic components, as was found also to be true for the succeeding Llandovery and early Wenlock deposits of the whole Oslo Region (Cocks & Worsley 1993).

Reviews of the Ordovician–Silurian boundary beds in the Oslo Region have been published by Cocks (1988), and Heath & Owen (1991). In the Oslo–Asker District the Upper Ordovician Langøyene Formation is conformably followed by the basal organic-rich shales of the Lower Silurian Solvik Formation. However, periods of non-deposition may have occurred at the boundary. West of the Asker District in the Sylling area there undoubtedly is a hiatus between the Ordovician–Silurian, where basal Silurian strata with *Strictlandia lens lens* rest on a small-scale karst unconformity (Baarli 1988). This is comparable to what is observed in core 13/2-U-2. The relationship between the Ordovician and Silurian beds in the Ringerike area is more obscure and a local paraconformity is postulated there. The overlying beds of the Sælabonn Formation are shallow-water storm deposits with lenses of displaced shelly faunas (Thomsen & Baarli 1982); their detailed age is indeterminate, but probably includes the later Rhuddanian. In the Hadeland area the Skøyen Group appears to straddle the Ordovician–Silurian boundary (Heath & Owen 1991, Braithwaite et al. 1995); in Brummundal the lower Ashgill beds of the Mjøsa Limestone are succeeded by the Helgøya Quartzite of probable Aeronian age. In the south of the region, earliest Llandovery strata are known from Porsgrunn (Cocks 1988).

The Ordovician–Silurian boundary in core 13/2-U-2 is somewhat obscure. The macrofaunas and microfossil assemblages suggest that Unit C is of latest Ashgill age. The macrofossil evidence indicates a late Rhuddanian age for the overlying Unit D, although an earliest Aeronian age cannot be excluded for the top of the core. The presence of a lowermost Silurian hiatus in core 13/2-U-2, comparable to that found in the Brummundal area and in Ringerike, is thus probable, but more information is needed before this can be confirmed or rejected. There is no trace of the relict Ordovician fauna noted from the early Silurian of the Asker area (Baarli & Harper 1986). The beds in Unit D can be tentatively identified with the Solvik Formation (Worsley et al. 1983; Baarli 1985) in the central Oslo Region.

It should also be noted that accounts which suggested a gradual continuous transgression of the Oslo Region throughout the early Silurian (e.g. Spjeldnæs 1957; Seilacher & Meischner 1964; Bjørlykke 1974) so that the basal deposits of the Sælabonn Formation in Ringerike would correlate with the upper parts of the Solvik Formation of Oslo and Asker, were questioned by Worsley et al. (1983). These authors suggested that marine depositional environments were rapidly established in the Early Rhuddanian in all but the northernmost districts of the region, with coastal deposits of the Sælabonn Formation in western and southern districts passing eastwards into the distal environments of the shale-dominated Solvik Formation. In a recent study Heath & Owen (1991) divided the uppermost Ordovician and lowest Silurian succession in Hadeland into the Kalvsjø Formation comprising nodular limestones and shales, the Hirnautian Klinkenberg Formation forming a heterogenic unit of mixed carbonates and siliciclastics, and the overlying siliciclastic Sælabonn Formation of earliest Silurian age. The Klinkenberg and Sælabonn formations together comprise the Skøyen Group. According to Heath & Owen (1991) low stands in sea level are marked by karst surfaces at or near the tops of the Kalvsjøen and Klinkenberg formations, and a major sea-level rise is reflected in the rapidly deposited sediments of the Sælabonn Formation.

The lithology and faunas of Unit D in core 13/2-U-2 closely resemble those found in the Solvik Formation in the Oslo–Asker district, which is interpreted as being deposited in a moderately deep shelf environment. There the Solvik Formation conformably overlies the Ashgill Langøyene Formation. The Solvik Formation has been dated as spanning the entire Rhuddanian, and there is no evidence of a large hiatus at the Ordovician–Silurian boundary (Fig. 14).

In conclusion, the deposits of core 13/2-U-2 reflect a Late Ashgill regressive event, followed by an Early Llandovery relatively sudden rise in sea level, representing a transgressive event comparable to those observed in the Oslo Region (Johnson & Worsley 1982) and also in the Welsh area in Britain (Ziegler et al. 1968b). Although the Lower Silurian sediments rest conformably on the uppermost Ashgill beds, a hiatus between the uppermost Ordovician and the Lower Silurian might be present, comparable to that observed in the western and northern areas of the Oslo Region.

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