Graptolite biostratigraphy of the lower Silurian of the Sommerodde-1 core, Bornholm, Denmark

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The Sommerodde-1 core provides a continuous record through the subsurface of southern Bornholm from the Wenlock Series (Silurian) through to the Lower Cambrian. The Silurian graptolite biostratigraphy of the core is described. For the Rhuddanian and Aeronian (lower and middle Llandovery), the succession and thickness of biozones are very similar to those in the Øleå rivulet nearby. For the upper Llandovery, the lower Telychian *Spirograptus guerichi* and *Sp. turriculatus* biozones are significantly thicker in the core than in Øleå, whilst the uppermost Telychian (represented by more than 30 m of strata in nearby sections) is largely absent in the core. This is likely to be a reflection of synsedimentary faulting influencing deposition. It has previously been suggested that much of the Sheinwoodian is missing on Bornholm; this is not the case. The Sheinwoodian is represented by an apparently continuous sequence, at least 31 m thick, in the Sommerodde-1 core.

Keywords: Silurian, graptolite, Llandovery, Wenlock, biostratigraphy, Denmark.

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The purpose of this paper is to document the graptolite biostratigraphy of the lower Silurian of the Sommerodde-1 core, Bornholm. Initially, the work was to be undertaken simply to provide a biostratigraphical framework for ongoing geochemical studies with the expectation that the succession and thickness of Llandovery biozones would be very similar to those recorded by Bjerreskov (1975) from the Øleå and Læså sections less than 1.5 km and 8 km respectively west-north-west of the Sommerodde well site (Fig. 1). For the Rhuddanian and Aeronian this was indeed the case, but for the lowermost and particularly uppermost Telychian the succession in the Sommerodde-1 core surprisingly proved to be significantly different from the exposed sections. The differences and some possible explanations are discussed below. Sheinwoodian strata (i.e. base *Cyrtograptus murchisoni* Biozone to base *C. lundgreni* Biozone) are not exposed on Bornholm and it has been suggested that there is a stratigraphical gap at this level (Beier *et al.* 2000, fig. 3). Therefore, demonstrating whether any Sheinwoodian strata are in fact present in the Bornholm subsurface was an important aim of our work. Finally, lower Homerian graptolitic tuffaceous sandstones and mudstones have been recorded in boulders from the beach west of Sommerodde (Bjerreskov & Jørgensen 1983). Similar lithologies occur towards the top of the Sommerodde-1 core (unit G5 of Schovsbo *et al.* 2015). Dating the base of this unit (and therefore the onset of this sandstone deposition) was a further objective of our investigations.

The Sommerodde-1 core: locality and methods

The Sommerodde-1 core (DGU 248.62), with a diameter of 5.5 cm, was drilled November–December 2012 as close as technically possible to the Sommerodde beach locality on the southern coast of Bornholm described by Bjerreskov & Jørgensen (1983), where the youngest Silurian strata exposed on the island can be accessed at low tide (Schovsbo *et al.* 2015; Fig. 1). The youngest

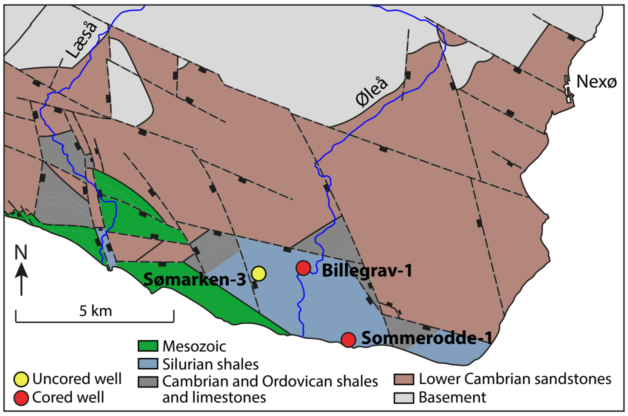


Fig. 1. Map of southern Bornholm showing the location of the Sommerodde-1 well and other wells, and stream and beach sections referred to in the text (modified from Schovsbo *et al.* 2015, fig. 2). Faults are marked by dashed lines (with black rectangle on downthrown side).

Palaeozoic strata, of Wenlock age, were encountered at 6.5 m in the core. The well had a termination depth of 250.3 m, within the Lower Cambrian. The GPS co-ordinates of the Sommerodde-1 borehole location are 54.997202° latitude, 15.01870836° longitude (WGS84 geode); for other details, please go to http://data.geus.dk/JupiterWWW/borerapport.jsp?borid=472234.

The core was sampled for graptolite biostratigraphy by DKL and NW during early August and early September 2016. Given that Koren' & Bjerreskov (1997) had described the upper Hirnantian – middle Rhuddanian graptolite biostratigraphy of the Billegrav-1 core 3 km north-west of Sommerodde-1, and in order to retain the integrity of the core as far as possible, only limited sampling was made of this stratigraphical interval. Likewise, as the thickness of the *Metabolograptus persculptus* Biozone to the upper *Lituigraptus convolutus* Biozone strata in the Sommerodde-1 core was almost identical to that recorded by Bjerreskov (1975) and Koren' & Bjerreskov (1997) who monographed the graptolites from the Øleå section and adjacent Billegrav-1 core, collections were made simply to establish graptolite biozones where possible (Fig. 2), again with the aim of minimizing damage to the core through sampling. For the Telychian and Wenlock, however, samples were collected at some levels more intensively, in part because preliminary examination of the core revealed significant differences in the Telychian from that exposed in the Øleå and Læså sections, and for the Wenlock because Sheinwoodian strata had not previously been recorded from Bornholm. Inevitably, with only 5.5 cm diameter nearly horizontal bedding surfaces available, there were some levels within the core where key biostratigraphical indicators were not found and thus biozonal boundaries are uncertain.

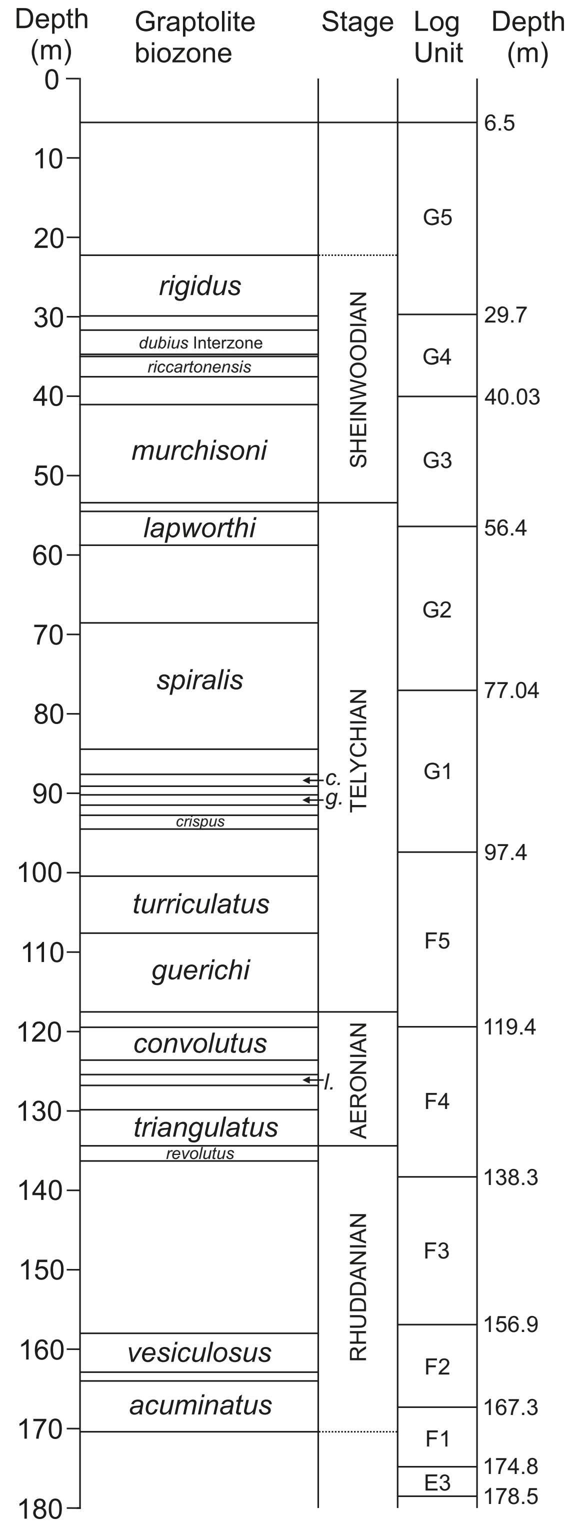


Fig. 2. Summary of the graptolite biozones recognized in the Sommerodde-1 core. Intervals not assigned to a graptolite biozone did not possess biostratigraphically definitive graptolite assemblages. The boundary between the "Rastites Shale" and "Cyrtograptus Shale" is at the same level as between log units F5 and G1, at 97.4 m. Graptolite genus names are omitted. Abbreviations: *c.* – *crenulata*; *g.* – *griestoniensis*; *l.* – *leptotheca*.

Fig. 3. Sommerodde-1 core boxes 44 (left) and 39 (right). Core box 44 (162.63–166.50 m) is entirely within log stratigraphical unit F2 and includes the transition from the *Parakidograptus acuminatus* Biozone to the *Cystograptus vesiculosus* Biozone (Rhuddanian). Core box 39 (144.67–148.20 m) is entirely within the highly distinctive log stratigraphical unit F3, comprising alternating dark grey mudstones and pale grey carbonate cemented horizons, and is of Rhuddanian (most probably *Cystograptus vesiculosus* Zone) age.

Fig. 4. Sommerodde-1 core boxes 32 (left) and 28 (right). Core box 32 (118.66–122.36 m) includes the top of log stratigraphical unit F4, comprising very dark mudstones of *Lituigraptus convolutus* Zone (Aeronian) age and the lowermost part of log stratigraphical unit F5 which consists of unfossiliferous grey silty mudstones. Core box 28 (103.93–107.40 m) is higher within log stratigraphical unit F5 and is entirely of *Spirograptus turriculatus* Zone (Telychian) age.

Fig. 5. Sommerodde-1 core boxes 22 (left) and 19 (right). Core box 22 (83.15–86.60 m) is entirely within log stratigraphical unit G1. Graptolites from the lower part of the *Oktavites spiralis* Biozone (Telychian) occur between 83.75 m and 84.38 m. Core box 19 (71.80–75.45 m) is entirely within log stratigraphical unit G2, dominated by greenish grey mudstones, of middle *Oktavites spiralis* Zone (Telychian) age.

Fig. 6. Sommerodde-1 core boxes 14 (left) and 13 (right). Core box 14 (53.65–57.07 m) includes the boundary between log stratigraphical units G2 and G3, the base of G3 (at 56.4 m) marked by the base of the pale limestone. The highest *Cyrtograptus lapworthi* Biozone (Telychian) graptolites occur at 54.50 m. Above this level in this core box only long-ranging species were found. Core box 13 (50.10–53.65 m) is entirely within log stratigraphical unit G3, monotonous grey mudstones, with the lowest Sheinwoodian graptolite (*Cyrtograptus murchisoni*) recorded at 53.37 m.

Fig. 7. Sommerodde-1 core boxes 9 (left) and 6 (right). Core box 9 (35.52–38.90 m) is entirely within log stratigraphical unit G4, monotonous dark grey mudstones. The base of the *Monograptus riccartonensis* Biozone (Sheinwoodian) is at 37.52 m. Core box 6 (24.50–28.20 m) is entirely within the lower part of log stratigraphical unit G5, interbedded siltstones/sandstones and mudstones. The core in this box is entirely of *Cyrtograptus rigidus* (late Sheinwoodian) age.

Fig. 8. Locations of sections referred to in the text with sedimentation influenced by the migration of the depocentre within the Baltic peripheral foreland basin (modified from Schovsbo *et al.* 2016, fig. 1)

This affects, for example, from a depth of 22.12 m (the highest level with the upper Sheinwoodian index species *Cyrtograptus rigidus*; see Fig. 17A) to 6.5 m (the highest Silurian strata within the core) within which only long-ranging species (particularly *Monograptus flemingii*; see Fig. 18A) were seen.

A total of 330 samples bearing graptolites identifiable to species level was examined and yielded a total of 120 species. Undoubtedly the overall diversity of graptolites is much higher in the core, particularly in the Rhuddanian and Aeronian.

The core has been photographed in its entirety. Representative examples of lithologies and the transition from the Llandovery to the Wenlock Series are shown in Figs 3–7.

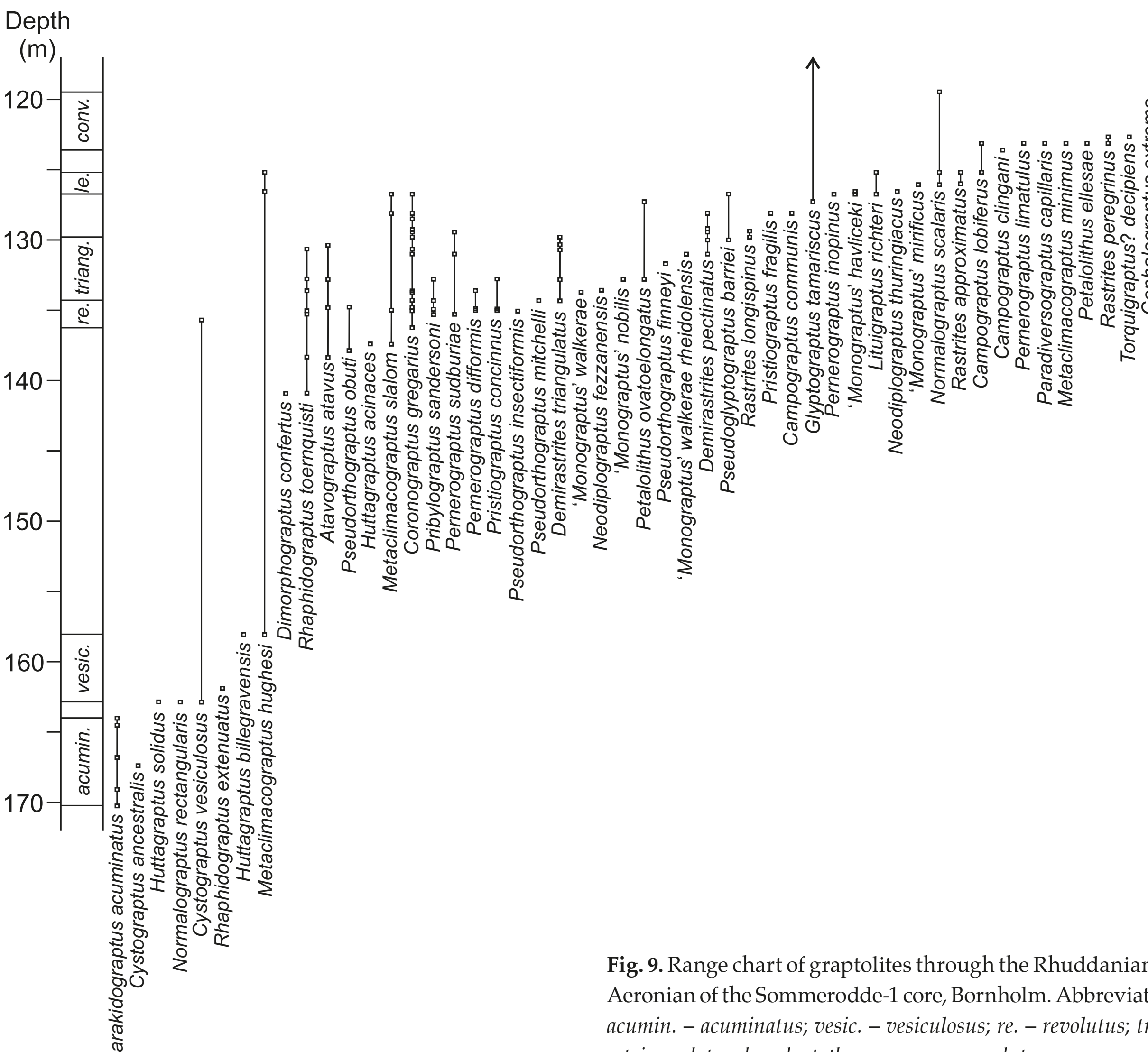


Fig. 9. Range chart of graptolites through the Rhuddanian and Aeronian of the Sommerodde-1 core, Bornholm. Abbreviations: *acumin.* – *acuminatus*; *vesic.* – *vesiculosus*; *re.* – *revolutus*; *triang.* – *triangulatus*; *le.* – *leptotheca*; *conv.* – *convolutus*.

Geological setting: the Baltic peripheral foreland basin

During the Silurian the Bornholm area lay within the peri-Tornquist sub-basin of the Baltic peripheral foreland basin generated as a result of the ongoing oblique collision of Baltica and Avalonia. Water depth was estimated by Bjerreskov & Jørgensen (1983) to have been 1000 ± 300 m during the early Homerian. Beier *et al.* (2000) and Jaworowski (2000) recorded the delayed appearance north-eastwards of turbiditic strata from the Caledonian Deformation Front (CDF), indicating migration of the depocentre within the basin. In the offshore German G14-1/86 well (Fig. 8), drilled *c.* 33 km north-east of Rügen, the lowermost Telychian *Spirograptus guerichi* Biozone is in excess of 150 m thick (based upon the First Appearance Datum (FAD) of *Spirograptus guerichi* and Last Appearance Datum (LAD) of *Glyptograptus fastigatus* shown by Maletz 1997, fig. 1) with dominant facies including turbiditic sandstones (McCann 1996). This compares with the *c.* 10 m thick *guerichi* Biozone in the Sommerodde-1 core, consisting primarily of mudstones. Somewhat further from the CDF, the *Streptograptus crispus* Biozone in the Slagelse-1 borehole (Fig. 8) is recorded from depths of 2811 m to 2637 m (Vecoli & Samuelsson 2001) and is thus dramatically expanded (174 m thick) by comparison with Bornholm where the biozone is at most 7.5 m thick in the Sommerodde-1 core. Moving much further to the north-east of the CDF, on Bornholm turbidites are not recorded until the Wenlock Series, from the lower Homerian *lundgreni* Biozone (Bjerreskov & Jørgensen 1983; Böhnke & Katzung 2001) and from the upper Sheinwoodian *rigidus* Biozone in the Sommerodde-1 core. Turbiditic and/or storm sandstones of *rigidus* Zone age were also recorded by Bjerreskov (1986) from the Maglarp 1 well (Fig. 8), Scania (Sweden) at a similar distance from the CDF to Bornholm. Similarly, Beier *et al.* (2000) stated that Vejbæk *et al.* (1994) had recorded more than 370 m of turbiditic siltstones and shales from the middle and upper Wenlock of the Pernille-1 well (depths 3245 m to 3622 m), *c.* 30 km south-west of Bornholm (Fig. 8). Note, however, that Bjerreskov (1992) examined graptolites from the Pernille-1 well only from the 3615 m to 3623 m interval. The assemblages were dominated by long-ranging species, but included *Cyrtograptus perneri*, based upon which Bjerreskov (1992) assigned the strata to the upper Sheinwoodian. The stratigraphical range of *C. perneri* has subsequently been shown by Williams & Zalasiewicz (2004) to extend well into the lower Homerian *lundgreni* Biozone. The age of the 8 m of strata examined by Bjerreskov (1992) is therefore either late Sheinwoodian or early Homerian. Finally, at an even greater distance northeastwards from the CDF, at Örup (Fig. 8) in Scania (Sweden), sandy-siltstone turbidites appear in the Gorstian (Lindström 1960).

Changes to the graptolite biozonation since the work of Bjerreskov (1975)

Below we discuss previous work on Silurian graptolitic strata on Bornholm and then describe and compare the Sommerodde-1 core record with previously published work, in particular the monographic study by Bjerreskov (1975). As there have been some changes to the Llandovery graptolite biozonation and revisions of some taxa since Bjerreskov's (1975) work, those that affect definitions or interpretations of her biozones are discussed here.

Bjerreskov (1975) referred strata yielding *Akidograptus ascensus*, but not *Parakidograptus acuminatus*, from the Bavnegård well (renamed Sømarken-3 by Pedersen & Klitten 1990; Fig. 1), 1 km west of the Øleå section, to the *acuminatus* Biozone. Subsequently, Koren' & Bjerreskov (1997) showed in the Billegrav-1 core (drilled immediately adjacent to the Øleå section; Fig. 1) that the FAD of *A. ascensus* was 4.7 m vertically below that of *Pa. acuminatus* and therefore they recognized separate *ascensus* and *acuminatus* biozones. The LADs of *A. ascensus* and *Pa. acuminatus* in the Billegrav-1 core were at the same depth. It is thus very likely that the strata from the Bavnegård [= Sømarken-3] well assigned by Bjerreskov to the *acuminatus* Biozone would now largely (or perhaps entirely) be assigned to the *ascensus* Biozone.

The stratigraphically lowest exposed strata in the Øleå section are of mid Rhuddanian age and were assigned by Bjerreskov (1975) to the *Huttagraptus acinaces* Biozone. This interval is referred to the *Cystograptus vesiculosus* Biozone in many regions (Loydell 2012). Bjerreskov (1975) used the *acinaces* Biozone in preference to the *vesiculosus* Biozone because *Cystograptus vesiculosus* was restricted to a 0.5 m thickness of the section. In the Billegrav-1 core, however, *C. vesiculosus* was found by Koren' & Bjerreskov (1997) to be present at numerous levels, with its FAD a short distance above the LADs of *A. ascensus* and *Pa. acuminatus*. The FAD of *Huttagraptus acinaces* in the Billegrav-1 core was about 2 m above that of *C. vesiculosus* and about 3 m below that of *Atavograptus atavus*. In Great Britain the *acinaces* Biozone is *underlain* by the *atavus* Biozone (Zalasiewicz *et al.* 2009), so the relative order of appearance is reversed in the Billegrav-1 core and the FAD of *H. acinaces* is stratigraphically very low. Use of a middle Rhuddanian *vesiculosus* Biozone (following the approach of Koren' & Bjerreskov 1997) therefore seems preferable to recognition of separate *atavus* and *acinaces* biozones.

Bjerreskov (1975) recorded that the basal part of her *Coronograptus gregarius* Biozone was characterized by the FADs of both *Coronograptus gregarius* and *Demirastrites triangulatus*. The presence of the latter indicates the Aeronian Stage. Exposure was poor in the lowermost part of her *gregarius* Biozone and lacking for more than 3 m beneath this level. Elsewhere in the world, *Co. gregarius* has its FAD in the upper Rhuddanian: in the *Pernerograptus revolutus* Biozone (e.g. Zalasiewicz *et al*. 2009) or broadly equivalent *Coronograptus cyphus* Biozone (e.g. Štorch 2015). It is usual now in Europe to subdivide the lower half of the Aeronian into three biozones. In ascending order in Avalonia these are *Demirastrites triangulatus*, *Neodiplograptus magnus* and *Pribylograptus leptotheca* whereas in peri-Gondwanan Europe there are *Demirastrites triangulatus*-*D. pectinatus*, *D. simulans* and *P. leptotheca* biozones. *Neodiplograptus magnus* has not been recorded from Bornholm, whereas Øleå is the type locality for *D. simulans*, so it would seem that the peri-Gondwanan (rather than the Avalonian) biozonation for the lower Aeronian can be applied more successfully on Bornholm.

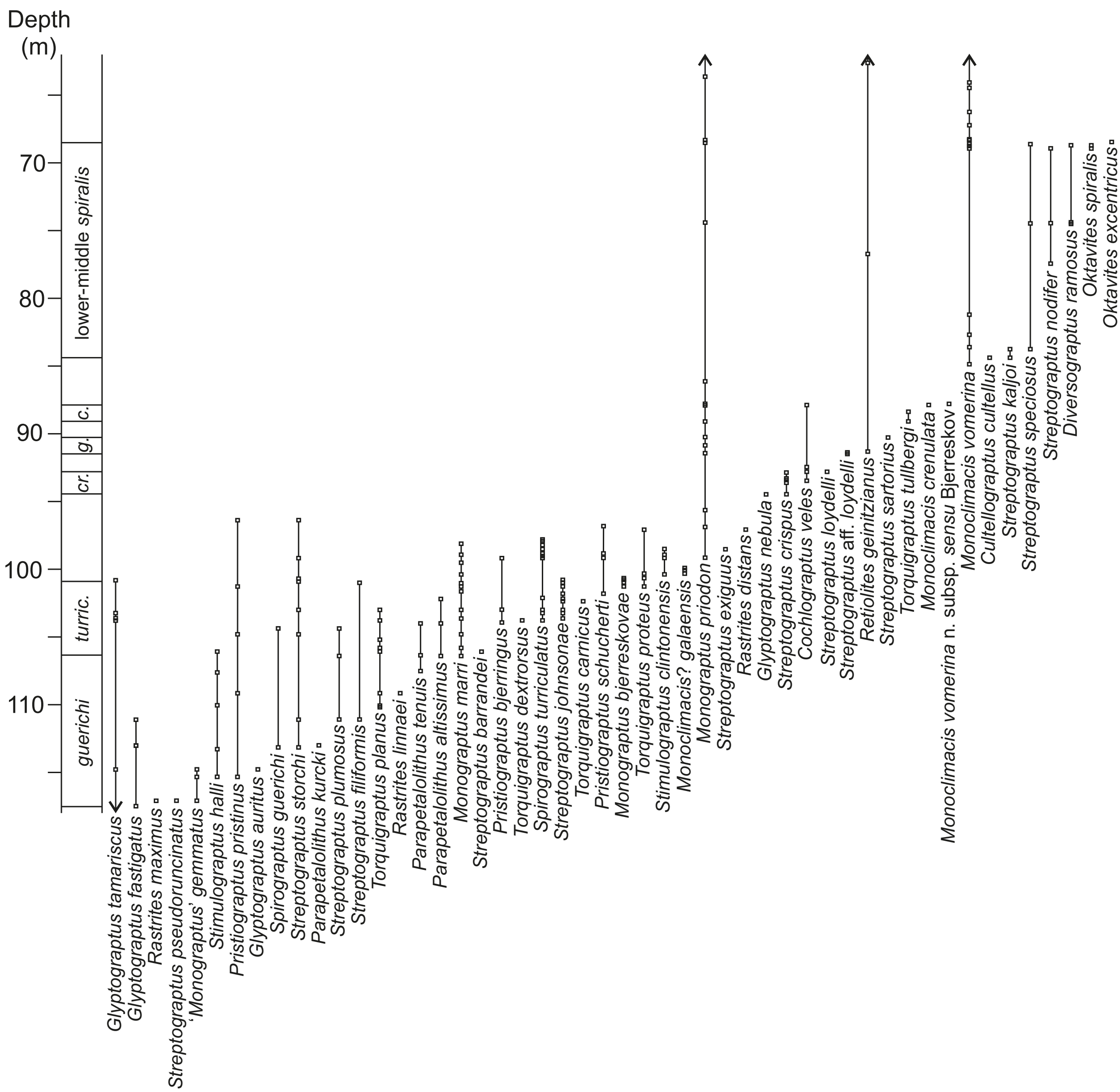


Fig. 10. Range chart of graptolites through much of the Telychian of the Sommerodde-1 core, Bornholm. Abbreviations: *turric.* – *turriculatus; cr.* – *crispus; g.* – *griestoniensis; c.* – *crenulata.*

Bjerreskov (1975) illustrated two species under the name *Monograptus* [now *Lituigraptus*] *convolutus*. That figured in her plate 12, figure D is *L. convolutus*; her figure 23F, however, depicts *L. richteri*, a species indicative of the *leptotheca* Biozone (Štorch 1998). In addition, Bjerreskov (1975) recorded *Petalolithus folium* from the lower part of her *convolutus* Biozone. *Petalolithus folium* is far more typical of the *leptotheca* Biozone (Štorch 1998) than of the *convolutus* Biozone into which its stratigraphical range only just extends (Štorch 1998). Bjerreskov's (1975) *convolutus* Biozone therefore comprises what would today be assigned to the upper part of the *leptotheca* Biozone as well as the *convolutus* Biozone *sensu stricto*.

Loydell *et al.* (1993) divided the lowermost Telychian *Spirograptus turriculatus* Biozone into two: a *Spirograptus guerichi* Biozone succeeded by a *S. turriculatus* Biozone. Both biozones are present in the Øleå section. Above the *turriculatus* Biozone, the biozones used by Bjerreskov (1975) are those currently widely used. It is likely that her *griestoniensis* Biozone includes in its upper part strata that would now be assigned to the *Monoclimacis crenulata* Biozone (based upon our records of this biozone in the Sommerodde-1 core).

Towards the top of the Telychian, although *Cyrtograptus insectus* was found in the Øleå section by Bjerreskov (1975), it was from a level above the FAD of *Cy. centrifugus*. *Cyrtograptus insectus* ranges into the lower part of the *centrifugus* Biozone (Štorch 1994a), but has its FAD in Wales (Loydell & Cave 1996) and Bohemia (Štorch 1994a) below that of *Cy. centrifugus* where an *insectus* Biozone is recognized. If strata of *insectus*

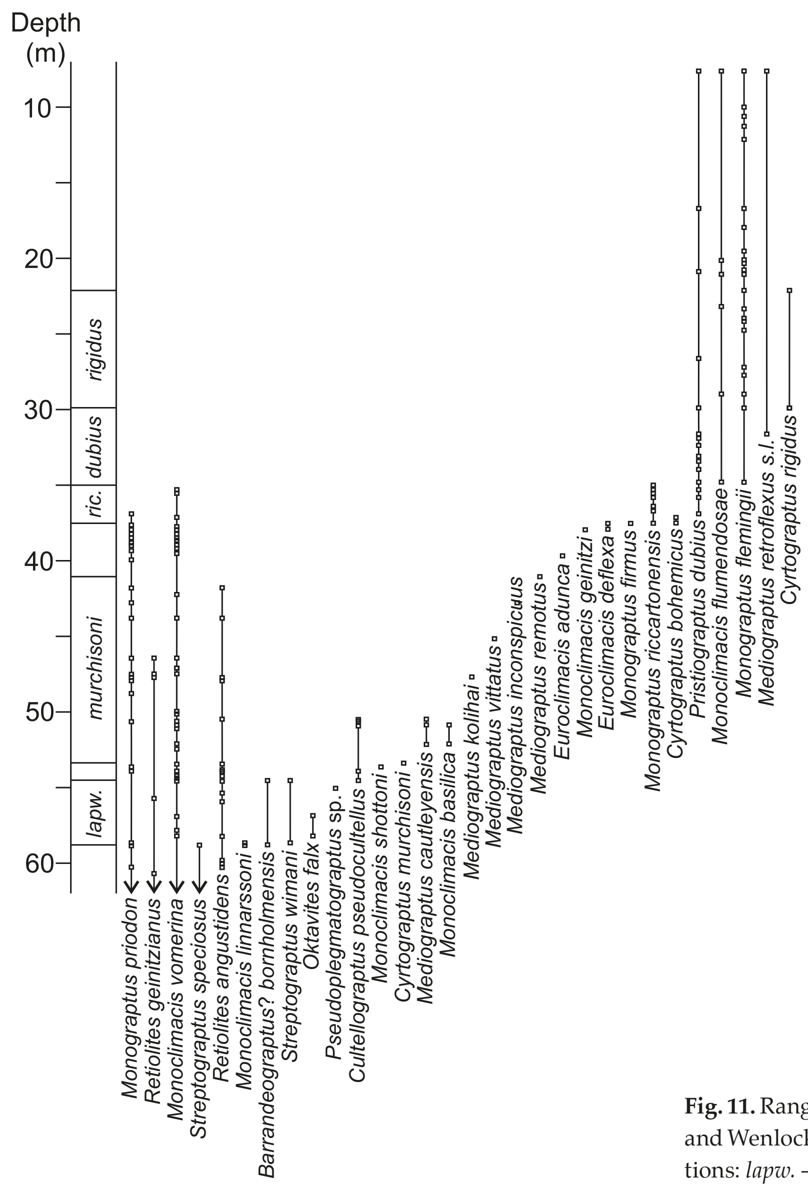
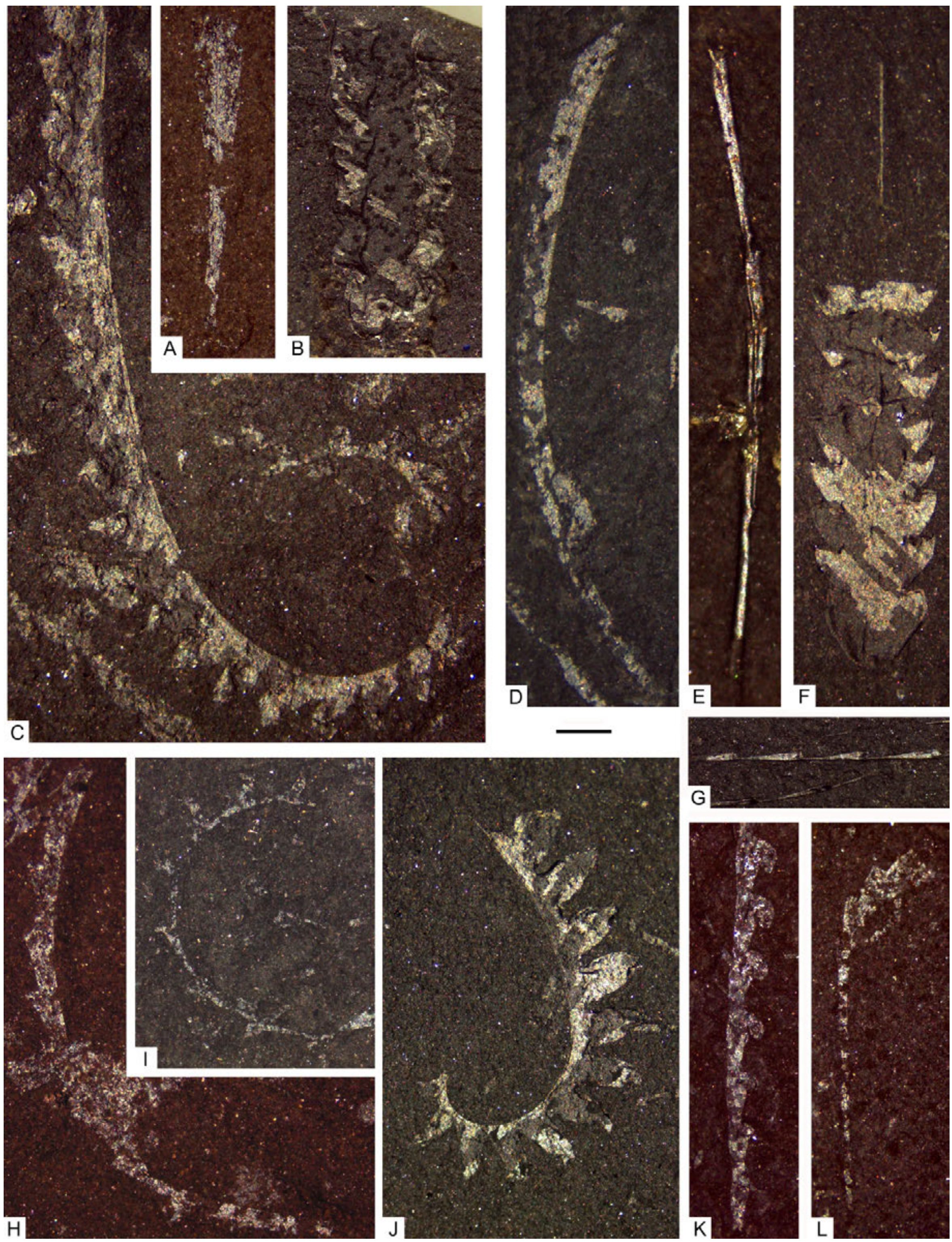


Fig. 11. Range chart of graptolites through the upper Telychian and Wenlock of the Sommerodde-1 core, Bornholm. Abbreviations: *lapw.* – *lapworthi*; *ric.* – *riccartonensis*.

Zone age occur in the Øleå section they presumably are those assigned by Bjerreskov (1975) to the upper *Cy. lapworthi* Biozone from which she described the fauna as "impoverished" and containing only stratigraphically long-ranging species and small fragments of *Cyrtograptus*.



Late twentieth century graptolite biostratigraphical work on Bornholm

Bjerreskov (1975) summarized work prior to her research on the Silurian of Bornholm; the reader is referred to her monograph for details of publications from the nineteenth and first half of the twentieth century.

The most important section studied by Bjerreskov (1975) was that along the rivulet Øleå which exposes strata ranging from the middle Rhuddanian *acinaces* [now = *vesiculosus*] Biozone to the uppermost Telychian *centrifugus* Biozone with an overall stratigraphical thickness in excess of 110 m. Two Telychian biozones (*Oktavites spiralis* and *Cy. centrifugus*) were shown to comprise approximately half of the overall thickness. Bjerreskov's (1975) figure 5 very usefully shows the extent of exposure of the various stratigraphical levels. Overall, significantly less than half of the interpreted total stratigraphical thickness of the section is represented by exposures, with some of Bjerreskov's biozones (e.g. *gregarius*) well exposed (>75% exposure) and others much less so (e.g. *spiralis*: about one-third of the overall stratigraphical thickness is exposed; and *revolutus*: only 60 cm exposed). As a result, Bjerreskov's placement of some biozonal boundaries and estimates of biozonal thicknesses of necessity were approximate.

A faulted section along the rivulet Læså, approximately 6 km west of Øleå, and a continuous exposure along the coastal shoreline east of the mouth of the Læså, provided Bjerreskov (1975) with additional exposures of the Telychian *crispus*, *spiralis* and *lapworthi* biozones together with a nearly 30 m thick continuously exposed section through the uppermost Telychian *centrifugus* Biozone.

Bjerreskov's (1975) only material from the upper Hirnantian (*persculptus* Biozone) through to the *acinaces* Biozone (middle Rhuddanian) was from the Bavnegård [=Sømarken-3] well, drilled 1 km due west of Bjerreskov's Øleå locality 8. Here, 4.4 m (vertical thickness) of *persculptus* Biozone is overlain by 5 m yielding *Akidograptus ascensus*, succeeded by a further 10.5 m yielding *Dimorphograptus* and therefore post-*acuminatus* Zone in age. *Parakidograptus acuminatus* was not encountered.

Koren' & Bjerreskov (1997) described in detail the monograptids from the Billegrav-1 core, drilled on the north-west side of the Øleå rivulet, adjacent to Bjerreskov's (1975) locality 4. They also provided a range chart of all graptolites from the core ranging from the upper Hirnantian (*persculptus* Biozone) through to the highest strata in the core from the middle Rhuddanian (*vesiculosus* Biozone). Bjerreskov (1975, fig. 2) recorded a 12° southerly stratal dip. Allowing for this dip, stratigraphical thicknesses in the Billegrav-1 core are as follows: *persculptus* Biozone – 2.1 m; *ascensus* Biozone – 4.6 m; *acuminatus* Biozone – 3.5 m; and (incomplete) *vesiculosus* Biozone – 16.55 m.

Strata stratigraphically higher than the *centrifugus* Biozone (the uppermost Telychian biozone, immediately below the *murchisoni* Biozone) have not been recorded from exposures on Bornholm. Bjerreskov & Jørgensen (1983), however, described the sedimentology and graptolite fauna of boulders of tuffaceous sandstone and dark mudstone on the beach for 1 km west from Sommerodde. They considered that the boulders were derived from a 20–25 m thick sequence. The sandstones yielded very abundant but low diversity, often current-oriented graptolite assemblages comprising *Monograptus flemingii*, *Pristiograptus pseudodubius* and *P.* sp.. More diverse assemblages were recorded from the mudstones and included common *Cyrtograptus hamatus* and a single *Cy. lundgreni*, both indicative of the lower Homerian (upper Wenlock) *lundgreni* Biozone.

Graptolite biostratigraphy of the Sommerodde-1 core

Range charts showing all of the species identified, together with the graptolite biozones recognized, are provided as Figs 9–11. Graptolites from the core,

◀ **Fig. 12.** Graptolites from the Rhuddanian and Aeronian of the Sommerodde-1 core, Bornholm. Scale bar represents 1mm (A–D, F–L) or 0.5 mm (E). **A:** *Parakidograptus acuminatus* (Nicholson), MGUH 31.632, 170.23 m, *acuminatus* Biozone. **B:** *Cystograptus vesiculosus* (Nicholson), MGUH 31.633, 135.68 m, *revolutus* Biozone. **C:** *Pernerograptus difformis* (Törnquist), MGUH 31.634, 133.62 m, *triangulatus* Biozone. **D:** *Huttagraptus solidus* Štorch & Feist, MGUH 31.635, 162.86 m, *vesiculosus* Biozone. **E:** *Huttagraptus acinaces* (Törnquist), MGUH 31.636, 137.33 m, *vesiculosus* Biozone or *revolutus* Biozone. **F:** *Cystograptus ancestralis* Štorch, MGUH 31.637, 167.40–167.41 m, *acuminatus* Biozone. **G:** *Pristiograptus fragilis* (Rickards), MGUH 31.638, 128.12 m, between the *triangulatus* and *leptotheca* biozones. **H:** *Coronograptus gregarius* (Lapworth), MGUH 31.639, 136.24–136.25 m, *revolutus* Biozone. **I:** '*Monograptus*' *nobilis* Törnquist, MGUH 31.640, 132.78–132.79 m, *triangulatus* Biozone. **J:** *Demirastrites pectinatus* (Richter), MGUH 31.641, 129.26 m, upper *triangulatus* or *magnus* Biozone. **K:** *Campograptus lobiferus* (M^cCoy), MGUH 31.642, 123.12–123.13 m, *convolutus* Biozone. **L:** *Pernerograptus limatulus* (Törnquist), MGUH 31.643, 123.12–123.13 m, *convolutus* Biozone.

including those of greatest stratigraphical importance, are illustrated in Figs 12–19. The figured graptolites are housed at the Natural History Museum of Denmark, MGUH 31.632–31.708. Graptolite preservation is highly variable within the core, from quite poorly preserved flattened specimens through to three dimensional pyrite internal moulds with surrounding periderm. None of the specimens showed evidence of tectonic distortion.

The lowest sample examined, from 170.23 m, yielded *Parakidograptus acuminatus* (Fig. 12A), indicating the *acuminatus* Biozone. *Cystograptus ancestralis* (Fig. 12F) was found in the 167.40–167.41 m sample. This species is restricted to the upper *ascensus* to approximately

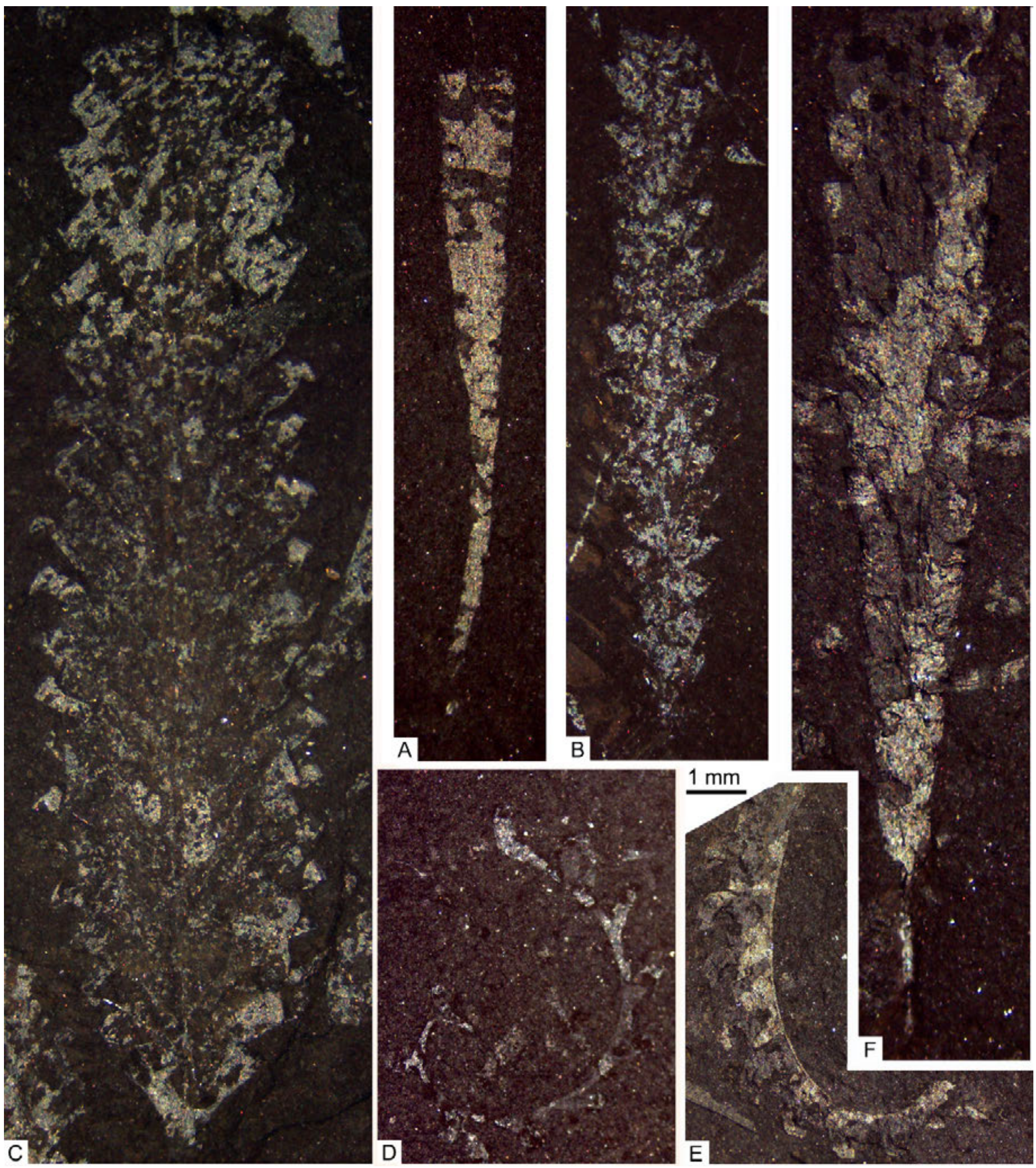


Fig. 13. Graptolites from the Rhuddanian and Aeronian of the Sommerodde-1 core, Bornholm. **A:** *Rhaphidograptus extenuatus* (Elles & Wood), MGUH 31.644, 161.90 m, *vesiculosus* Biozone. **B:** *Pseudorthograptus mitchelli* Štorch, MGUH 31.645, 134.30 m, *triangulatus* Biozone. **C:** *Petalolithus ovatoelongatus* (Kurck), MGUH 31.646, 132.78–132.79 m, *triangulatus* Biozone. **D:** *Torquigraptus*? *decipiens* (Törnquist), MGUH 31.647, 122.68 m, *convolutus* Biozone. **E:** *Campograptus clingani* (Carruthers), MGUH 31.648, 123.60–123.61 m, *convolutus* Biozone. **F:** *Rickardsograptus thuringiacus* (Kirste), MGUH 31.649, 126.56 m, *leptotheca* Biozone.

lower half of the *acuminatus* Biozone (Štorch 1996; Koren' & Bjerreskov 1997). The base of the *vesiculosus* Biozone must lie between the highest sample with *Pa. acuminatus* (164.02 m) and the lowest with *Cystograptus vesiculosus* (162.86 m). *Huttagraptus solidus* (Fig. 12D) is also present in the 162.86 m sample. This species is restricted to the lower part of the *vesiculosus* Biozone in the Billegrav-1 core (where it was recorded by Koren' & Bjerreskov 1997 as *Huttagraptus* sp. 1). As noted above, in order to retain the integrity of the core and because Koren' & Bjerreskov (1997) had undertaken such a detailed study of the *vesiculosus* Biozone in the Billegrav-1 core, few samples were taken from the middle Rhuddanian. It is worth noting that Koren' & Bjerreskov (1997) recorded a vertical thickness of 16.9 m of *vesiculosus* Biozone in the Billegrav-1 core and that Bjerreskov's (1975) *acinaces* [= *vesiculosus*] Biozone extended upwards to *c.* 5.5 m stratigraphically below the FAD of *Demirastrites triangulatus* which marks the base of the Aeronian. It is very likely, therefore, that most of the Rhuddanian interval in the Sommerodde-1 core shown on Figs 2, 9 and 20 as unzoned belongs within the *vesiculosus* Biozone.

The lowest sample that could be assigned confidently to the upper Rhuddanian *revolutus* Biozone was from 136.24–136.25 m. At this level *Coronograptus gregarius* (Fig. 12H) was represented by typical stratigraphically early specimens with narrow rhabdosomes and a 4 mm long sicula. The presence of *C. vesiculosus* (Fig. 12B) at 135.68 m demonstrates that this level is still within the lower part of the *revolutus* Biozone (Zalasiewicz *et al.* 2009). By 135.05 m a higher level in the *revolutus* Biozone (Zalasiewicz *et al.* 2009; Štorch 2015) is indicated by *Pernerograptus difformis* (Fig. 12C).

Demirastrites triangulatus (Fig. 14H), index species of the lowest Aeronian biozone, was first encountered at 134.30 m. *Pseudorthograptus finneyi* (Fig. 14G), a species recorded only from the lower part of the *triangulatus* Biozone (Štorch 2015) was found at 131.69 m. *Demirastrites pectinatus*, indicative of the upper *triangulatus* and *magnus* biozones in Britain (recorded as *Monograptus triangulatus fimbriatus* by Zalasiewicz *et al.* 2009), was first encountered in the 131.01–131.02 m sample. Strata from this level up to at least 129.80 m (highest occurrence of *D. triangulatus*) can be assigned to the upper *triangulatus* Biozone. Strata above this, up to 128.11 m (the LAD of *D. pectinatus*), belong either within the upper *triangulatus* Biozone or the *magnus* Biozone.

The lowest level assignable to the *leptotheca* Biozone was at 126.75 m, where several taxa (*Lituigraptus richteri* (Fig. 14B), *Pernerograptus inopinus*, '*Monograptus*' *havliceki*) typical of this biozone (Štorch 1998) were found. *Lituigraptus richteri* occurs also at 125.19 m. In the 123.60–123.61 m sample the presence of *Campograptus clingani* (Fig. 13E) indicates the *convolutus* Biozone (Štorch 1998; Zalasiewicz *et al.* 2009). *Cephalograptus extrema* (Fig. 14K), which first appears in the upper *convolutus* Biozone, was found at 119.46 m, only 6 cm below the base of the unfossiliferous silt- and mudstones (base of Schovsbo *et al.*'s 2015 unit F5). Bjerreskov (1975) had found *Ce. extrema* to be restricted to the uppermost 10 cm of the *convolutus* Biozone in the Øleå section.

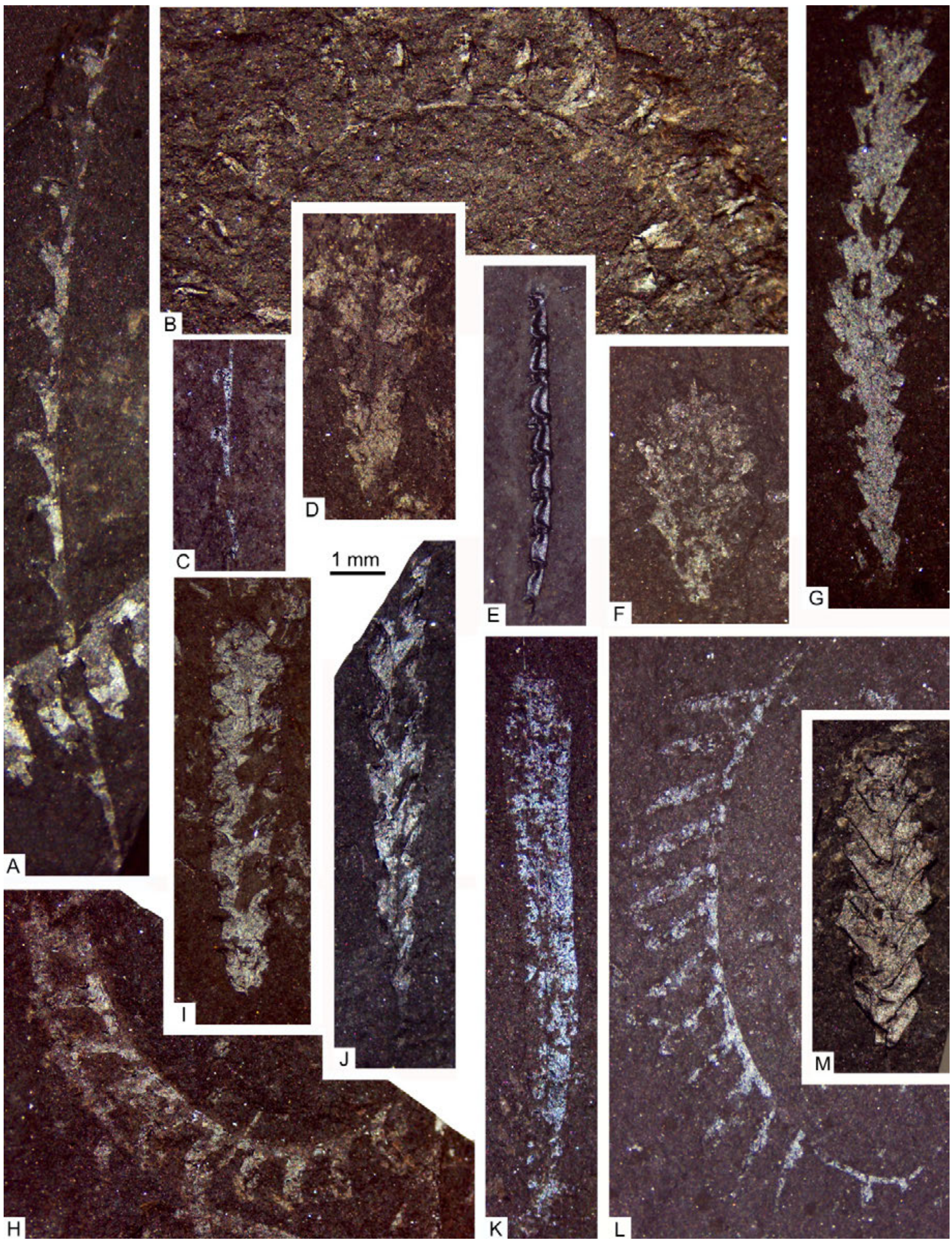
No upper Aeronian (*Stimulograptus sedgwickii* and *St. halli* Biozone) graptolitic horizons are present in the Sommerodde-1 core (or in the Øleå section). A typical lowermost Telychian *guerichi* Biozone species (*Glyptograptus fastigatus*; Fig. 14J) occurs in the first graptolitic level, at 117.52 m, above the unfossiliferous silt- and mudstones and this species, together with other lower and middle *guerichi* Biozone species, continues up to 111.10 m. A level higher in the *guerichi* Biozone (Loydell *et al.* 2015) is indicated by the appearance of *Torquigraptus planus* (Fig. 15H) at 110.18 m.

Parapetalolithus tenuis (Fig. 14M) has its first occurrence at 107.51 m and is the first indicator of the *turriculatus* Biozone. Above this, typical lowermost *turriculatus* Biozone assemblages (including *T. planus*) continue up to 103.00 m. In Wales the *turriculatus* Biozone has been divided into subzones (Loydell 1991; Zalasiewicz 1994). The order of appearance of two of the subzonal taxa in the Sommerodde-1 core, *Streptograptus johnsonae* (Fig. 15D) and *Torquigraptus proteus* (Fig. 16F), is in agreement with Welsh and other records: *Str. johnsonae* has its FAD at 103.63 m with its LAD at 100.90 m; *T. proteus* has its FAD at 101.27 m (Fig. 10). Zalasiewicz (1994) erected a *carnicus* Subzone for the highest part of the *turriculatus* Biozone. The presence of *T. carnicus* (Fig. 15D) at 102.36 m, within the stratigraphical range of *St. johnsonae* and below the first appearance of *T. proteus*, indicates that *T. carnicus* has a longer stratigraphical range than previously recognized and its presence in a graptolite assemblage should not therefore be seen as unequivocal evidence for the uppermost *turriculatus* Biozone.

A species noted to be a good indicator of the uppermost part of the *turriculatus* Biozone to lower *crispus* Biozone in the Øleå section (Bjerreskov 1975) and in Wales (Zalasiewicz 1994) is *Monoclimacis*? *galaensis* (Fig. 15G). In the Sommerodde-1 core it occurs in a narrow stratigraphical interval, from 99.90 m to 100.35 m. Pin-pointing the base of the *crispus* Biozone is difficult, because several species have ranges that straddle the *turriculatus*/*crispus* Biozone boundary and *Str. crispus* (Fig. 16J) is often rare in the lower part of its biozone (Bjerreskov 1975; Zalasiewicz 1994). In the Sommerodde-1 core its lowest record is in the 94.44–94.46 m sample. Evidence for the upper part of the *crispus* Biozone is provided by the co-occurrence of *Str. crispus* and *Str. loydelli* (Fig. 16E) between 92.86 m and 92.80 m.

Zalasiewicz (1994) noted that *Str.* aff. *loydelli* (Fig. 16D) is restricted to the lower *griestoniensis* Biozone in Wales, a level from which it was also recorded from Latvia (Loydell *et al.* 2003). This species occurs from 91.49 m to 91.37 m. A level no higher than lower *Monoclimacis griestoniensis* Biozone is indicated by the presence of *Str. sartorius* (Fig. 19F) at 90.28 m.

The next level to yield biostratigraphically useful graptolites was at 89.09 m. Here *Torquigraptus tullbergi* (Fig. 17B) indicates the *crenulata* Biozone; assemblages



indicative of this biozone, including the biozonal index (Fig. 19E) continue up to 87.87 m.

In the Øleå section, Bjerreskov (1975) recorded 2 m of non-graptolitic strata beneath the *spiralis* Biozone. Similar largely unfossiliferous strata are present at the same stratigraphical level in the Sommerodde core where they are succeeded (as in Øleå) by a typical lower *spiralis* Biozone assemblage including *Cultellograptus cultellus* (Fig. 16I) and *Streptograptus kaljoi* (Fig. 16K; assigned to *Str. anguinus* by Bjerreskov; see Loydell *et al.* 2003) between 84.38 m and 83.75 m.

Evidence for the middle part of the *spiralis* Biozone is provided by the first occurrence of *Str. nodifer* (Fig. 16H) at 77.44 m, with *Oktavites excentricus* (Fig. 17G), a species first described by Bjerreskov 1975 from the middle *spiralis* Biozone on Bornholm, occurring at 68.52 m. Bjerreskov (1975) noted that the upper part of the *spiralis* Biozone was characterized by occurrences of long-ranging species (e.g. *Monoclimacis vomerina* and *Retiolites*) – the same is true in the Sommerodde-1 core (Figs 10, 11).

Streptograptus wimani (Fig. 15C) occurs at 58.65 m indicating that the *lapworthi* Biozone has been reached. It occurs also between 54.50 m and 54.55 m, but with *Cultellograptus pseudocultellus* (Fig. 17F) with which it has not previously been recorded. *Streptograptus wimani* is a distinctive, stratigraphically short-ranging species, recorded only from the lower part of the *lapworthi* Biozone, from both graptolitically continuous sections (e.g. in Bohemia and Spain; Štorch 1994a; Loydell *et al.* 2009) and also sections which are more sporadically graptolitic (e.g. Banwy River, Wales; Aizpute, Latvia; Loydell & Cave 1996; Loydell *et al.* 2003). *Cultellograptus pseudocultellus* is also highly distinctive, but less frequently recorded than *Str. wimani*, and stratigraphically much longer ranging, occurring in Bohemia from the upper *lapworthi* Biozone through to the lower Sheinwoodian *murchisoni* Biozone (Štorch 1994a). Extension of the currently recorded overall stratigraphical range of *Str. wimani* and/or *Cu. pseudocultellus* is required based upon their Sommerodde co-occurrence. With both species previously recorded from the *lapworthi* Biozone, a level within this biozone seems reasonable, particularly as Bjerreskov (1975) estimated the biozone to be approximately 5 m thick. Extending the stratigraphical range downwards of the longer ranging, less frequently recorded species (*Cultellograptus pseudocultellus*) is the option that we favour.

Above the level with *Cu. pseudocultellus* and *Str. wimani* are 0.875 m of strata yielding only stratigraphically long-ranging species (mostly *Monograptus priodon* and *Retiolites angustidens*). *Monoclimacis shottoni* (Fig. 16N) occurs at 53.63 m. This species was first described by Rickards (1965) from the *centrifugus* Biozone of several localities in northern England and subsequently has been recorded only from the lower to middle *insectus* Biozone of the Banwy River section, Wales (Loydell & Cave 1996). Because of the paucity of records, its overall stratigraphical range is therefore uncertain and particularly the level of its appearance, largely because of the general lack of graptolitic sections through the upper *lapworthi* Biozone. The Sommerodde specimen is the first record outside Avalonia.

Only 0.255 m above the level with *Mcl. shottoni* a well preserved proximal end of *Cyrtograptus murchisoni* (Fig. 18D) was found at 53.37 m, marking the lower Sheinwoodian *murchisoni* Biozone. Thus, from the highest strata attributable to the *lapworthi* Biozone to the base of the *murchisoni* Biozone are only 1.13 m of strata, whereas Bjerreskov (1975) recorded nearly 30 m of *centrifugus* Biozone (the biozone preceding *murchisoni*) from the Læså rivulet and adjacent coastal sections. Possible reasons for this major difference in the uppermost Telychian stratigraphical records on Bornholm are discussed below.

The presence of *Mediograptus remotus* (Fig. 19I) at 41.05 m indicates a level within the upper part of the *murchisoni* Biozone (Štorch 1994a), from which it has been recorded also elsewhere in the Baltic region (Loydell *et al.* 1998, 2003). Above this level assemblages are dominated by *Monoclimacis vomerina* (Fig. 17H) and *M. priodon* until the FAD of *Monograptus riccartonensis* (Fig. 16L) at 37.52 m. The *murchisoni* Biozone therefore has a minimum thickness of 12.32 m. Typical, low diversity *riccartonensis* Biozone assemblages continue to 35.01 m above which, from 34.80 m to 31.61 m, the

◀ **Fig. 14.** Graptolites from the Aeronian and Telychian of the Sommerodde-1 core, Bornholm. **A:** '*Monograptus*' *walkerae rheidolensis* Rickards, Hutt & Berry, MGUH 31.650, 131.01–131.02 m, *triangulatus* Biozone. **B:** *Lituigraptus richteri* (Perner), MGUH 31.651, 126.75 m, *leptotheca* Biozone. **C:** '*Monograptus*' *gemmatus* (Barrande), MGUH 31.652, 115.37 m, *guerichi* Biozone. **D:** *Neodiplograptus fezzanensis* (Desio), MGUH 31.653, 133.62 m, *triangulatus* Biozone. **E:** *Streptograptus pseudoruncinatus* (Bjerreskov), MGUH 31.654, 117.13 m, *guerichi* Biozone. **F:** *Petalolithus ellesae* Bouček & Přibyl, MGUH 31.655, 123.12–123.13 m, *convolutus* Biozone. **G:** *Pseudorthograptus finneyi* Štorch & Kraft, MGUH 31.656, 131.69 m, *triangulatus* Biozone. **H:** *Demirastrites triangulatus* (Harkness), MGUH 31.657, 134.30 m, *triangulatus* Biozone. **I:** *Pseudoglyptograptus barriei* Zalasiewicz & Tunnicliff, MGUH 31.658, 126.75 m, *leptotheca* Biozone. **J:** *Glyptograptus fastigatus* Haberfelner, MGUH 31.659, 113.02 m, *guerichi* Biozone. **K:** *Cephalograptus extrema* Bouček & Přibyl, MGUH 31.660, 119.46 m, *convolutus* Biozone. **L:** *Rastrites peregrinus* Barrande, MGUH 31.661, 122.68 m, *convolutus* Biozone. **M:** *Parapetalolithus tenuis* (Barrande), MGUH 31.662, 106.35 m, *turriculatus* Biozone.

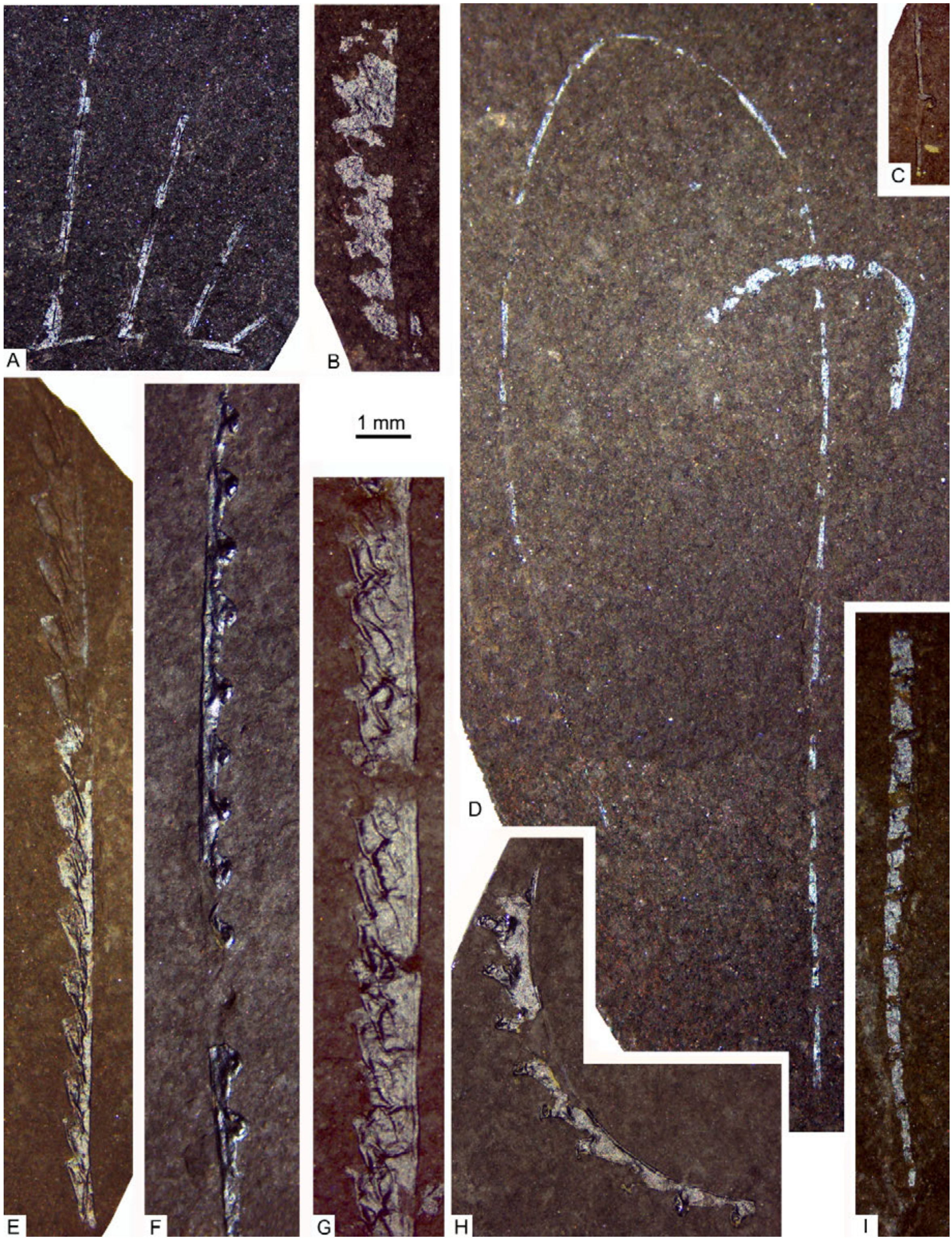


Fig. 15. Graptolites from the Telychian of the Sommerodde-1 core, Bornholm. **A:** *Rastrites linnaei* Barrande, MGUH 31.663, 109.16 m, *guerichi* Biozone. **B:** *Pristiograptus bjerringus* (Bjerreskov), MGUH 31.664, 103.92 m, *turriculatus* Biozone. **C:** *Streptograptus wimani* (Bouček), MGUH 31.665, 54.54 m, *lapworthi* Biozone. **D:** *Torquigraptus carnicus* (Gortani) and *Streptograptus johnsonae* Loydell, MGUH 31.666 and 31.667, 102.36 m, *turriculatus* Biozone. **E:** *Pristiograptus schucherti* Bjerreskov, MGUH 31.668, 98.84 m, *turriculatus* Biozone or *crispus* Biozone. **F:** *Streptograptus barrandei* (Suess), MGUH 31.669, 106.08 m, *turriculatus* Biozone. **G:** *Monoclimacis*? *galaensis* (Lapworth), MGUH 31.670, 99.92 m, *turriculatus* Biozone or *crispus* Biozone. **H:** *Torquigraptus planus* (Barrande), MGUH 31.671, 106.09 m, *turriculatus* Biozone. **I:** *Streptograptus storchi* Loydell, MGUH 31.672, 99.18 m, *turriculatus* Biozone or *crispus* Biozone.

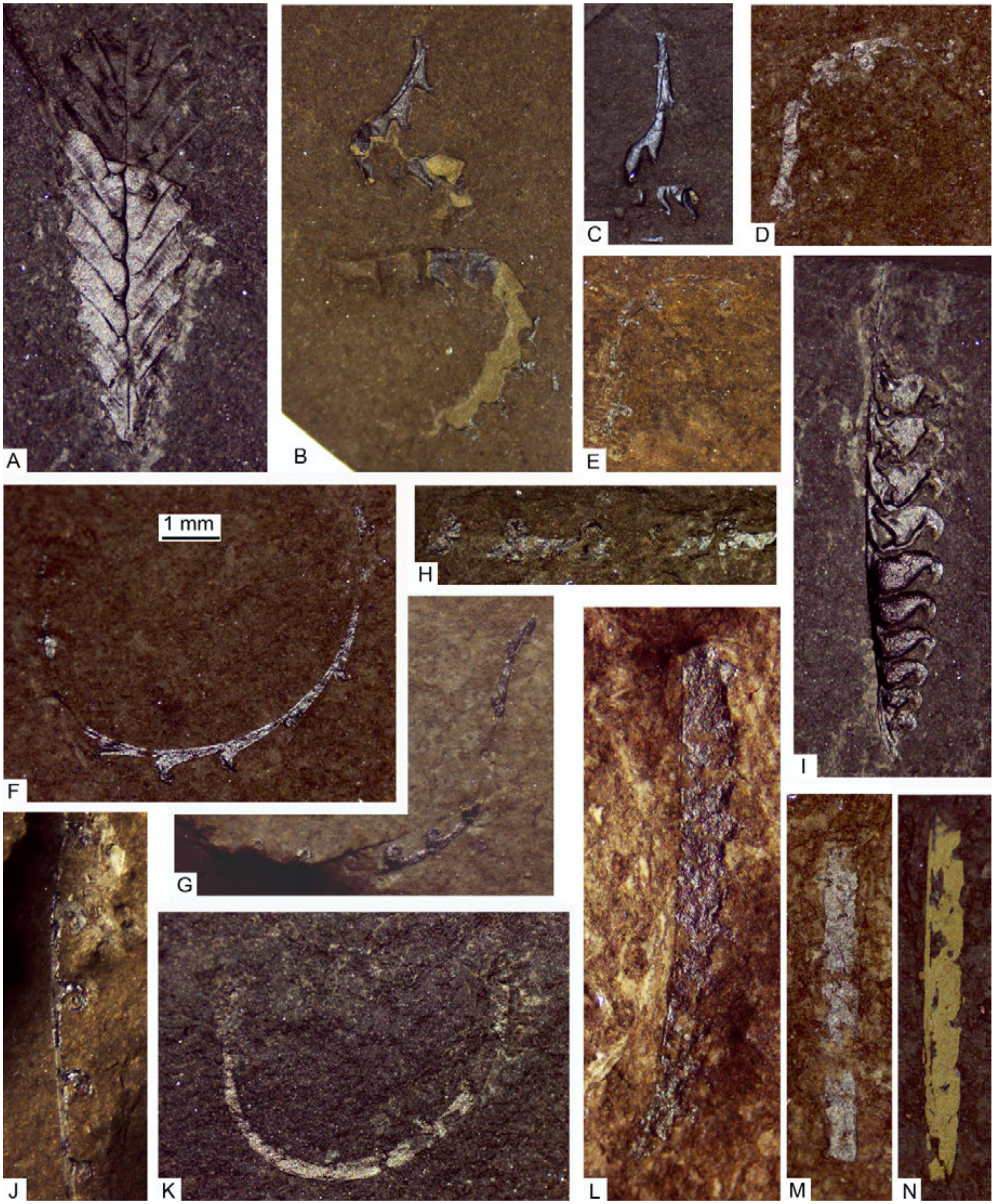


Fig. 16. Graptolites from the Telychian and Sheinwoodian of the Sommerodde-1 core, Bornholm. **A:** *Parapetalolithus altissimus* (Elles & Wood), MGUH 31.673, 106.40 m, *turriculatus* Biozone. **B:** *Spirograptus turriculatus* (Barrande) with curved sicula, MGUH 31.674, 99.01 m, *turriculatus* Biozone or *crispus* Biozone. **C:** *Spirograptus turriculatus* (Barrande) with almost straight sicula, MGUH 31.675, 103.78 m, *turriculatus* Biozone. **D:** *Streptograptus* aff. *loydelli* Štorch & Serpagli, MGUH 31.676, 91.37 m, *griestoniensis* Biozone. **E:** *Streptograptus loydelli* Štorch & Serpagli, MGUH 31.677, 92.85 m, *crispus* Biozone. **F:** *Torquigraptus proteus* (Barrande), MGUH 31.678, 100.33 m, *turriculatus* Biozone or *crispus* Biozone. **G:** *Streptograptus exiguus* (Lapworth), MGUH 31.679, 98.52 m, *turriculatus* Biozone or *crispus* Biozone. **H:** *Streptograptus nodifer* (Törnquist), MGUH 31.680, 68.93 m, *spiralis* Biozone. **I:** *Cultellograptus cultellus* (Törnquist), MGUH 31.681, 84.36 m, *spiralis* Biozone. **J:** *Streptograptus crispus* (Lapworth), MGUH 31.682, 93.61 m, *crispus* Biozone. **K:** *Streptograptus kaljoi* Loydell, Männik & Nestor, MGUH 31.683, 83.75 m, *spiralis* Biozone. **L:** *Monograptus riccartonensis* Lapworth, MGUH 31.684, 36.70 m, *riccartonensis* Biozone. **M:** *Euroclimacis deflexa* (Bouček), MGUH 31.685, 37.52 m, *riccartonensis* Biozone. **N:** *Monoclimacis shottoni* Rickards, MGUH 31.686, 53.63 m, between the *lapworthi* and *murchisoni* biozones.

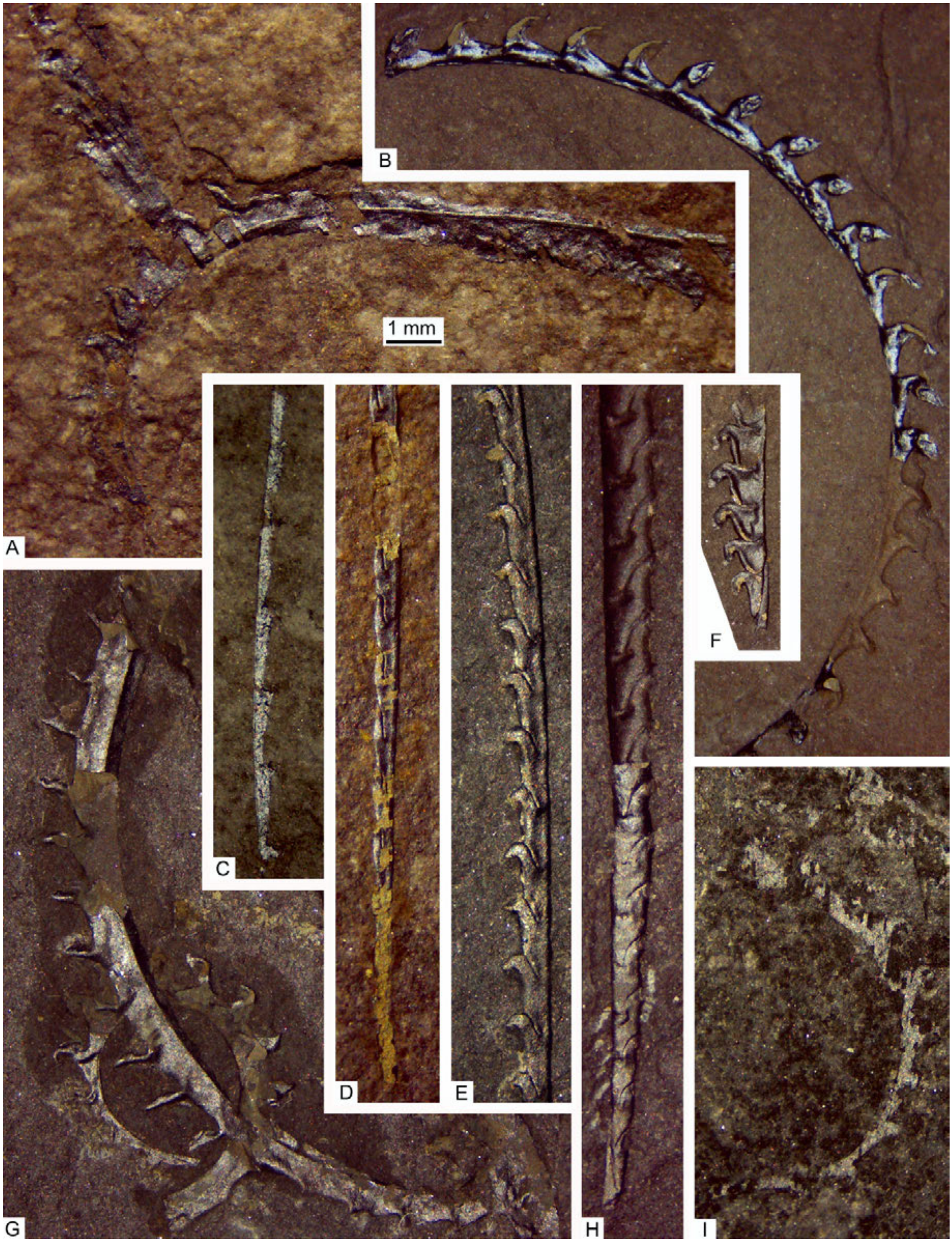


Fig. 17. Graptolites from the Telychian and Sheinwoodian of the Sommerodde-1 core, Bornholm. **A:** *Cyrtograptus rigidus* Tullberg, MGUH 31.687, 22.13 m, *rigidus* Biozone. **B:** *Torquigraptus tullbergi* (Bouček), MGUH 31.688, 89.09 m, *crenulata* Biozone. **C:** *Diversograptus ramosus* Manck, MGUH 31.689, 68.70 m, *spiralis* Biozone. **D:** *Monoclimacis linnarssoni* (Tullberg), MGUH 31.690, 58.83 m, *lapworthi* Biozone. **E:** *Streptograptus speciosus* (Tullberg), MGUH 31.691, 58.81 m, *lapworthi* Biozone. **F:** *Cultellograptus pseudocultellus* (Bouček), MGUH 31.692, 54.54 m, *lapworthi* Biozone. **G:** *Oktavites excentricus* (Bjerreskov), MGUH 31.693, 68.52 m, *spiralis* Biozone. **H:** *Monoclimacis vomerina* (Nicholson), MGUH 31.694, 53.87 m, between the *lapworthi* and *murchisoni* biozones. **I:** *Cyrtograptus bohemicus* Bouček, MGUH 31.695, 37.14 m, *riccartonensis* Biozone.

most common species present is *Pristiograptus dubius* (Fig. 18C), which is accompanied at some levels by other long-ranging taxa (Fig. 11). A *dubius* Interzone, succeeding the *riccartonensis* Biozone, has been recognized in both Bohemia (Štorch 1994b) and Britain (Zalasiewicz *et al.* 2009) and appears applicable to the Sommerodde-1 core section also.

Cyrtograptus rigidus (Fig. 17A), the stratigraphical range of which is restricted to the upper Sheinwoodian *rigidus* Biozone, occurs in the 29.88–29.90 m sample and also at 22.13 m. Within the *rigidus* Biozone and above 29.88 m up to the highest graptolitic sample, at 7.61–7.62 m, the long-ranging *Monograptus flemingii* (Fig. 18A) dominates assemblages and is accompanied by stratigraphically non-diagnostic taxa; demonstrating whether the highest 14.51 m of strata in the core are of late Sheinwoodian or early Homerian (*lundgreni* Zone) age is therefore not possible using the graptolites recovered. Verniers *et al.* (2008) suggested that

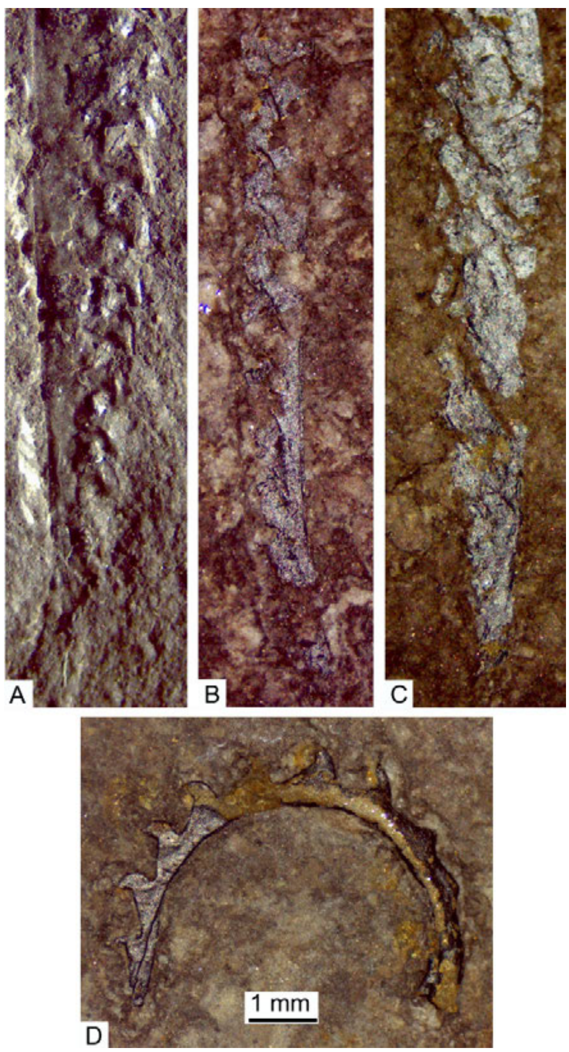


Fig. 18. Graptolites from the Sheinwoodian of the Sommerodde-1 core, Bornholm. **A:** *Monograptus flemingii* (Salter), MGUH 31.696, 22.13 m, *rigidus* Biozone. **B:** *Monoclimacis flumendosae* (Gortani), MGUH 31.697, 23.18 m, *rigidus* Biozone. **C:** *Pristiograptus dubius* (Suess), MGUH 31.698, 33.98–33.99 m, *dubius* Interzone. **D:** *Cyrtograptus murchisoni* Carruthers, MGUH 31.699, 53.37 m, *murchisoni* Biozone.

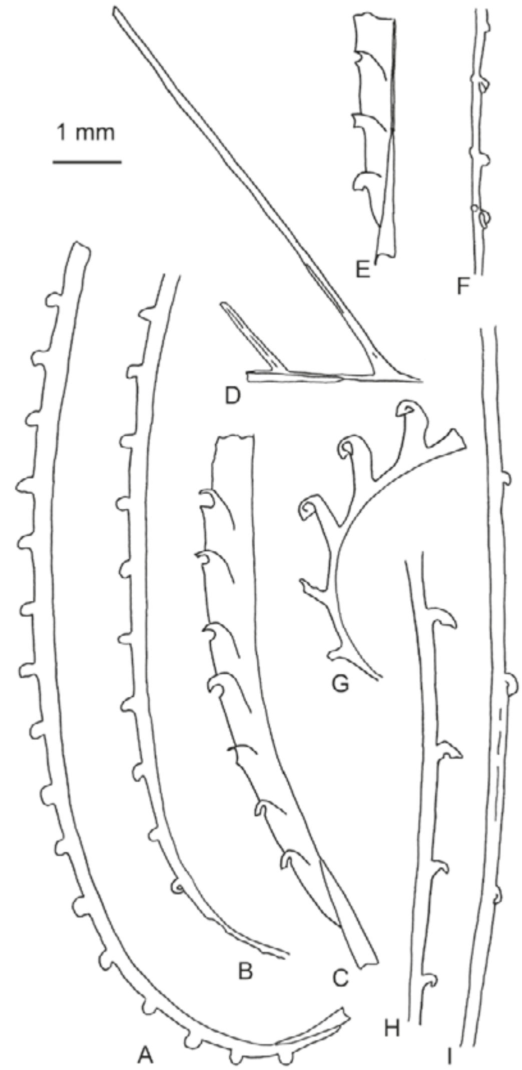


Fig. 19. Graptolites from the Aeronian–Sheinwoodian of the Sommerodde-1 core, Bornholm. **A:** *Mediograptus inconspicuus* (Bouček), MGUH 31.700, 42.78 m, *murchisoni* Biozone. **B:** *Mediograptus vittatus* Štorch, MGUH 31.701, 45.15–45.16 m, *murchisoni* Biozone. **C:** *Euroclimacis adunca* (Bouček), MGUH 31.702, 39.67 m, between the *murchisoni* and *riccartonensis* biozones. **D:** *Rastrites maximus* Carruthers, MGUH 31.703, 117.14 m, *guerichi* Biozone. **E:** *Monoclimacis crenulata* (Elles & Wood), MGUH 31.704, 87.87 m, *crenulata* Biozone. **F:** *Streptograptus sartorius* (Törnquist), MGUH 31.705, 90.28 m, *griestoniensis* Biozone. **G:** '*Monograptus*' *mirificus* Štorch, MGUH 31.706, 125.19 m, *leptotheca* Biozone. **H:** *Mediograptus kolihai* (Bouček), MGUH 31.707, 47.68 m, *murchisoni* Biozone. **I:** *Mediograptus remotus* (Elles & Wood), MGUH 31.708, 41.05 m, *murchisoni* Biozone.

the Sheinwoodian of Bornholm was represented by "hiatuses or a simple condensed section". There is no evidence for any breaks in the Sheinwoodian of the Sommerodde-1 core and it has a thickness of at least 31 m.

Schovsbo *et al.* (2015) assigned the uppermost 23.5 m of strata in the core to their unit G5 and noted that it "includes numerous silty to sandy beds similar to those exposed on the beach [in boulders] just south of the well location" as described by Bjerreskov & Jørgensen (1983). What was not seen in the core, however, was the up to 40 cm thick bed with rip-up clasts at its base recorded from the beach west of Sommerodde by Bjerreskov & Jørgensen (1983), suggesting that the core does not include the entirety of the volcaniclastic unit (G5). Schovsbo *et al.* (2016) came to the same conclusion, stating that the G5 log zone was not completely penetrated by the Sommerodde-1 well and recognizing the top of the G5 unit in other wells, e.g. Pernille-1 (Fig. 8).

Biostratigraphy of log stratigraphical units

Schovsbo *et al.* (2015) divided the Lower Palaeozoic of the Sommerodde-1 well into log stratigraphical units based upon gamma ray, formation resistivity and P-wave-velocity records. These are shown on Figs 2 and 20, with depths in some cases slightly modified from Schovsbo *et al.* (2015). Of the various units recognized by Schovsbo *et al.* (2015), F1–F5 and G1–G5 are of Silurian age (although F1 has its base in the uppermost Ordovician). Schovsbo *et al.* (2015) assigned units F1–F5 to the "Rastrites shale" and G1–G5 to the "Cyrtograptus shale". Graptolitic strata from below the *acuminatus* Biozone were not examined by us, but it seems reasonable to assume, based upon graptolite records from the Billegrav-1 core (Koren' & Bjerreskov 1997), that the base of unit F1 (transition to black shale) is within the Hirnantian *persculptus* Biozone. The base of Unit F2 is within the *acuminatus* Biozone. Unit F3 is a very distinctive unit, both lithologically (Fig. 3) and geophysically (Fig. 20), comprising alternating dark grey mudstones and pale grey carbonate cemented horizons (its base and top are defined, respectively, by the lowest and highest carbonate concretions). Its base lies significantly (nearly 6 m) above the base of the *vesiculosus* Biozone and the unit may be restricted to this biozone (based on the thicknesses of the biozone recorded by Bjerreskov 1975 and Koren' & Bjerreskov 1997). The base of unit F4 clearly lies within the upper Rhuddanian, in strata from which few graptolites were collected, and is of either latest *vesiculosus* or earliest *revolutus* Zone age. Unit F4 encompasses the upper Rhuddanian and much of the Aeronian, its top (and thus base of unit F5) being marked by the conspicuous lithological change from black mudstones of late *convolutus* Zone age to unfossiliferous grey silty mudstones (Fig. 4).

The base of G1 and therefore of the "Cyrtograptus shale" is at 97.4 m (Fig. 20) in strata of either late *turriculatus* or early *crispus* Zone age. This is in agreement with Pedersen's (1922) and Laursen's (1940) biostratigraphical placement of the boundary. Bjerreskov (1971) recommended abandoning the division of the Silurian of Bornholm into "Rastrites" and "Cyrtograptus shales" on the basis that the only obvious lithological boundary within the Llandovery on Bornholm is that at the top of the *convolutus* Biozone. She also pointed out that the names are misleading: *Rastrites* is not common in the "Rastrites shale", and *Cyrtograptus* does not appear until the *lapworthi* Biozone; in the Sommerodde-1 core this is almost 40 m above the base of the "Cyrtograptus shale".

The base of Unit G2 is within the middle part of the *spiralis* Biozone and that of G3 (Fig. 6) within the lower part of the *lapworthi* Biozone. Schovsbo *et al.* (2015) noted that the base of G4 is marked by a change to darker lithologies. This occurs high in the *murchisoni* Biozone. The highest unit, G5, which is that which includes numerous siltstone and sandstone beds (Fig. 7) and is represented by boulders on the shore west of Sommerodde (Bjerreskov & Jørgensen 1983), has its base within the *rigidus* Biozone (upper Sheinwoodian).

Comparison of the Llandovery of the Sommerodde-1 core with other Bornholm sections

A very useful marker level within the Llandovery of Bornholm is the pronounced change from black mudstones, which yield graptolites of the upper *convolutus* Biozone, to the overlying unfossiliferous grey silty mudstones (Fig. 4). This occurs at a depth of 119.4 m within the Sommerodde-1 core and was used by Schovsbo *et al.* (2015) as the boundary between their log stratigraphical units F4 and F5. Another easily recognizable lithological change (the base of Schovsbo *et al.*'s 2015 F1 unit) is at 174.8 m within the upper Hirnantian at the level where pale coarser clastic sedimentary rocks are replaced by overlying graptolitic shales. The interval from the base of unit F1 to the base of F5 in the Sommerodde-1 core is represented by a vertical thickness of 55.4 m, equating to a slightly lower stratigraphical thickness allowing for stratal dip. The biozonal thicknesses provided by Bjerreskov (1975) and Koren' & Bjerreskov (1997) for the combined Billegrav-1 core and Øleå sections indicate a very similar stratigraphical thickness here of around 52 m for the equivalent interval (upper Hirnantian to top *convolutus* Biozone). It would seem therefore that there is no significant lateral variation in the thickness of Rhuddanian and Aeronian graptolite biozones between Sommerodde-1 and the other documented sections on Bornholm. The same appears to be true for much of the Telychian also, but with two exceptions: in the lowermost Telychian (*guerichi* and *turriculatus* biozones) and most notably in the uppermost part of the stage (upper *lapworthi* to *centrifugus* biozones). The thickness differences and their possible causes are discussed below.

In the Øleå section the *guerichi* and *turriculatus* biozones combined have a calculated maximum thickness of about 12 m (Bjerreskov 1975), whereas in the Sommerodde-1 core the equivalent interval is 17–23 m thick (depending upon at what depth the *turriculatus*/*crispus* Biozone lies: the boundary is difficult to define in the Sommerodde-1 core – see above). The most likely explanation is that part of the sequence is missing in the Øleå section as a result of faulting. No faults were recorded by Bjerreskov, but much of the interval was not exposed (Bjerreskov 1975, fig. 2). Looking at the

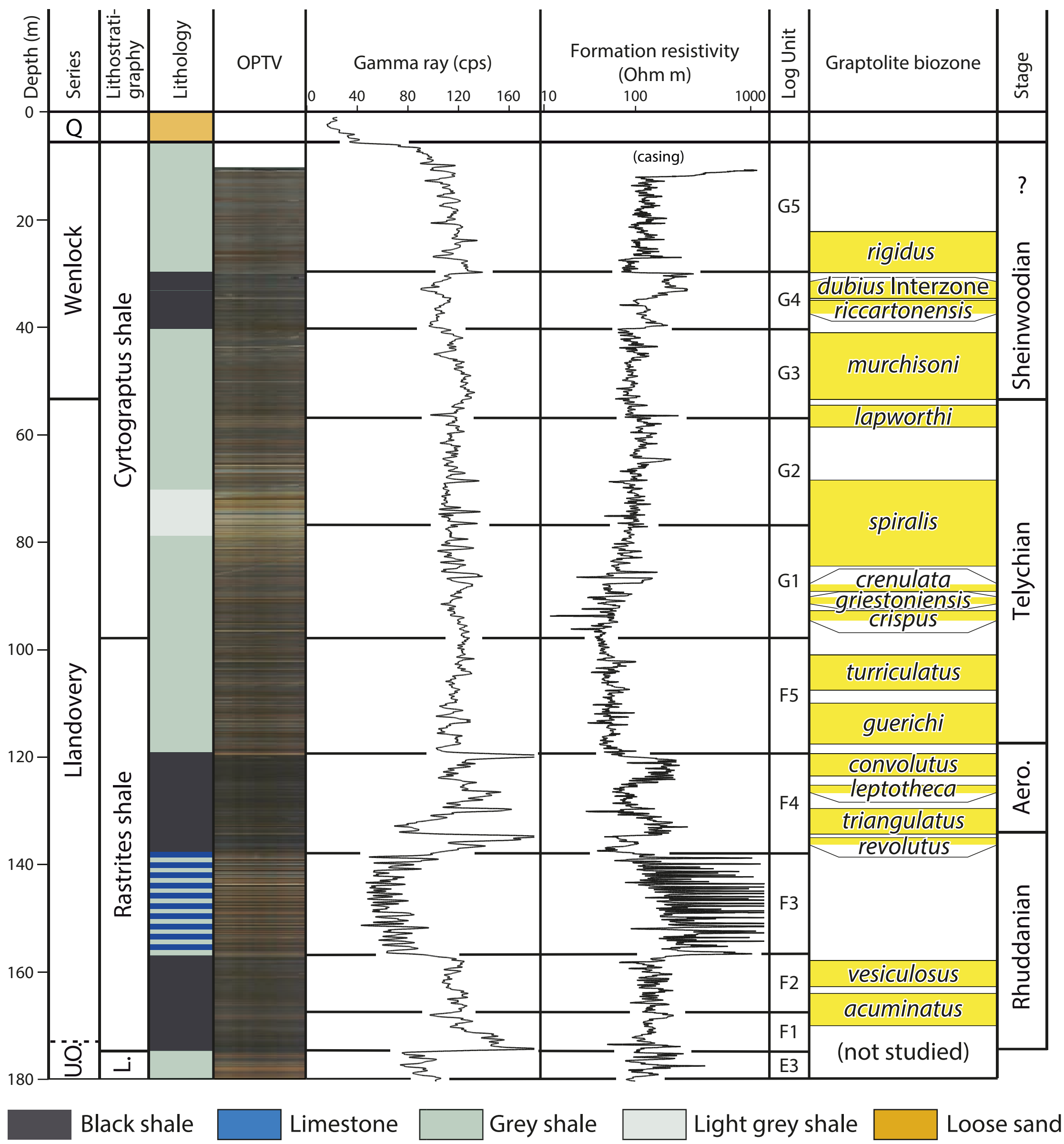


Fig. 20. Summary of the log stratigraphy, biostratigraphy and chronostratigraphy of the Sommerodde-1 core (modified from Schovsbo *et al.* 2015). Abbreviations: L – Lindegård Formation; Q – Quaternary; UO – Upper Ordovician.

thickness of strata between the top of the *convolutus* Biozone and the FAD of the common and distinctive *Streptograptus johnsonae* (Fig. 15D), in Øleå there are about 8 m (Bjerreskov 1975, fig. 5), whereas in the Sommerodde-1 core the thickness is nearly 16 m. This strongly suggests that any fault(s) in the Øleå section must lie within the *guerichi* or lowermost *turriculatus* Biozone. This inference is corroborated by unpublished data from the Billegrav-2 well, located adjacent to the exposure of the *turriculatus* Biozone in the Øleå section (loc. 14b of Bjerreskov 1975), where 18 m of combined *guerichi* and *turriculatus* biozones were encountered immediately below the Quaternary cover. However, as the top of the *turriculatus* Biozone is not present in the core, the total biozone thickness must be even greater. Slightly further down, a fault cuts the Billegrav-2 core at 32 m and we assume that it is the same fault that affects the thickness calculation of Bjerreskov (1975). As noted by Schovsbo *et al.* (2015, p. 12), no fault zones have been identified in the Sommerodde-1 core.

The biggest difference between the Sommerodde-1 core sequence and other Bornholm sections is in the uppermost Telychian, where between the highest bed attributable to the *lapworthi* Biozone and the base of the *murchisoni* Biozone are only 1.13 m of strata in the core. By comparison, Bjerreskov (1975) recorded nearly 30 m of *centrifugus* Biozone (the biozone preceding *murchisoni*) from the Læså rivulet and adjacent coastal sections and 20–25 m of the same biozone (without reaching its top) representing the youngest strata in the Øleå section. The Øleå and Læså sections are exposed less than 1.5 km and 8 km respectively west-north-west of the Sommerodde drill site, so such a dramatic difference, particularly given the similarity of the Rhuddanian and Aeronian, was entirely unexpected. There is no evidence for faulting at this or any other level within the Sommerodde-1 core, so the explanation presumably must reflect depositional factors.

The strata between the highest *Streptograptus wimani* (*lapworthi* Biozone) at 54.50 m and appearance of *Cyrtograptus murchisoni* at 53.37 m are entirely unremarkable, comprising interbedded sparsely graptolitic mudstones and non-graptolitic bioturbated mudstones (Fig. 6). Bjerreskov (1975, p. 16), however, described the upper part of the *lapworthi* Biozone in the Øleå section as follows: "… the lithology is an alternation of dark grey to greenish bands … with a few 10 cm thick bands of recrystallized oolitic limestones." No comparable oolitic limestones are present in the Sommerodde-1 core; the only limestone within the *lapworthi* Biozone is not oolitic and occurs at a lower level within the biozone, approximately half-way between the lowest and highest appearances of *S. wimani*. So it would seem either that the oolitic limestone was deposited only locally or was subsequently eroded from the Sommerodde area. Given that the presence of oolitic limestone indicates high energy conditions in the area and oolites are often of limited lateral distribution, either explanation is plausible. It should be noted also that the presence of oolites seems inconsistent with the c. 1000 m water depth proposed for the early Homerian by Bjerreskov & Jørgensen (1983), unless there was dramatic subsidence in the area between the late Llandovery and late Wenlock.

At first sight, more difficult to explain is the extraordinary reduction in thickness of the uppermost Telychian *centrifugus* Biozone from 20–30 m in the Øleå and Læså sections to at most 1.13 m in the Sommerodde-1 core. Either extreme condensation or an unconformity, presumably obscured by subsequent bioturbation, is required in the Sommerodde area. In order to generate the different sedimentation history between Sommerodde and the Øleå and Læså sections, synsedimentary fault movements would be required. Vejbæk *et al.* (1994) noted that variations in the Lower Palaeozic sedimentary records of Scania and Bornholm enabled recognition of "minor block movements during the Early Palaeozoic", and abrupt changes in thickness of Silurian successions are shown on either side of faults in the Baltic subsurface east of Bornholm (Poprawa *et al.* 1999; Ūsaitytė 2000). So faulting, presumably uplifting the Sommerodde area so that it was a site of reduced deposition and/or erosion, seems the most likely explanation for the difference in its upper Telychian record from that of the Øleå and Læså sections. Interestingly, a comparable scenario affecting a slightly higher Silurian interval (lower Sheinwoodian) has been described from Estonia (Männik *et al.* 2014) where a localized unconformity with at least four conodont biozones missing has been recognized and attributed probably to the contemporaneous formation of the Pärnu Uplift. Männik *et al.* (2014) concluded that the stratigraphical gap in western Estonia was a reflection of the tectonic evolution of the Baltoscandian foreland basin. A similar conclusion can be drawn for Sommerodde.

Conclusions

Graptolite assemblages from the Sommerodde-1 core enable identification of lower Silurian graptolite biozones from the lower Rhuddanian *acuminatus* Biozone through to the upper Sheinwoodian *rigidus* Biozone, including, contrary to what was suggested by Beier *et al.* (2000) and Verniers *et al.* (2008), a complete sequence of Sheinwoodian biozones. For the Rhuddanian and Aeronian the succession and thickness of biozones is very similar to that in exposed sections and drillings nearby. The lower Telychian (*Spirograptus guerichi* and *S. turriculatus* biozones) are significantly thicker in the core, however, whilst the uppermost Telychian (represented by more than 30 m of strata in nearby sections) is much reduced in thickness and is likely to include an unconformity (obscured by bioturbation). This thickness difference is likely to be a reflection of synsedimentary faulting in the Silurian foreland basin influencing the deposition. The geophysical log stratigraphical units of Schovsbo et al. (2015) can be tied to the graptolite biostratigraphy. The tuffaceous sandstones of the highest unit (G5) make their first appearance in the upper Sheinwoodian *Cyrtograptus rigidus* Biozone.

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