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A Cambrian–Ordovician boundary section in the Rafnes–Herøya submarine tunnel, Skien–Langesund District, southern Norway

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Rock specimens and contained fossils collected in 1976 from a submarine tunnel driven between Herøya and Rafnes in the Skien–Langesund area of southern Norway, have been restudied. The contained fossils include olenid and agnostoid trilobites, graptolites and brachiopods, groups described in detail for the first time from the area and documenting a Cambrian–Ordovician boundary section unique in the district where the upper Cambrian Alum Shale Formation is elsewhere overlain by the Middle Ordovician Rognstranda Member of the Huk Formation (Kundan in terms of Baltoscandian chronostratigraphy). The hiatus at the base of the Huk Formation is thus smaller in the section described herein, beginning at a level within rather than below the Tremadocian. Estimated thickness of the Alum Shale includes 10–12 m of Miaolingian and 20–22 m of Furongian strata with trilobite zones identified, and a Tremadocian section of 8.1 m identified by species of the graptolite *Rhabdinopora* in the basal 2.6 m and *Bryograptus ramosus* at the top. The Tremadocian section is preserved in a postulated zone of synsedimentary subsidence along the Porsgrunn–Kristiansand Fault Zone, while at the same time there was extensive erosion across an emergent, level platform elsewhere in the Skien–Langesund District and the southern part of the Eiker–Sandsvær District to the north. Aspects of stratigraphy and tectonics are highlighted together with a discussion on the Cambrian–Ordovician boundary locally and worldwide.

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Introduction

As a part of the construction phase of the Rafnes petrochemical plant (1974–78) located in the Skien–Langesund District of southern Norway, a submarine pipeline tunnel was driven below the Frierfjorden, connecting the (then) Norsk Hydro (now Yara) industrial plant at Herøya on the eastern shores of the fjord, with the Rafnes site situated on the western shores of the Frierfjorden (Fig. 1). On final completion, the tunnel was flooded and sealed off and thus made inaccessible. Profile details and engineering planning and execution issues of the 3.6 km-long tunnel are given by Lien et al. (1978). The tunnel entrance on the Herøya side started just above sea level and descended through the Cambrian–Ordovician rocks at a rate of 1:6, levelling out within the Precambrian basement 250 m below sea level. The tunnel profile and deep crossing were designed based on geological interpretation of the results of a seismic survey across the Frierfjorden, revealing the water depth of 100 m followed by a 100 m thickness of Quaternary sediments above the basement rocks in the deepest part of the fjord. The anticipated stratigraphy of the Cambrian–Ordovician section relied on the established stratigraphy of the Skien–Langesund District known from the works of Brøgger (1884), Størmer (1953) and Henningsmoen (1960), in particular. These applied the previous numerical "etage" stratigraphic nomenclature, which has now been replaced by formal formation names (see Owen et al., 1990).

During the mining phase (in 1976), one of us (KR) was given the task of mapping the lithological boundaries and faults encountered in the 1400 m-long eastern part of the tunnel for comparison with their anticipated locations.

A characteristic feature of the Cambrian–Ordovician stratigraphy of the Skien–Langesund District, as seen in several outcrops, is the large unconformity between the Cambrian–Ordovician Alum Shale Formation and the overlying Rognstanda Member of the Huk Formation (Volkhovian-Kundan) of Arenig–Llanvirn age (for stratigraphy of the Skien–Langesund area, see Owen et al., 1990). This implies that strata from the uppermost Cambrian, Tremadocian and Arenig–Llanvirn are missing in this district of the Oslo Region. It was therefore a huge surprise when the routine search for fossils in the tunnel wall produced Rhabdinopora graptolites and other Tremadocian graptolites and brachiopods in shales stratigraphically below the thin and characteristic Huk Formation limestone. It now allows the recognition of a Cambrian–Ordovician boundary in the area and narrows the temporal extent of the hiatus in this part of the Oslo Region.
These finds have been only briefly reported earlier (Rønning, 1976, 1978; Nilssen, 1985), hence the detailed documentation in the present paper.

Material and methods

The tunnel investigation was carried out at intermittent periods in 1976 during the excavation of the tunnel and was, in general, hampered by poor light and dirty tunnel walls. Several intervals of cast concrete covering unstable zones obliterated parts of the section. Tunnel length control was by marks installed on the tunnel wall every 50 m, labelling the distance from the tunnel entrance. The formations were mapped by noting the main lithology at each 10 m interval between length marks along the tunnel, while a routine search for fossils was performed to corroborate the stratigraphic position.

In the Alum Shale Formation, all observed limestone concretions were sampled for fossils. Sampling order was by measured tunnel length, taking into consideration the faulting involved and not necessarily by stratigraphic position. However, the concretions were not numerous and several were anthraconitic and barren.

The Tremadocian part of the Alum Shale Formation was sampled stratigraphically every 5 cm, after establishing the datum 0 m at the base of a limestone layer 0.1 m above what subsequently appeared to be the base of the *Rhabdinopora* interval (at –0.1 m). The stratigraphic base of the Huk Formation is at 8.0 m in this sampling scheme, omitting the 1.9 m thick igneous sill (Permian) located within the Tremadocian succession. Barren shale samples were generally not bagged. Each sample size was modest; larger slabs were not possible to break loose.

The tunnel section was also investigated for possible faults and igneous dykes and sills, but the stratigraphic control was commonly not detailed enough to determine the throw on the several minor faults, many of which were covered by concrete. The true stratigraphic thickness of individual formations in the tunnel, such as the Alum Shale Formation but not the Tremadocian section, and the overlying Huk Formation, is hence somewhat uncertain.

The rich material collected is stored in the Natural History Museum, Oslo, with PMO-numbers on figured specimens. No specimens were whitened prior to photographing, except Fig. 7E.

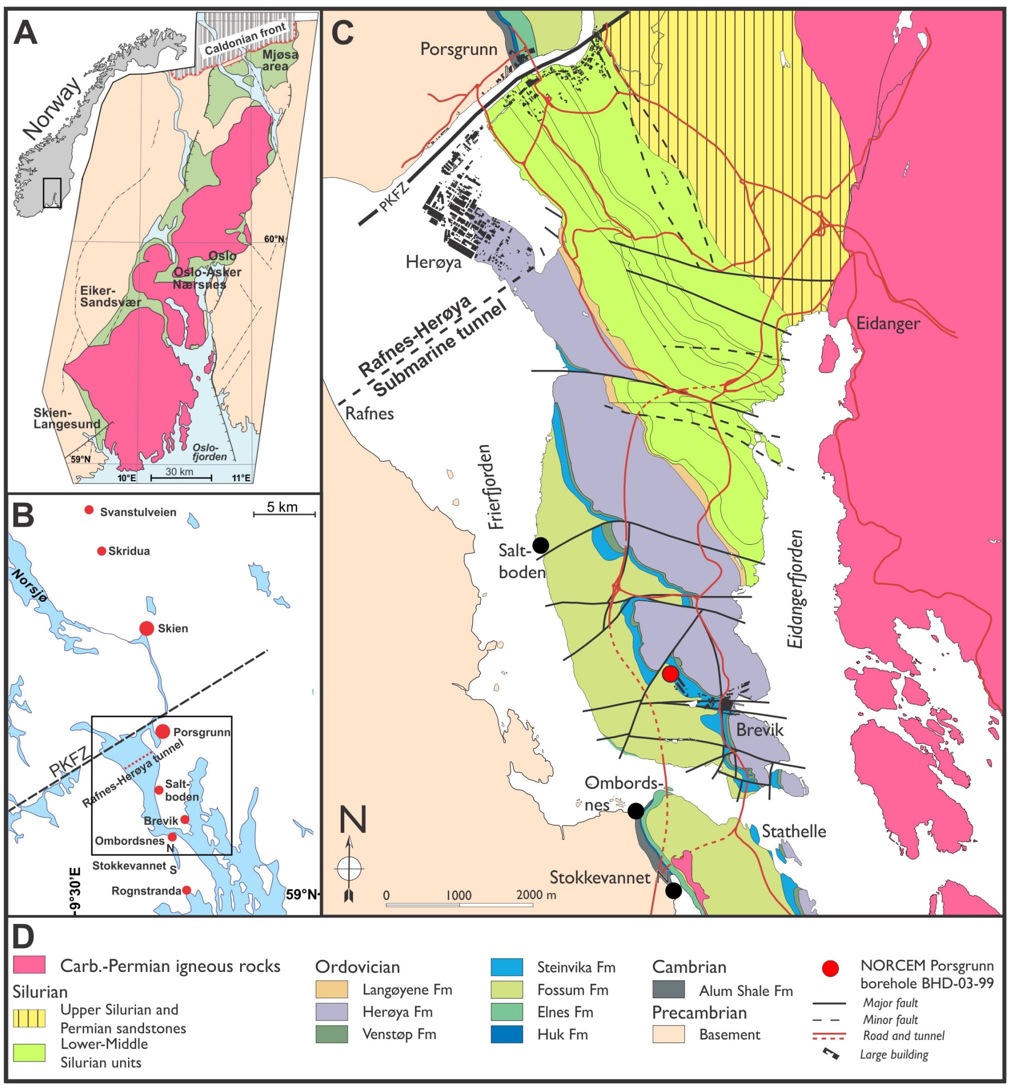

Figure 1. Geographical setting of study area. (A) Simplified geological map of the Oslo Region with Lower Palaeozoic deposits coloured green. (B) Location of outcrops and boreholes mentioned from the Skien–Langesund District. (C) Geological map of the study area. Modified from Schovsbo et al. (2018). *(D) Legend.*

Geological Setting

The Skien–Langesund District forms the southwestern part of the Oslo Region (Størmer, 1953). Cambrian–Silurian rocks of the district crop out in a narrow (50 x 2–5 km) N–S belt, bordered to the west by Precambrian basement rocks, and to the east by Permian–Carboniferous sedimentary and volcanic rocks and plutons (Fig. 1C). The main published works on the Cambrian–Silurian strata in this district still are those of Brøgger (1884) on the Cambrian and Ordovician (and the Permian faulting), Størmer (1953) on the Middle Ordovician, and Kiær (1908) on the Silurian. These works form the basis for the current formal stratigraphy of the Skien–Langesund District provided for the Ordovician by Owen et al. (1990) and by Worsley et al. (1983) for the Silurian. Some of the Ordovician names can be traced to the work of Dahll (1857).

In contrast to other geographical districts of the Oslo Region, the Cambrian–Silurian rocks of the Skien–Langesund District did not suffer the end-Silurian Caledonian folding and thrusting (Bruton et al., 2010). However, proximity to the Permian plutons to the east caused contact metamorphism of the strata, and fossils vary in preservation along W–E transects.

The major Porsgrunn–Kristiansand Fault Zone (PKFZ) cuts through the Precambrian and Lower Palaeozoic rocks (Fig. 1), with an apparent southward downthrow of the latter in the order of 1000 m. The PKFZ is an old Precambrian lineament, originally a major thrust zone, later reactivated several times as an extensional fault zone (Starmer, 1993; Gabrielsen et al., 2002). The Rafnes–Herøya submarine tunnel is aligned parallel to the PKFZ some 2 km to the south (Fig. 1C).

The base of the Cambrian in the Skien–Langesund District is marked by the Stokkevannet formation (informal name, Schovsbo et al., 2018), a sandstone underlying the Alum Shale Formation. The thickness of the sandstone varies in the range of 6–16 m south of the PKFZ (Brøgger, 1884; Vogt, 1929; Schovsbo et al., 2018) and is reduced to 3 m (Dahll, 1857; Brøgger, 1884) and even less, 0.3–1 m (unpublished), in the Skridua–Svanstulveien area located some 15–20 km north of the PKFZ (Fig. 1B). Lack of fossils in the Stokkevannet formation makes dating conjectural, but at Skridua, Brøgger (1884) identified interbedding of alum shale in the top part, while in a core section at Rognstranda, 12 km south of the tunnel location (Fig. 1B), Henningsmoen (1952) reported basal shales with trilobites typical of the *Paradoxides paradoxissimus* Superzone, thus indicating a Miaolingian age (mid-Cambrian), at least for the top part. However, Nielsen & Schovsbo (2011) assigned an early Cambrian age to the Stokkevannet formation based on regional correlations (e.g., at Krekling in the Eiker–Sandsvær District) and a sequence-stratigraphic approach for the early Cambrian across Scandinavia. The sand/mudstone interbedding at the top is then interpreted as a result of reworking when transgression and sedimentation resumed after the global Hawke Bay Regressive Event and contemporaneous uplift in Scandinavia (Nielsen & Schovsbo, 2015).

Good exposures for detailed stratigraphic investigations of the Alum Shale Formation are hard to find in the Skien–Langesund District due to foothill scree cover and heavy vegetation. In 1946, several cores were cut through the Alum Shale Formation at various localities as part of a uranium resource project by the goverment, but detailed stratigraphic data were not published, except for palaeontological data included in faunal lists (Henningsmoen, 1957).

Only recently has a continuous and detailed stratigraphic section through the Alum Shale Formation in the Skien–Langesund District been presented. Schovsbo et al. (2018) produced a Gamma Ray (GR) log from the Cambrian strata based on spectral GR core scanning of the core cut in 1999 at the Norcem Brevik site (termed the Porsgrunn borehole in Fig. 1). Unfortunately, the core did not afford fossil sampling. This log was then compared with similar log data from Alum Shale Formation cores from

Scania (Sweden) and Bornholm (Denmark), where the formation is biostratigraphically well constrained. The Porsgrunn core revealed a total Alum Shale Formation thickness of 28.8 m, comprising a Miaolingian section of 14 m, and a Furongian (upper Cambrian) section of 14.8 m (omitting intruded sills). No Tremadocian section was recognised. These figures are in line with or somewhat thicker than the 11–12 m Miaolingian interval (i. e. *Paradoxides paradoxissimus* and *Paradoxides forchhammeri* superzones) found by Brøgger (1884) at Skridua in the northern part of the district, and the 12 m Furongian (including the *Agnostus pisiformis* Zone) reported by Henningsmoen (1952) from a core at Rognstranda in the south. Brøgger (1884) measured an overall Furongian of 25 m at Ombordsnes (Fig. 1B, C), and assessed a similar thickness at Skridua. However, he probably included the intruded sills in his measurement (at least 8 m within the upper part along the present road section at Ombordsnes) as he only specified a 2 m-thick sill within the *Agnostus pisiformis* beds.

The Cambrian–Tremadocian stratigraphy of the Rafnes–Herøya tunnel

An interpreted geological cross-section along the tunnel transect with the submarine topography and Quaternary sediment thickness distribution is provided (Fig. 2), based on the marine seismic survey (unpublished) shot above the transect. The seismic data reveal the submarine continuation of the steep boundary escarpment of the Cambrian–Ordovician rocks typical of the landscape to the south of the tunnel location. The Lower Palaeozoic strata of the Skien–Langesund District typically dip eastwards towards the Permian plutons, and are cut by numerous faults and igneous dykes related to the Permian rifting of the Oslo Region. All the Middle–Late Ordovician formations described from outcrops in the Skien–Langesund District can be recognised in the tunnel section. However, a detailed stratigraphic investigation is beyond the subject of this work.

Between the dark Alum Shale Formation and the dark mudstones of the Elnes Formation, there is a distinct, 2.5 m-thick limestone unit, for simplicity termed the Huk Formation on Fig. 2. This unit is found throughout the Skien–Langesund District (Brøgger, 1884). In the older literature, this limestone section was treated as a single unit: “Orthoceras Limestone”, or stage 3c. This is now assigned to two formations (Owen et al., 1990), e.g., the lower, more massive limestone with common pelmatozoan fragments and cephalopods belongs to the Huk Formation (Rognstranda Member), and the upper part of interbedded, bioturbated micritic limestone and mudstnes with common asaphid trilobites, is assigned to the Elnes Formation (Helskjer Member). In the tunnel section these units have thicknesses of 1.4 m and 1.1 m, respectively. The Huk Formation limestone rests unconformably on the Alum Shale Formation of Tremadocian age. This lower contact is planar with occasional undulations up to 5 cm, and bears no indication of tectonic deformation. Within the basal 0.2 m, hand specimens of the Huk Formation reveal scattered phosphorite pebbles, shale pebbles, pyritised sideritic(?) ooids, and millet-seed quartz grains, set in a burrowed, argillaceous, dolomitic, medium- to coarse-grained crinoidal biosparite.

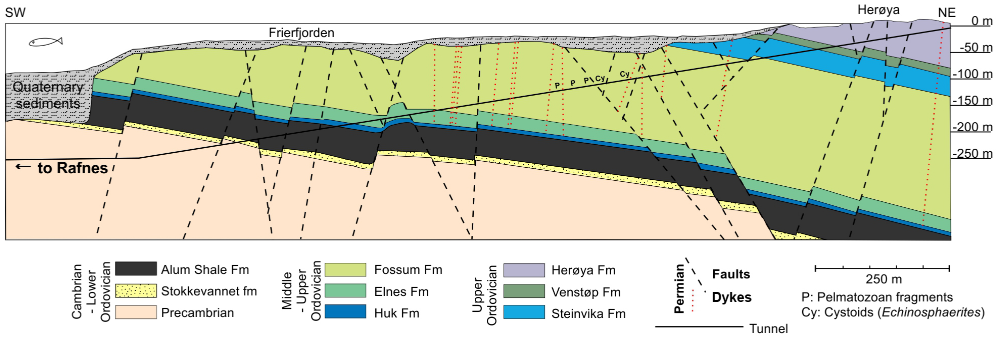

Figure 2. Interpreted geological NE–SW cross-section along the eastern half of the Rafnes–Herøya tunnel transect. The thinner formations are somewhat exaggerated.

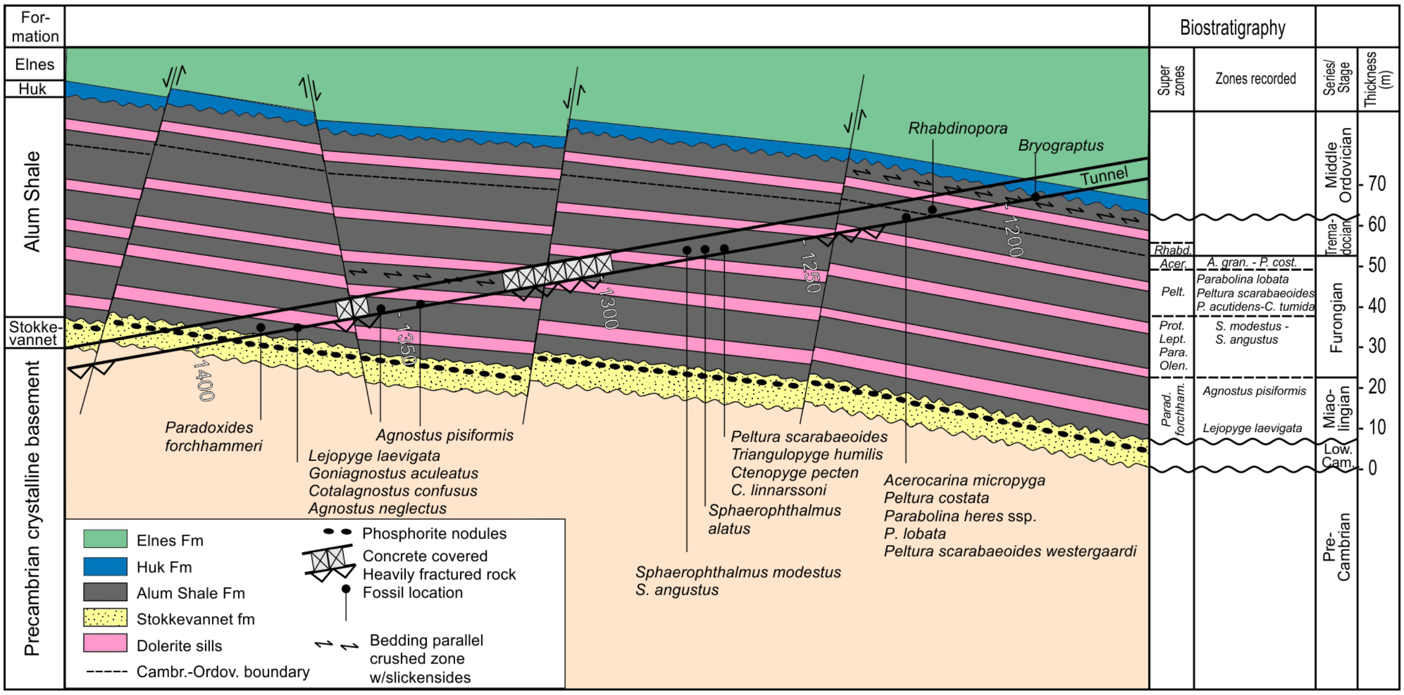

Figure 3. Interpreted detailed geological cross-section of the Cambrian–Tremadocian interval of the tunnel. The stratigraphic zonation given on the right-hand side is based on the fossil content along the tunnel transect.

A more detailed interpretation of the cross-section of the Alum Shale Formation and the underlying Stokkevannet formation interval is provided (Fig. 3), including the several dolerite sills of Permian age within the Alum Shale Formation, which are typical of the area (omitted in Fig. 2 for simplicity). The faults all have only minor throws and are interpreted based on observed fracture zones and bedding dip changes across concrete-covered intervals, and the location of igneous sills.

The Stokkevannet formation sandstone is 7–8 m thick and rests unconformably on a porphyritic granite, a common lithology in the Precambrian just south of the PKFZ of this area (Røsholt, 1967). The contact between the Precambrian basement and the Cambrian sandstone is found at a measured tunnel length of 1405 m (Fig. 3). The contact is slightly undulating with a local relief of up to 1 m and with a thin basal conglomerate in the topographic lows, followed by a burrow-mottled, dark-coloured sandstone, except for a 0.25 m-thick pale zone containing dark, presumably phosphorite nodules at the top, similar to the cored section at Brevik (Schovsbo et al., 2018). A 0.4 m-thick dolerite sill separates the sandstone from the alum shale above (not shown on Fig. 3). Above the thin sill, the Alum Shale Formation is pale olive-grey, containing lingulate brachiopods and changes to dark grey mudstone followed by a 0.2 m-thick anthraconitic limestone where a few pyrite aggregates and phosphorite nodules occur. Some of the finely crystalline, thin intervals have a laminated texture with coarsely granulated trilobite fragments similar to *Paradoxides forchhammeri*(?), and brachiopod fragments. Above this limestone the typical dark grey Alum Shale Formation with intercalated dark limestone lenses extends up to the Huk Formation.

The thickness of the Alum Shale Formation in the tunnel section appears to be in the order of 38–42 m (omitting the dolerite sills), with a Miaolingian succession of 10–12 m within the *Paradoxides forchhammeri* Superzone. The Furongian succession is 20–22 m thick, followed by a Tremadocian succession of 8.1 m (Fig. 4).

The base of the Tremadocian corresponds with tunnel length 1217 m (Fig. 3), close to a 0.2–0.3 m-thick limestone layer (Fig. 4). The limestone is coarsely anthraconitic in the upper 10 cm, otherwise finely

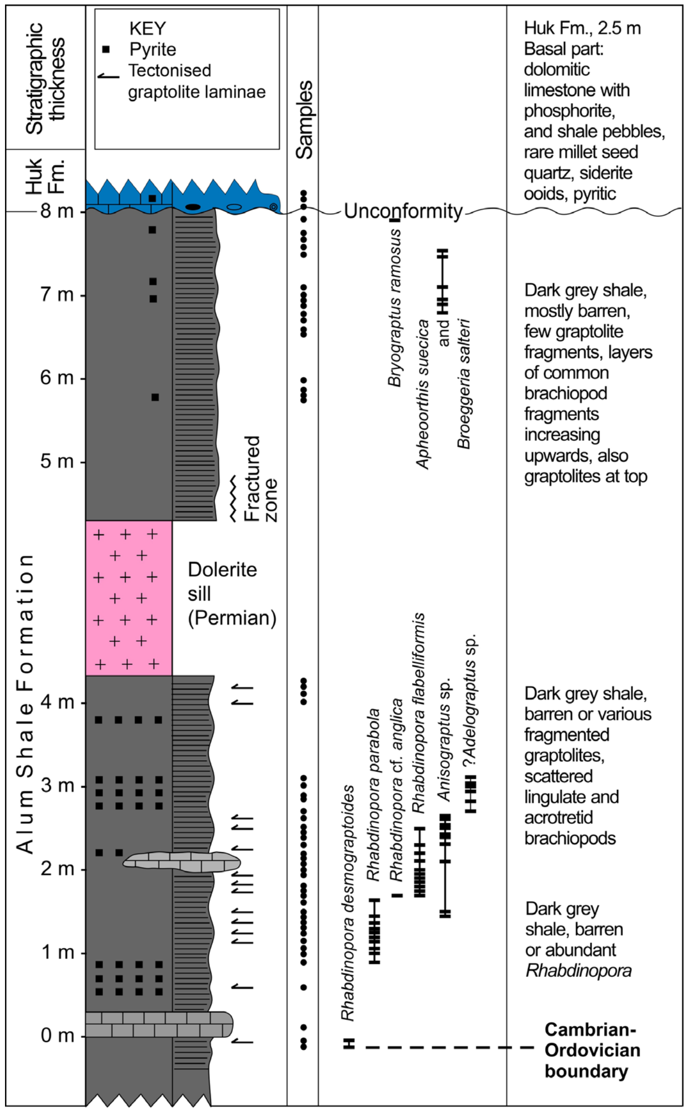

Figure 4. The Cambrian–Ordovician boundary and the stratigraphy of the Tremadocian succession, showing the lithology, and graptolite and brachiopod range chart of the Rafnes–Herøya tunnel section. The C–O boundary is set at the first occurrence of Rhabdinopora *specimens below a dark limestone at the 0 m level.*

crystalline and laminated and contains species of *Rhabdinopora*. The stratigraphically lowermost appearance of this graptolite occurs in the shale 0.1 m below the limestone (Fig. 4) and stratigraphically about 2 m above the last Furongian trilobites recorded.

The *Rhabdinopora* occurrence extends stratigraphically for c. 2.6 m (Fig. 4), where thin horizons with abundant pyrite «augen» occur at some intervals. Lingulate brachiopods occur at 1.8 m and are common above 6 m where they tend to occur in thin concentrations, commonly consisting of fragmented specimens. The uppermost 0.3 m of the shale becomes slightly siltier, but the colour stays dark grey throughout the entire unit. Within the very top few cm, just below the unconformity towards the overlying Huk Formation, there is a thin layer of mixed brachiopods and graptolites, including *Bryograptus ramosus* (Brøgger, 1882).

Several laminae, especially within the *Rhabdinopora* zone, show slickensides (Fig. 4).

Discussion

The Cambrian–Ordovician succession of the Rafnes–Herøya tunnel differs from other localities in the Skien–Langesund District by having a less complete basal Miaolingian succession with no *Paradoxides paradoxissimus* Superzone fauna recorded. Unfortunately, Furongian strata spanning the *Olenus*–*Protopeltura* superzones, if present, were covered by concrete to strengthen the fractured rock (Fig. 3) and were not investigated. However, a more complete late Furongian succession is recognised, and in particular, a Tremadocian interval is present with deposition originally extending at least into the *Bryograptus* zone.

The distribution and thickness of the Stokkevannet formation sandstone in a regional N–S transect (Fig. 5A, B) suggests a basin deepening, and possibly a slope break across the PKFZ, although with local variations in the basin topography that were sand infilled. A general thinning of the sandstone northwards towards the Fen–Alnø regional high (Bergström & Gee, 1985) is as expected.

The limestone at the base of the Alum Shale Formation in the tunnel section may possibly be correlated with the suggested Andrarum Limestone Gamma Low (AGL) equivalent in the Porsgrunn core (Schovsbo et al., 2018). The *Paradoxides paradoxissimus* Superzone is either very condensed or missing in the tunnel section, suggesting winnowing and non-deposition. This is puzzling considering the several metres (5–6 m) thickness at the other locations in the district, including at Skridua to the north. In the likely basin configuration (Fig. 5B), the Skridua locality, during the initial alum mud deposition

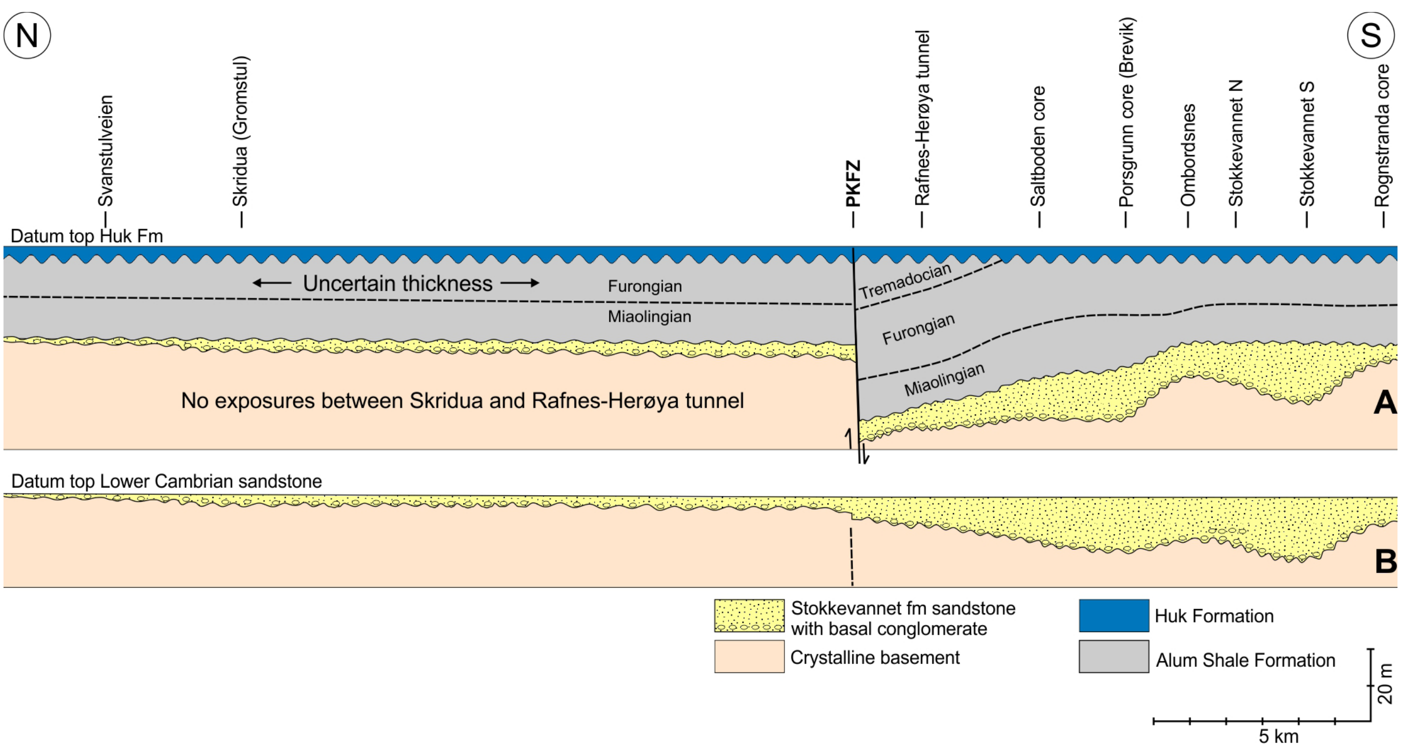

Figure 5. N–S correlation of the Cambrian–Tremadocian succession in the Skien–Langesund District. (A) The expanded Alum Shale Formation thickness and preservation of the Tremadocian interval found in the Rafnes–Herøya tunnel suggests subsidence along the PKFZ in the late Furongian–Tremadocian. The inferred angular unconformity below the Huk Formation was not observed, i.e. too low angle (<1°) to be separated from the general eastward dip of the strata in the tunnel. The Saltboden core location is the nearest data point with no observed Tremadocian or uppermost Furongian Superzone to the south of the tunnel location. No section details have been published from this core, except for palaeontological records (Henningsmoen, 1957). (B) Early Cambrian basin configuration and topography suggested by the thickness distribution of the Stokkevannet formation sandstone. A thickness expansion trend across the PKFZ is implied, although data locations to the north are sparse and far away.

time, was situated in an area where sedimentation was more active than at the tunnel site where winnowing and non-deposition was the case. One may speculate whether this signifies an episode of local inversion along the PKFZ associated with the Hawke Bay Event contemporaneous uplift across Scandinavia (Nielsen & Schovsbo, 2015).

The remaining Miaolingian and the Furongian section is comparable to that of the Porsgrunn core in being thicker than the equivalent in the Ombordsnes–Rognstranda area, indicating that there may be a northward/eastward component of increasing thickness south of the PKFZ. Factors controlling this are unknown but both local and regional lateral and stratigraphic thickness changes are a common feature of the Alum Shale Formation in Baltoscandia (Buchardt et al., 1997; Artyushkov et al., 2000; Nielsen et al., 2014) reflecting a combination of eustatic sea-level changes, and local deposition or non-deposition. Thus, the Skien–Langesund District north of the Porsgrunn–Kristiansand Fault (Fig. 5) appears to have been part of a level, stable platform undergoing erosion during the early Ordovician, while to the east of the fault, the tunnel section up to the base of the Huk Formation includes the Tremadocian. This platform included the southern part of the Eiker–Sandsvær District to the north, where the Huk Formation rests on the Alum Shale Formation with *Peltura scarabaeoides* at the top (Owen et al., 1990). East of the platform at Krekling, the Alum Shale Formation expands to more than 80 m, with notable thickening of the Miaolingian and early Furongian sections (Brøgger, 1878; Høyberget & Bruton, 2008; Hammer & Svensen, 2017; for details see Schovsbo et al. 2018, pp.15–17).

An alternative to explaining the gap between the Alum Shale Formation and the Huk Formation by non-deposition and erosion was presented by Bockelie & Nystuen (1985) who envisaged a Caledonian sole thrust flat along the base of the Huk Fm, and a ramp preserving the Tremadocian section. This view is not supported by the present data. Although various tectonised zones exist within the Alum Shale Formation and the overlying formations in the Skien–Langesund District, these have attitudes related to the Permian faults and sill intrusions, and the easterly tilting towards the Permian plutons. Neither in the Skien–Langesund District nor in the Eiker–Sandsvær District, is such a thrust model supported by field data (Owen et al., 1990).

The graptolites

Especially for the identification of the species of the genus *Rhabdinopora* (earlier: *Dictyonema*), it is clear that as stated by Bulman (1954, p. 11): '*none of the many varietal forms of flabelliforme is universally restricted to a narrow horizon, and furthermore, there will be found throughout the succession many examples which can only be identified as* Dictyonema flabelliforme *s. l., or referred with some qualification to described varieties.*'. Thus, the identification of the specimens is problematic from the fragmented material at hand. Only a few other graptolites have been collected from the tunnel succession, including representative specimens from the mid-Ordovician Elnes Formation. The most important graptolites, however, are *Rhabdinopora* spp. from the basal Ordovician. These are discussed in more detail.

The section from which *Rhabdinopora* specimens were collected is 2.6 m in thickness and started at -0.1 m, below a black limestone bed at 0.0 m (Fig. 4). The collection consists of 42 samples that were unevenly collected through the succession. Thus, the lower 1 m is poorly represented with only 4 samples. 20 samples cover the 1.0–2.0 m interval, while the 2.0–3.0 m interval is covered by 14 samples. The graptolites are generally poorly preserved and fragmentary and no complete colonies have been collected. Therefore, the identification of the *Rhabdinopora* species is based on the dimensions of the meshwork of their tubaria only.

The specimens at the -0.1–0.0 m level (Fig. 6B, F) show a robust meshwork with undulating stipes 0.5–0.6 mm wide. The dissepiments are 0.2–0.3 mm wide, rarely more and show distinctly wider attachment sites on the stipes. Thus, the meshes commonly appear rounded. The material is here referred to *Rhabdinopora desmograptoides* (Hahn, 1912), following the identifications of Bulman (1954) for the *Rhabdinopora* material of the Oslo region.

Many specimens and fragments from the interval 0.9 m to 1.45 m can be referred to *Rhabdinopora parabola* (Bulman, 1954; Fig. 6C–E, G), based on the density of the stipes and the development of the dissepiments. The dissepiments are thin, quite irregularly developed and often obliquely oriented. The material thus resembles *R. parabola* and the slightly younger *Rhabdinopora canadensis* (Bulman, 1950) (see Cooper et al., 1998), while the number of stipes in 10 mm more clearly indicates that the material belongs to *R. parabola.*

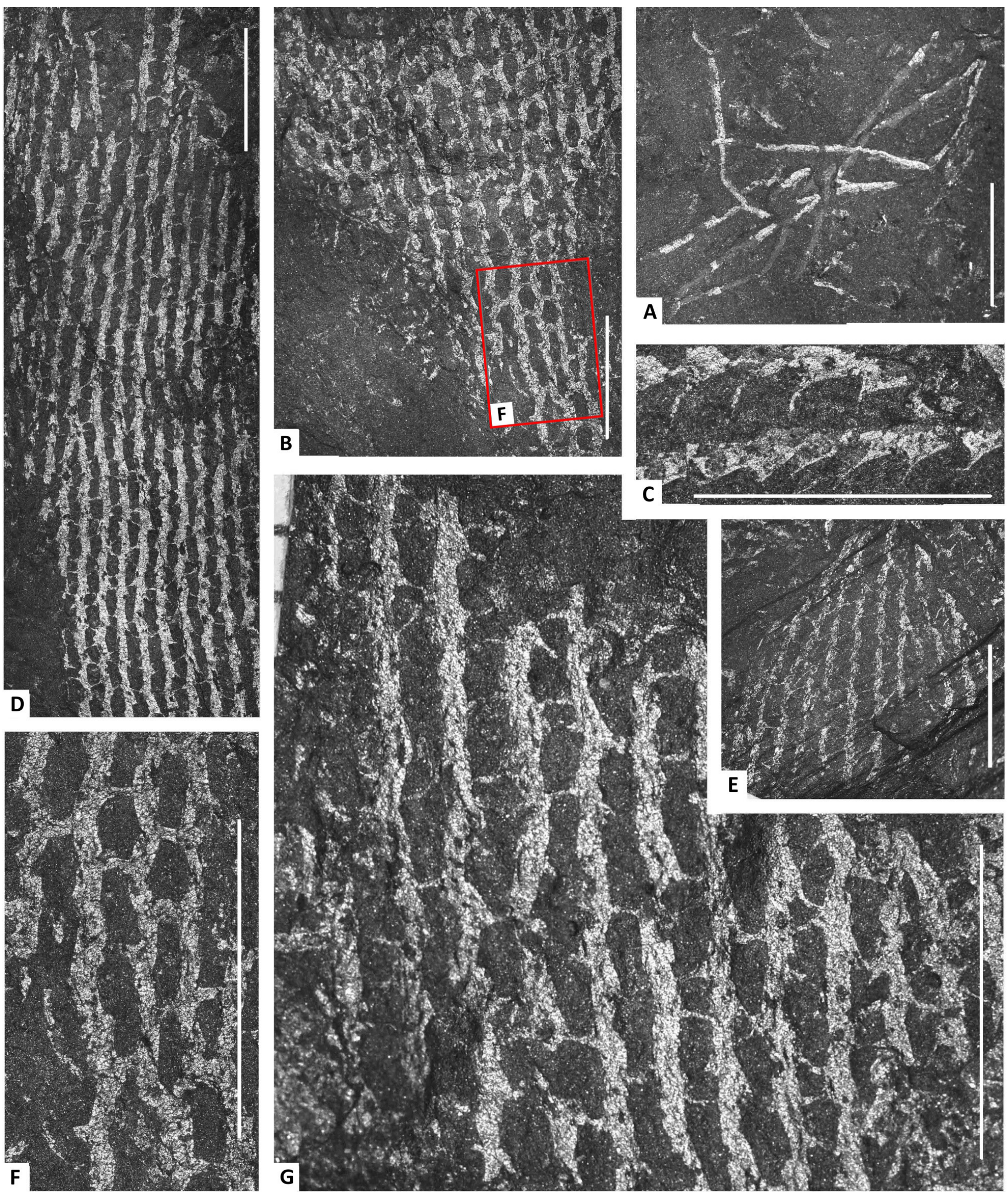

Figure 6. Graptolites from the lowermost part of the Tremadocian succession. (A) Anisograptus *sp., fragments, 1.45 m. PMO 235.065. (B, F)* Rhabdinopora desmograptoides *(Hahn), fragment showing undulating stipes and wide dissepiments, -0.1–0.0 m. B: PMO 235.066, F: PMO 235.070. (C–E, G)* Rhabdinopora parabola *(Bulman). (C, D) details of the thecal apertures with extended rutelli (C) from large fragment (D), 1.0 m. C: PMO 235.067, D: PMO 235.068. (E) fragment showing near proximal end, 1.0–1.1 m. PMO 235.069. (G) larger fragment with thin, irregular dissepiments, 1.3 m. PMO 235.071. All scale bars = 5 mm.*

Specimens in the interval of 1.7–2.5 m can be referred to *Rhabdinopora flabelliformis* (Eichwald, 1840). The species can be identified by the number of stipes in 10 mm and the density of the slender dissepiments (Fig. 7A). The specimens are quite variable in the dimensions and a distal fragment is close to *Rhabdinopora anglica* (Bulman, 1927) with its very loosely spaced dissepiments (Fig. 7B). A single, nearly complete proximal end (Fig. 7C) shows the sicula, but the number of first-order stipes is impossible to determine. The thecae often show distinct rutelli (Fig. 7F, G) and in a few fragments indications of a stolon system can be observed (Fig. 7E).

Layers crowded with juvenile specimens of *Rhabdinopora* can be found at 1.35–1.40 m (Fig. 8A) and 1.6–1.7 m. In these layers, larger specimens have not been found and it may be debatable whether the material belongs to *Rhabdinopora* or *Anisograptus*, which should be present in the interval. However, the declined habit of the largest specimens indicates that the material should be referred to *Rhabdinopora.* A number of levels (1.9 m; 2.0 m; 2.3 m; 2.5–2.55 m) are also crowded with small fragments of graptolites. Due to the fragmentation, this material is impossible to determine. The material looks similar to that described and illustrated by Størmer (1938) from the late Tremadocian Bjørkåsholmen to the Arenig Tøyen formations, but here the round holes interpreted by Størmer as gas bubbles are not present.

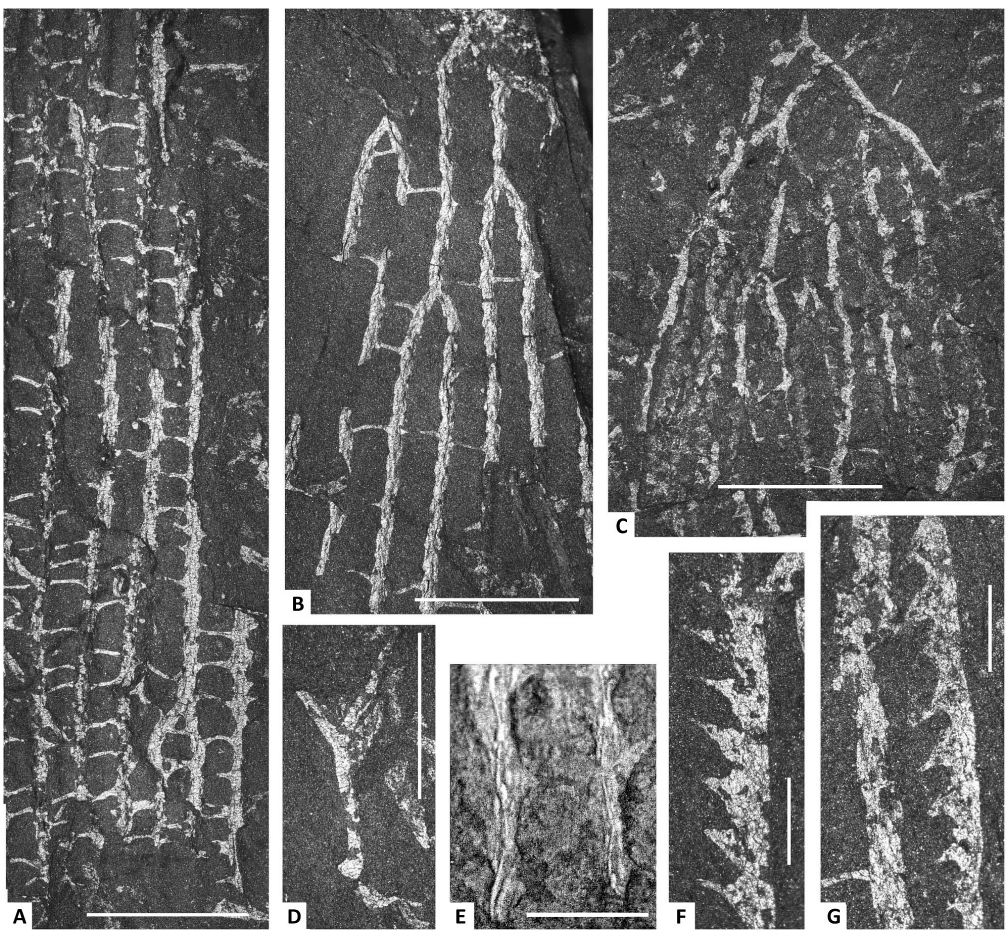

Figure 7. Graptolites from the Rhabdinopora flabelliformis *Biozone. (A, C, E–G)* Rhabdinopora flabelliformis *(Eichwald). (A) long fragment, 1.7–1.75 m. PMO 235.072. (C) poorly preserved proximal end, 1.8 m. PMO 235.074. (E) stipe fragment in dorsal view showing stolon system, specimen coated, 2.0 m. PMO 235.076. (F) stipe fragment showing pointed thecal apertures, 1.95 m. PMO 235.077. (G) Stipe fragment in lateral view, showing thecae, 1.8 m. PMO 235.078. (B)* R. *cf.* anglica*, distal fragment with low-density dissepiments, 1.75 m. PMO 235.073. (D)* Anisograptus *sp., fragment, 2.1–2.15 m. PMO 235.075. Scale bars = 5 mm (A–D) and 1 mm (E–G).*

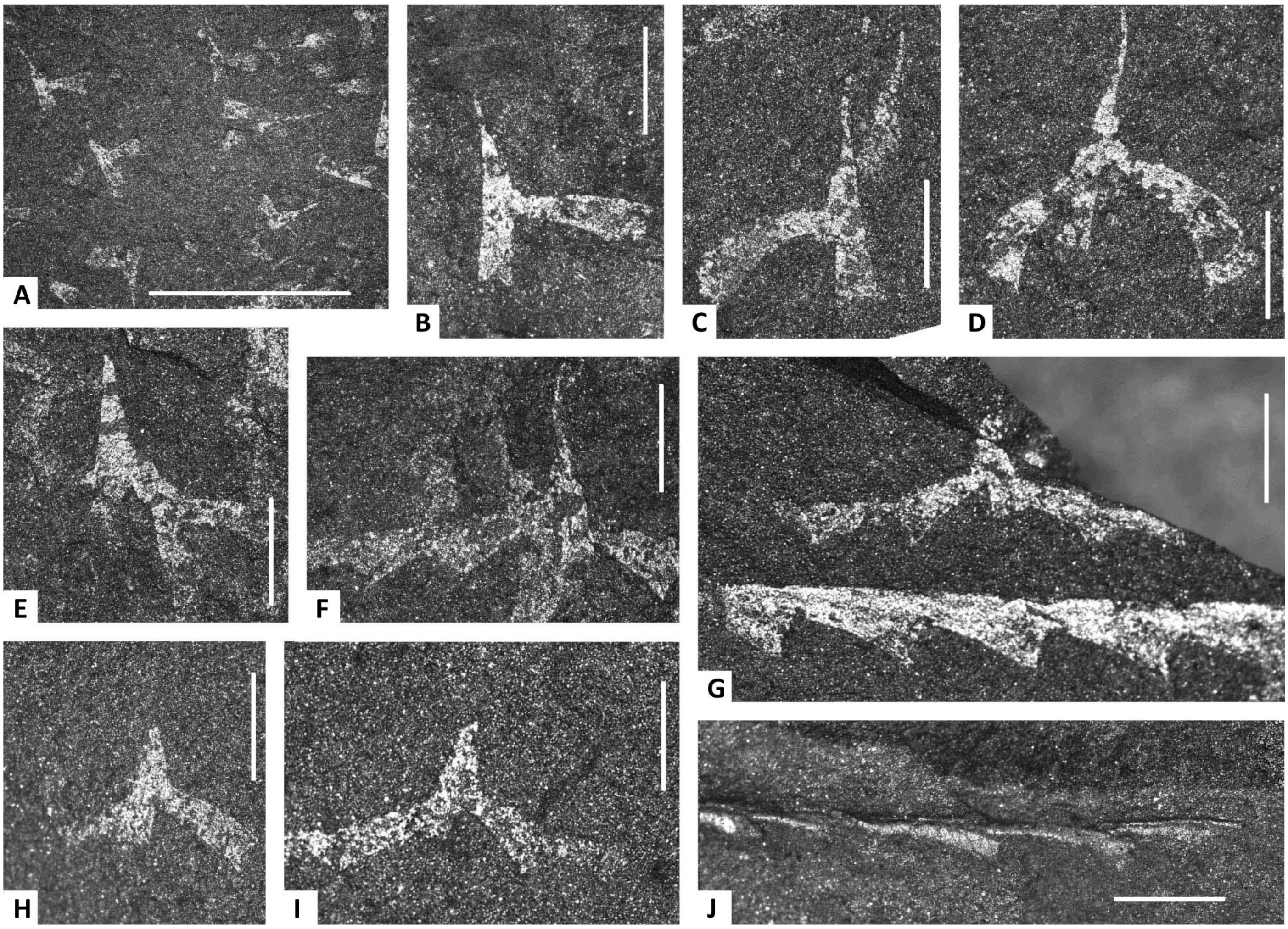

Figure 8. Proximal ends and details. (A–E) Rhabdinopora *specimens. (A) Assemblage of juveniles, 1.35–1.4 m. PMO 235.079. (B) Sicula with first theca, 1.85 m. PMO 235.080. (C) Sicula with first theca and incomplete sicula, 1.3–1.4 m. PMO 235.081. (D) Juvenile with first thecal pair, 1.3–1.4 m. PMO 235.082. (E) small specimen, 0.9 m. PMO 235.083. (F–J)* Anisograptus *and* Adelograptus *specimens. (F) Subhorizontal proximal end, 2.5–2.55 m. PMO 235.084. (G) Proximal end and stipe fragment, 2.6 m. PMO 235.085. (H) Proximal end, 2.5 m. PMO 235.086. (I) Proximal end, 2.6–2.67 m. PMO 235.087. (J) Stipe fragment in relief, preserved as pyritic internal cast, showing low thecal overlap and inclination, 3.0 m. PMO 235.088. Scale bars = 1mm.*

Specimens identified as ?*Anisograptus* sp. are common in the interval from 1.4–1.5 m and 2.6–2.7 m. None of the fragmented specimens show the triradiate proximal end clearly, but the available proximal ends have more horizontal to sub-horizontal stipes (Fig. 8F–I) than the declined to pendent *Rhabdinopora* (Fig. 8A–E).

In the interval from 2.7 m to 3.10 m, numerous fragments and a few proximal ends may be referred to *Adelograptus* sp. with reservation. The stipe fragments show a low thecal inclination (Fig. 8G, J) and the sicula can be seen to be more highly inclined towards the stipes (Fig. 8H, I) than in the specimens identified as *Anisograptus*. The interval does not include any specimens or fragments of *Rhabdinopora*.

Bryograptus ramosus (Brøgger, 1882) (Fig. 9H) occurs in the uppermost centimetres of the Alum Shale Formation below the Huk Formation (Fig. 4), indicating a late Tremadocian age.

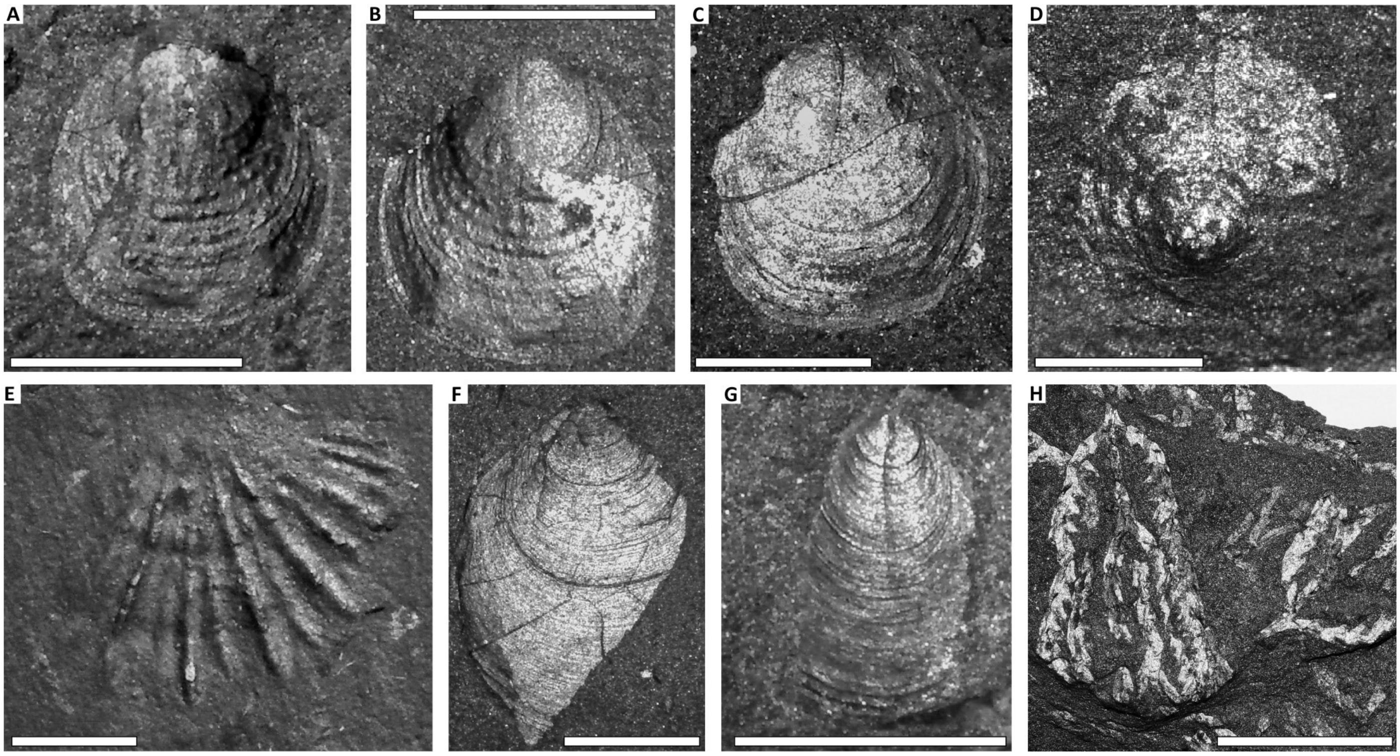

Figure 9. (A–C, F, G) Broeggeria salteri *(Holl), upper level 6.9–7.6 m. (A–C) Dorsal valves. A: PMO 235.089, B: PMO 235.090, C: PMO 235.091. (F, G) Ventral valves. F: PMO 235.094, G: PMO 235.095. (D) Acrotretid, reminiscent of* Ottenbyella *Popov & Holmer, ventral valve, lower level 3.1 m, PMO 235.092. (E)* Apheoorthis *cf.* suecica *Tjernvik, upper level 6.9–7.6 m, PMO 235.093. (H)* Bryograptus ramosus *Brøgger, uppermost level 8.0 m, PMO 235.096. All scale bars = 5 mm.*

The Cambrian–Ordovician boundary

Species of the genus *Rhabdinopora* represent the first planktic graptoloids and appear close to the base of the Ordovician System (Cooper et al., 1998, 2001).

Bulman (1954) described the biostratigraphy of the *Rhabdinopora* group from the Oslo Region and recognised the *Rhabdinopora flabelliformis*, *R. norvegicum* and *Anisograptus* biozones at Hammersborg (Oslo) and the *R. socialis, R. flabelliformis, R. norvegicum* and *Anisograptus* biozones in the Tøyen section in the city of Oslo. Bruton et al. (1982, 1988) proposed the Nærsnes section in the Oslo Region as a candidate for the GSSP of the Cambrian–Ordovician boundary based largely on the graptolite record. The Green Point section in the Cow Head Group of western Newfoundland was, however, chosen as the GSSP section and the conodont *Iapetognatus fluctivagus* selected as the index species for the boundary (Cooper et al., 2001). Subsequently, problems with the identification of the index species (Terfelt et al., 2012; Miller et al., 2014) led to a re-evaluation of the succession and a precise correlation with the previously suggested Xiaoyangqiao section of China was made (Zhou et al., 1984; Chen et al., 1985). Wang et al. (2019) discussed the base of the Ordovician System in the Xiaoyangqiao section close to Dayangcha, Jilin Province, China, which is now proposed as an Auxiliary Boundary Stratotype Section and Point (ASSP) (Wang et al., In review). The section bears the oldest *Rhabdinopora* specimens, identified as *Rhabdinopora proparabola* (Lin, 1986; Maletz et al., 2017). Higher levels bear *R. parabola*, initially described from the Tøyen section. Wang et al. (2019, In review) regarded *R. praeparabola* (Erdtmann, 1982) as poorly preserved juveniles of *R. parabola* and indicated that *R. proparabola* has so far only been reported from North China. Differences in the two taxa can largely be seen in the development of the nema in *R. parabola* and a three-vaned nematularium at the tip of the sicula in *R. proparabola* in which a nema is lacking. In the Rafnes–Herøya tunnel section, *R. desmograptoides* is the oldest recognised *Rhabdinopora* species, characterised by a dense mesh of undulating stipes and wide dissepiments, very unlike *R. proparabola* and *R. parabola* with their slender dissepiments and relatively straight stipes.

The biostratigraphic distribution of *R. desmograptoides* and *R. socialis* is poorly known (Cooper et al., 1998), but Cooper (1999) discussed the ecostratigraphy of the *Rhabdinopora* species and considered the two taxa as belonging to an inshore biotope fauna. Due to the numerous described *Rhabdinopora* species (see Erdtmann, 1982, 1988), a precise identification and interpretation is difficult, especially one based on highly fragmented material. Cooper et al. (1998) differentiated *R. canadensis* from *R. parabola* and considered both as successive subspecies of *R. flabelliformis*. The somewhat younger *R. flabelliformis* is followed by the characteristic *R. anglica* with its widely spaced dissepiments and coarse meshwork (Cooper et al., 1998, 2001). A single specimen reminiscent of *R. anglica* has been collected from a low level in the *R. flabelliformis* interval and is here assigned *R.* cf. *anglica* (Fig. 7B).

The brachiopods

Brachiopods have been collected from two broad levels within the Tremadocian section, a lower one beneath the dolerite sill and an upper level between 6.9 and 7.6 m. The black shales are characterised by patches of comminuted, phosphatic shell debris; the material is associated with a linguloid brachiopod. Complete specimens of the linguloid are rare but a number of shells identified as the elkaniid *Broeggeria salteri* (Holl, 1865) are generally well preserved and are associated with the debris at both levels (Fig. 9A–C, F, G). The shells have a rounded outline, weakly biconvex (though probably flattened by compaction), and the ventral valve is slightly longer than the dorsal valve, and with strong concentric growth lines.

Broeggeria salteri is common and widespread in alum shale facies in southern Scandinavia and beyond. Within the Oslo Region, it occurs in upper Tremadocian shales (Owen et al., 1990) within an assemblage dominated by *Broeggeria* itself, *Lingulella* and acrotretides together with some small orthidines (Harper, 1986).

Popov & Holmer (1994), in defining the *Broeggeria* Assemblage, noted its extensive distribution in late Cambrian and early Ordovician black shales in Scandinavia, Nova Scotia, the southern Urals, central Kazakhstan and the Kendyktas Range together with the Anglo-Welsh Basin (Avalonia) from where the type species was first described. More recently, the geographical range of the assemblage has been extended to the Purmamarca area of NW Argentina (see Benedetto et al. (2018) for fuller discussion of the distribution of the assemblage). The association is of low diversity, inhabiting open-shelf, dysaerobic, olenid-dominated environments and may appear during the transgression of black shale facies onto the shelf (Popov & Holmer, 1994).

The abundance of fragmented shells from Rafnes–Herøya suggests that the species was common and part of an otherwise sparse epibenthos, tracking dysaerobic environments (Popov et al., 2013), and possessing thin and fragile dorsal and ventral valves.

The ventral valve of an acrotretide is reported from the lower level (Fig. 9D). The valve is subconical with a very pronounced and swollen beak reminiscent of *Ottenbyella*, which occurs in the younger Bjørkåsholmen Formation (Popov & Holmer, 1994).

There is a single, small shell of a rhynchonelliformean brachiopod reported from the upper level (Fig. 9E). This dorsal valve has a transversely subquadrate outline, a rectimarginate commis-sure and an incipient sulcus. The costae are strong, sharp with subangular profiles. Costellae arise by intercalation (laterally) and by bifurcation (medianly); both costae and costellae are straight rather than curved. Concentric growth lines are locally marked. The shape, strength and configuration of ribs bear some resemblance to *Apheoorthis? suecica* Tjernvik, 1956 from Kinnekulle, Västergötland, Sweden. The Swedish shell is smaller than the Rafnes–Herøya exemplar, and has yet to develop a range of costellae.

The trilobites

In the Miaolingian and Furongian Series of the Alum Shale Formation, the collected trilobites are from metamorphosed limestone beds and lenses. Although the olenid and agnostoid fragments are compressed and poorly preserved, specific characters can be observed, and a detailed biozonation is determined (Fig. 3). No Cambrian trilobites or agnostoids have previously been figured from the Skien–Langesund District.

Brøgger (1884) reported agnostoids from the alum shale that are characteristic of the Miaolingian *Paradoxides paradoxissimus* and *P. forchhammeri* superzones, representing the *Ptychagnostus atavus, P. punctuosus* and the *Goniagnostus nathorsti* zones. According to Brøgger's estimates, a shale sequence corresponding to the *P. paradoxissimus* and the *P. forchhammeri* superzones are 5–6 m and 6 m in thickness, respectively. Schovsbo et al. (2018) reported the Miaolingian Series to be 14 m in thickness, based on lithological and geochemical data from investigations of the named Porsgrunn core some 7 km southeast of the Rafnes–Herøya Tunnel (Figs. 1 & 5). A 6 cm-thick phosphoritic limestone bed at the base of the shale is assumed equivalent with the *Exsulans* Limestone of the *Ptychagnostus gibbus* Zone (Schovsbo et al., 2018, fig. 3). The underlying *Paradoxides oelandicus* Superzone has only been found in the Caledonian Lower Allochthon in the Mjøsa area (Fig. 1A) outside the Oslo Region (Høyberget & Bruton, 2008).

According to Henningsmoen's (1957) measurements on a drillcore from Rognstranda 12 km south of the Rafnes–Herøya Tunnel (Figs. 1B & 5), the Furongian is about 12 m in thickness. Henningsmoen (1957) included the *Agnostus pisiformis* Zone in the Upper Cambrian at that time, but this zone is now assigned to the Miaolingian *Paradoxides forchhammeri* Superzone (see Nielsen & Ahlberg, 2019). Although no biozones are specifically determined from the Rognstranda core, the absence of the entire *Acerocarina* Superzone and the uppermost part of the *Peltura* Superzone is emphasised (Henningsmoen, 1957, p. 32, 1960, p. 137).

The Furongian of the Porsgrunn core is 14.8 m in thickness (Schovsbo et al., 2018) and recently, based on the gamma-ray (GR) correlation, the absence of the *Acerocarina* Superzone is also recognised from this core (Nielsen et al., 2020). Further interpretations of the GR log estimate the *Olenus* Superzone to be 1.6 m thick, the overlying *Parabolina* Superzone is 2.6 m, and the following *Leptoplastus* and *Protopeltura* superzones measure 0.9 m in combination. The succeeding *Peltura* Superzone slightly exceeds as much as 9 m in thickness, even in the absence of the *Parabolina megalops* Zone (Nielsen et al., 2020, table 1). The current investigation demonstrates a detailed trilobite zonation of the upper Miaolingian and upper Furongian strata in addition to those previously reported by Brøgger (1884) and Nielsen et al. (2020). The biostratigraphy and zonation of the Furongian Series described herein follow the revised superzonation and zonation provided by Nielsen et al. (2014; 2020). For comparison of zonal thicknesses of the Furongian strata throughout Scandinavia, see Nielsen et al. (2020, table 1).

A single, poorly preserved specimen of *Shumardia* was found at 2.7 m up in the Tremadocian section of the Alum Shale Formation (not figured), consisting of an internal cast of a cephalon showing the general shape and development of the genus. *Shumardia* has recently been discussed from the Tremadocian of Scandinavia (Ebbestad, 1999; Hoel, 1999). Wiman (1905) described *Shumardia (Conophrys) botnica* from the lower Tremadocian of Sweden, and Moberg (1900) recorded *Shumardia (Conophrys) oelandica* in the middle Tremadocian of Öland.

The *Paradoxides forchhammeri* Superzone (Miaolingian)

The material from the Rafnes–Herøya submarine tunnel contains agnostoids of the *Lejopyge laevigata* Zone and the *Agnostus pisiformis* Zone, thereby extending the Miaolingian succession of agnostoid zones in the district reported by Brøgger (1884).

The *Lejopyge laevigata* Zone is recognised by several agnostoid taxa confined to this zone, including *Goniagnostus aculeatus* (Angelin, 1851) (also assigned to the genera *Ptychagnostus* and *Acidusus* by others), *Cotalagnostus confusus* (Westergård, 1930 in Holm & Westergård, 1930) (Fig. 10A, B), *Agnostus neglectus* Westergård, 1946 (Fig. 10A) and the eponymous species *Lejopyge laevigata* (Dalman, 1828) (not figured). Fragments from larger and coarse-granulated exoskeletons are questionably assignable to *Paradoxides forchhammeri* Angelin, 1851. The *L. laevigata* Zone is previously reported from many districts in the Oslo Region and from the Caledonian Lower Allochthon strata (Høyberget & Bruton, 2008). The thickness of the *L. laevigata* Zone in the Herøya–Rafnes Tunnel cannot be established.

The *Agnostus pisiformis* Zone is recognised by scattered occurrences of *Agnostus pisiformis* (Wahlenberg, 1818) (Fig. 10C, D). Both cephala and pygidia were collected and the cephalon is characterised by simple, comparatively large and triangular basal lobes, the wide and concave border furrow and a median preglabellar furrow. The species occurs alone in the few samples presented in the material at hand. In the Eiker–Sandsvær District north of Skien–Langesund, the *Agnostus pisiformis* Zone exceeds a thickness of 12 metres (Brøgger, 1878; Høyberget & Bruton, 2008) and is elsewhere well known in the Oslo Region and from allochthonous surroundings (Høyberget & Bruton, 2008), but the thickness in the Skien–Langesund District is not known.

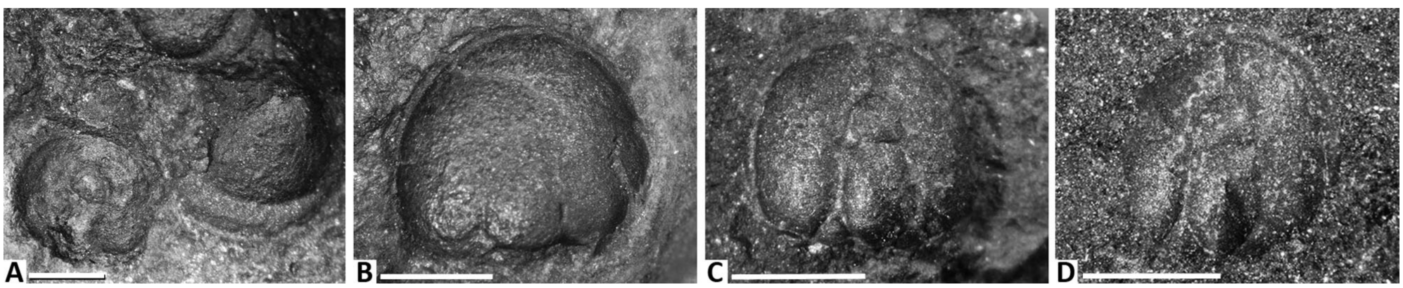

Figure 10. Agnostoids from the Paradoxides forchhammeri *Superzone, see Fig. 3 for location: (A)* Agnostus neglectus *Westergård (lower left), cranidium, PMO 235.062, and fragmented pygidia of* Cotalagnostus confusus *(Westergård) (upper and lower right),* L. laevigata *Zone. (B)* Cotalagnostus confusus*, cranidium, same slab and museum number as A. (C)* Agnostus pisiformis *(Wahlenberg), cranidium,* A. pisiformis *Zone. PMO 235.058 (D)* Agnostus pisiformis*, counterpart of cranidium,* A. pisiformis *Zone. PMO 235.061. All scale bars = 2 mm.*

The *Olenus–Protopeltura* superzones (Furongian)

The strata spanning the *Olenus, Parabolina, Leptoplastus* and the lower part of the *Protopeltura* superzones are currently not recorded, due to heavily fractured and concrete-covered rocks in the tunnel section (Fig. 3).

The *Sphaerophthalmus modestus–Sphaerophthalmus angustus* Zone (the uppermost zone in the *Protopeltura* Superzone) is indicated by the presence of both the eponymous taxa, which occur on the same bedding surface. The specimens are poorly preserved, but the subparallel-sided glabella, the long eye lobes and the very short (exsagittaly) post-ocular cheek are characteristic features of *Sphaerophthalmus modestus* (Henningsmoen, 1957) (Fig. 11A). *Sphaerophthalmus angustus* (Westergård, 1922) (Fig. 11B) is recognised by the tapering glabella with shallow furrows and the shape of the fixed cheeks.

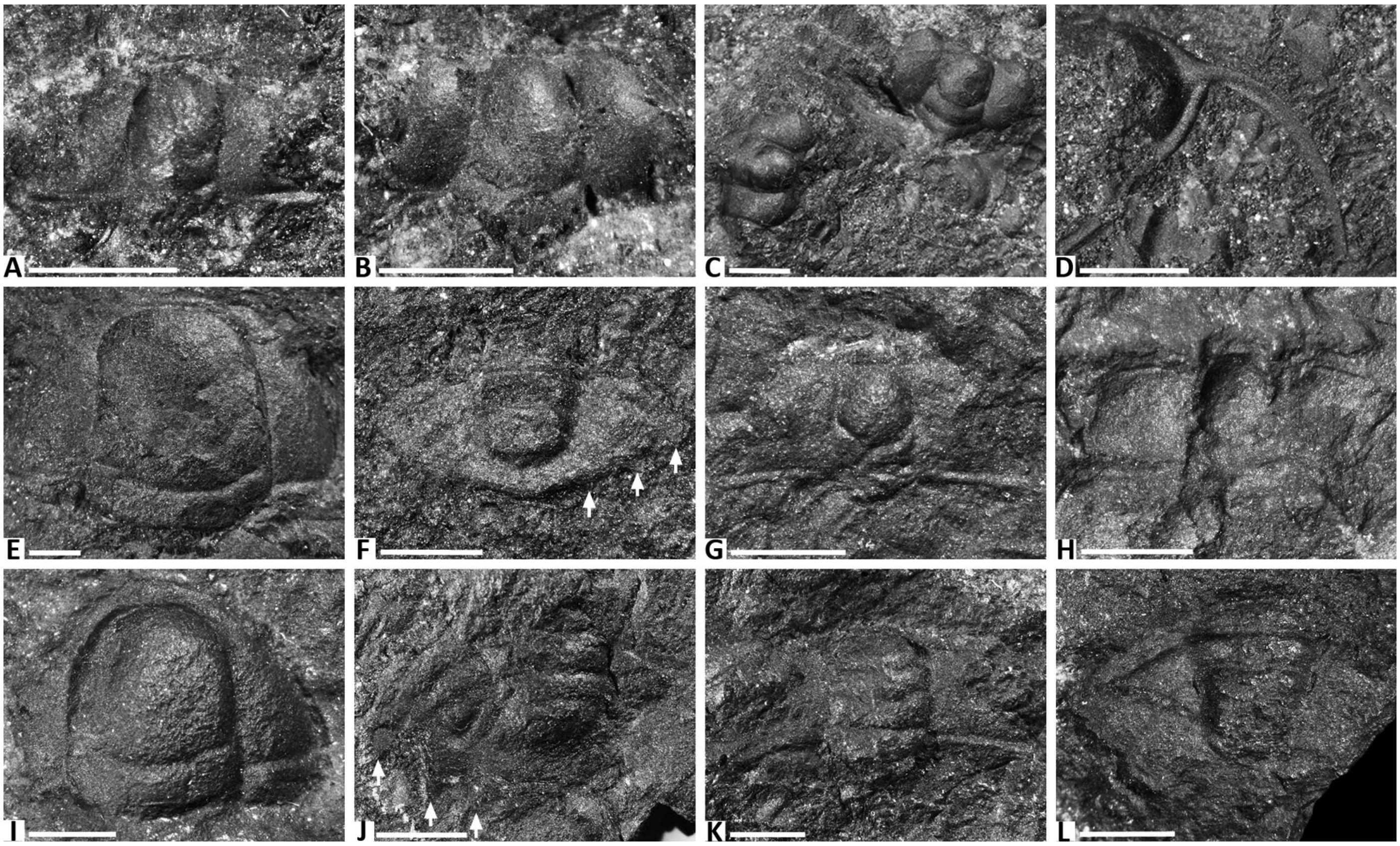

Figure 11. Trilobites from the Protopeltura *and* Peltura *superzones, see Fig. 3 for location: (A)* Sphaerophthalmus modestus *(Henningsmoen), cranidium. Note the very short (sag.) post-ocular cheek and subparallel glabella,* S. modestus–S. angustus *Zone, PMO 235.055. (B)* Sphaerophthalmus angustus *(Westergård), cranidium. Note the shallow glabellar furrows,* S. modestus–S. angustus *Zone, PMO 235.056. (C)* Sphaerophthalmus alatus *(Boeck), cranidia. Note the distinct glabellar furrows,* Peltura acutidens–Ctenopyge tumida *Zone, PMO 235.048. (D)* S. alatus, *librigena.* P. acutidens–C. tumida *Zone, PMO 235.049b. (E)* Peltura scarabaeoides scarabaeoides *(Wahlenberg), cranidium. P. scarabaeoides Zone, PMO 235.054. (F)* P. scarabaeoides scarabaeoides*, pygidium. Arrows point at the ventrally directed marginal spines.* P. scarabaeoides *Zone, PMO 235.050a. (G)* Ctenopyge pecten *(Salter), cranidium. Note the short (sag.) post-ocular cheek and oblique eye ridge.* P. scarabaeoides *Zone, PMO 235.053. (H)* Ctenopyge linnarssoni *Westergård, cranidium. Note the wide and prominent interocular region.* P. scarabaeoides *Zone, PMO 235.052. (I)* Peltura scarabaeoides westergaardi *Henningsmoen, cranidium.* Parabolina lobata *Zone, PMO 235.047. (J)* P. scarabaeoides westergaardi*, pygidium. Arrows point at the long posteriorly directed marginal spines.* P. lobata *Zone, PMO 235.038. (K)* Parabolina lobata *(Brøgger), cranidium. Note post-ocular cheek wider than glabella.* P. lobata *Zone, PMO 235.043. (L)* Peltura scarabaeoides *n. ssp., pygidium. Note undulating margin and comparatively narrow endlobe.* P. lobata *Zone, PMO 235.037. All scale bars = 2 mm.*

The *Peltura* Superzone (Furongian)

The *Peltura acutidens–Ctenopyge tumida* Zone is indicated by well-preserved specimens of *Sphaerophthalmus alatus* (Boeck, 1838) in abundance (Fig. 11C, D). The thickness of the zone is interpreted by gamma-ray (GR) correlation to be up to 1.3 m in the Porsgrunn core (Nielsen et al., 2020).

The overlying *Peltura scarabaeoides* Zone is quite thick, as reported from many districts in Scandinavia, comprising c. 6 m of the Porsgrunn core according to Nielsen et al. (2020). The fragmented sclerites from the Rafnes–Herøya tunnel are poorly preserved by compaction and metamorphism, but pygidia of *P. scarabaeoides* (Wahlenberg, 1818) (Fig. 11F) possessing the characteristically short and ventrally directed marginal spines are recognised. *Triangulopyge humilis* (Phillips, 1848), *Ctenopyge pecten* (Salter, 1864) (Fig. 11G) and *C. linnarssoni* Westergård, 1922 (Fig. 11H) sparsely co-occur with the eponymous species and are all confined to the *P. scarabaeoides* zone.

The presence of the stratigraphically succeeding *Parabolina lobata* Zone is indicated by determinable pygidia of *Peltura scarabaeoides westergaardi* (Henningsmoen, 1957) (Fig. 11J) and rare occurrences of *Parabolina lobata* (Brøgger, 1882) (Fig. 11K). *P. lobata* has transversally wide and exsagittaly short postocular cheeks, and *P. s. westergaardi* is recognised by the outline of the pygidial spines. A new subspecies of *Peltura scarabaeoides* (Fig. 11L), with an undulating and spineless margin of the pygidium, distinct co-marginal terrace lines and a slightly narrower axial endlobe compared to *P. s. westergaardi*, is also recognised from the tunnel material. This new subspecies is very common in the *P. lobata* Zone at Vestfossen in the Eiker–Sandsvær District, and more sparsely recognised from the Oslo–Asker District and from Västergötland, Sweden (MH, unpublished). *Peltura scarabaeoides* n. ssp. co-occurs everywhere with *P. s. westergaardi* and *P. lobata.* The cranidia of the three subspecies of *P. scarabaeoides* appear undifferentiated. According to Nielsen et al. (2020), the *Parabolina lobata* Zone is c. 2 m thick in the Porsgrunn core, based on GR correlation.

No trilobites indicative of the *Parabolina megalops* Zone are documented in the material from the Rafnes–Herøya Tunnel, in accordance with Henningsmoen (1960, p. 160) and the lack of correlative data in the Porsgrunn core (Nielsen et al., 2020). In line with an extremely low sea level, the zone is regionally only reported from Oslo and Slemmestad in Norway, and from the Scania District of southern Sweden (Nielsen et al., 2020).

The *Acerocarina* Superzone (Furongian)

Despite the reported absence of the entire *Acerocarina* Superzone in drillcores from Rognstranda (Henningsmoen, 1957, 1960) and Brevik (Nielsen et al., 2020), the present material located some 12 and 7 km from the drilling sites, respectively, contains trilobites indicative of the *Acerocarina granulata–Peltura costata* Zone. The thickness of the zone though, cannot be estimated, but an approximately 2 m-thick alum shale interval devoid of fossils is present between these trilobites and the lowermost Tremadocian graptolite. Small specimens of a pelturid taxon with the very small eye lobes placed far forwards are assigned to *Acerocarina micropyga* (Linnarsson, 1875) (Fig. 12A, B), a species only known to co-occur with *Peltura costata* (Brøgger, 1882) and *Parabolina heres* ssp. Brøgger, 1882 elsewhere in the Oslo Region (Nielsen et al., 2020) and confined to the *A. granulata–P. costata* Zone. Rather well-preserved specimens of *Parabolina heres* ssp. (Fig. 12C, D), showing the long preglabellar field and the comparatively narrow (tr.) fixigena, are recorded elsewhere in Scandinavia throughout the *Acerocarina* Superzone. Common fragments of a larger pelturine species may indicate the presence of *P. costata* as well (not figured).

Due to an increasing drop in the sea level towards the end of the Furongian (Nielsen et al., 2020), only the lowermost biozone of the *Acerocarina* Superzone is deposited in the Skien–Langesund District. This is also the case at Vestfossen in the Eiker–Sandsvær District farther north.

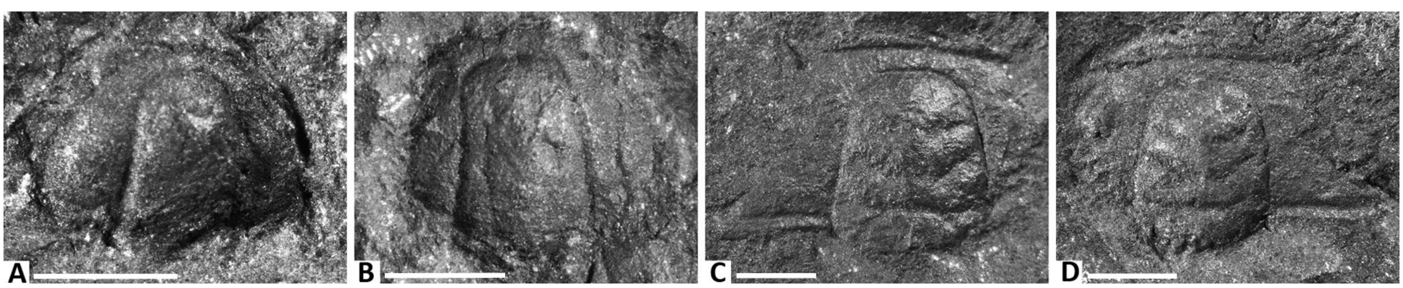

Figure 12. Trilobites from the Acerocarina *Superzone, see Fig. 3 for location: (A)* Acerocarina micropyga *(Linnarsson), partial cranidium, PMO 235.040. (B)* A. micropyga*, cranidium, showing compaction cracks, PMO 235.035. (C)* Parabolina heres *ssp. Brøgger, cranidium. Note long preglabellar field and post-ocular cheek narrower than glabella, PMO 235.039. (D)* P. heres *ssp., cranidium, PMO 235.045. All specimens from the* Acerocarina granulata–Peltura costata *Zone. All scale bars = 2 mm.*

Conclusions

A review of the stratigraphy and palaeontology of the geological section in the Rafsnes–Herøya submarine tunnel, Skien–Langesund District, southern Norway, documents the unconformity between the Alum Shale Formation (Furongian and Tremadocian) and Ordovician (Kundan) based on olenid and agnostoid trilobites and early graptolites. The area north of the Porsgrunn–Kristiansand Fault was part of a level, stable plaform undergoing erosion and non-deposition, while in the east, Tremadocian sediments were deposited in a synsedimentary basin between the Cambrian and the overlying Ordovician Huk Formation (Kundan in terms of Baltoscandian chronostratigraphy), and hence a unique stratigraphical Cambrian–Ordovician boundary succession is demonstrated.

Breaks in sedimentation have earlier been explained using a thrust model but this is not supported in a review of field data both here, in other areas of the Oslo Region and across the Baltic platform.

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