Lethaia
AN INTERNATIONAL JOURNAL OF PALAEONTOLOGY AND STRATIGRAPHY

Silurian stratigraphy and graptolite faunas of the Mora 001 and Solberga 1 drill cores, Siljan District, central Sweden

JÖRG MALETZ

LETHAIA

Maletz, J. 2021: Silurian stratigraphy and graptolite faunas of the Mora 001 and Solberga 1 drill cores, Siljan District, central Sweden. *Lethaia*, Vol. 54, pp. 610–630.

The Mora 001 and Solberga 1 drill cores provide the best available overview on the early Silurian (Llandovery, Rhuddanian to Telychian) graptolite succession available for the Siljan Ring impact structure of central Sweden. The Solberga 1 succession includes a nearly complete graptolite succession from the *Pernerograptus revolutus* Biozone (late Rhuddanian) to the *Oktavites spiralis* Biozone (late Telychian). Older graptolite faunas are unknown from the Siljan region. The Mora 001 drill core includes a graptolitic succession from the *Monoclimacis crenulata* Biozone to the *O. spiralis* Biozone, found in two lithostratigraphically separated lithological units here identified as the Kallholn Formation. A slice of the Orsa Sandstone Formation of possible later Silurian age is tectonically introduced into the Kallholn Formation in the Mora 001 drill core. The strong tectonic deformation of the Kallholn Formation in both drill cores can easily be understood through the Devonian impact history of the region. □ *Dalarna, graptolite biostratigraphy, lithostratigraphy, Siljan impact, Silurian.*

Jörg Maletz ✉ [Yorge@zedat.fu-berlin.de], Department of Geology, FU Berlin, Malteserstrasse 74-100 Berlin D-12249, Germany; *manuscript received on 15/12/2020; manuscript accepted on 18/02/2021.*

The Siljan Ring structure in central Sweden (Fig. 1A) has long been an enigma that has refused geological interpretation due to its poor exposure, complex sedimentology and tectonic structure (e.g. Törnquist 1871; Moberg 1910; Thorslund & Jaanusson 1960). Only in recent decades has it been made clear that the Siljan Ring structure can be interpreted as a meteorite impact (e.g. Fredriksson & Wickman 1963; Svensson 1971; Wickman 1981; Reimold *et al.* 2005; Lindström *et al.* 2008). Reimold *et al.* (2015) dated the impact at 380 Ma (Frasnian, Devonian), but a number of slightly different ages can be found in the literature (Elming & Bylund 1991; Reimold *et al.* 2005; Jourdan & Reimold 2012; Muhamad *et al.* 2015). The impact led to considerable tectonic distortion of the Palaeozoic sedimentary cover of the Siljan region and difficulties to understand the sedimentary succession as exposures show only small parts and the connections of individual lithological units often are unknown. The Lindström *et al.* (2008, p. 18) remark that 'there is a lot of tectonic reorientation of bedding but no chaos and generally good continuity in the exposed successions' might be a bit misleading, especially when looking at strata recognized in a number of more recent drill cores. Arslan *et al.* (2013) for example documented considerable tectonic distortion through the formation of the Devonian impact event from the Stumsnäs 1 drill core in the southern Siljan Ring, in which Ordovician sediments are sandwiched between Proterozoic igneous basement rocks.

The precise thickness of the Palaeozoic sedimentary succession remained uncertain, and the precise succession and correlation of the Ordovician and Silurian sediments is difficult to ascertain. Jaanusson (1982) estimated the thickness of the Ordovician in the intermound facies at no more than 100 m and Thorslund & Jaanusson (1960, p. 25) suggested a thickness of about 130 m. Rondot (1975) and Collini (1988) estimated a thickness of 350–500 m of Palaeozoic sediments through seismic data. Recent seismic investigations (Juhlin *et al.* 2012; Muhamad *et al.* 2015, 2017) suggested the presence of a 400-m thick Ordovician limestone succession followed by ca. 200-m thick Silurian shales in the Mora region of the western part of the Siljan Ring, but equivalent thicknesses in outcrop do not exist and only a 21.57-m thick succession of Ordovician limestones was found in the Mora 001 drill core (Lehnert *et al.* 2012, p. 88). Muhamad *et al.* (2015) indicated that the thickness of the Silurian deposits varies considerably in the Mora area. It is estimated that a Palaeozoic overburden of up to 2500 m has been removed through erosion including also considerable thicknesses of post-impact strata (e.g. Hossack & Cooper 1986; Ebbestad *et al.* 2007, p. 7).

The Silurian succession in the Siljan Ring structure is less well known than the Ordovician one and is

DOI 10.1111/let.12424

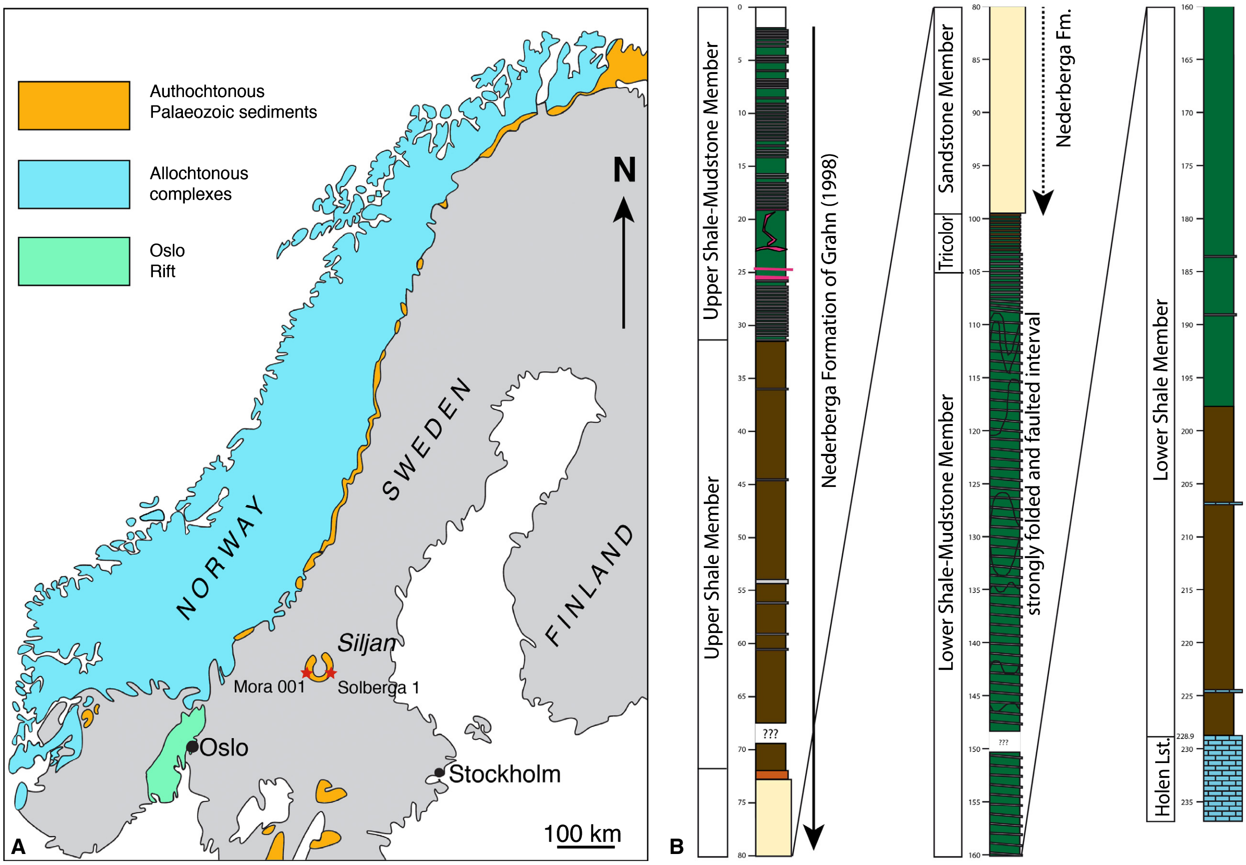

Fig. 1. A, map of Sweden showing the Siljan Ring and the Mora 001 and Solberga 1 drill core locations (after Gee *et al.* 2010, fig. 2). B, Mora 001 drill core lithology with units as identified by Lehnert *et al.* (2012). For key to lithology, see Figure 4.

quite incompletely exposed and accessible. Thus, the lithological column has to be pieced together from the various exposures and a number of drill cores in the region (e.g. Warburg 1910; Baarli *et al.* 2003; Lehnert *et al.* 2012). This is evident even from the earlier investigations in which several lithological units were differentiated, but the actual succession of these remained uncertain (see discussion in Ebbestad *et al.* 2007). The base of the Silurian is usually recognized at the base of the Kallholn Formation, unconformably overlying the Glisstjärn Formation of Hirnantian (late Ordovician) age in some sections (e.g. Baarli *et al.* 2003; Schmitz & Bergström 2007; Suzuki *et al.* 2009; Kröger *et al.* 2016). However, Lehnert *et al.* (2012) identified a carbonate-rich interval below the Kallholn Formation in the Solberga 1 drill core as the Motala Formation, but biostratigraphical data are not available to date the interval. The Motala Formation was defined in Östergötland and is biostratigraphically referred to the *Distomodus kentuckyensis* conodont Zone, corresponding to the *Huttagraptus acinaces* to *Pernerograptus revolutus* graptolite zones (Bergström & Bergström 1996). The Motala Formation was previously unknown from Dalarna, and Bergström *et al.* (2012, fig. 4) indicated that its base and top are based on unconformities in the Motala area of Östergötland. Ebbestad *et al.* (2015, fig. 2a) indicated a conformable sedimentological contact between the Motala Formation and the Kallholn Formation in the Siljan District based on the Solberga 1 drill core. A thick succession of Silurian shales, mudstones and sandstones in the Mora 001 drill core (Fig. 1B; showing the lithostratigraphical interpretation of Lehnert *et al.* 2012) has recently been interpreted to indicate active tectonism in the region. A substantial deepening of the depositional environment with high depositional rates was suggested, followed by the intercalation of a sandstone unit in the Silurian shales reflecting a regression in Wenlock times (Lehnert *et al.* 2012, p. 92). The authors correlated their sandstone member, the upper shale member and upper shale–mudstone member with the Nederberga Formation of Grahn (1998), an interpretation that affected considerably the interpretation of the Cambrian-Early Devonian platform to foreland basin evolution of Scandinavia by Wickström & Stephens (2020). The allochtonous nappes of the Caledonian orogen were transported more than 400 km over the Baltoscandian foreland basin onto the Fennoscandian Shield but, according to Gee *et al.* (2020), did not reach the Siljan region.

Lithostratigraphical units

A number of lithological or lithostratigraphical units have been described from the Silurian of Dalarna, most of them not precisely or at all dated by fossils (Fig. 2) and are in need of revision. These include the Kallholn Formation (earlier Kallholn Shale), the Styggforsen Limestone, the Nederberga Formation and the Orsa Sandstone. It was the hope that the newly made drill cores could also provide better information to understand the stratigraphical succession of the Silurian in the Siljan area. The investigation of the Mora 001 and Solberga 1 drill cores indicates the need of a detailed analysis of the lithostratigraphy of the Silurian succession of Dalarna, but also shows the structural complications due to impact-related modifications, which cannot be the focus of this investigation. Even though the lower part of the early Silurian Kallholn Formation of the Siljan region is well known by its graptolite faunas (e.g. Törnquist 1881, 1890, 1892; Hutt *et al.* 1970; Loydell 1991; Loydell & Maletz 2003, 2004, 2009; Maletz 2003; Loydell & Walasek 2019) and its graptolite biostratigraphy has recently been revised (Walasek *et al.* 2018), the higher part of the Silurian succession has commonly been cited, but has not been investigated in enough detail (cf. Baarli *et al.* 2003; Ebbestad *et al.* 2007, 2015) (Fig. 2). Recent investigations of the uppermost part of the Silurian (?) succession are not available (e.g. 'Nederberga Formation', Orsa Sandstone).

The understanding of the Silurian of Dalarna started with the investigation by Törnquist (1867), in which he identified the limestone layers at Styggforsen (spelled Stygforsen in earlier literature) as the 'Graptolitkalk', but it was identified as the Cementkalk by Törnquist (1871). Törnquist (1874) provided a detailed subdivision of the Silurian succession and Törnquist (1881) used the term *Retiolites* Shale (earlier Stygfors shale and limestone) and *Lobiferus* Shale (earlier Kallholn shale and limestone). Törnquist (1883, p. 8) finally adopted the *Rastrites* Shale for the lower interval, introduced by Linnarsson (1881) for this interval in Östergötland and subsequently referred to the *Rastrites* Shale, öfvergångslag and *Retiolites* Shale (Törnquist 1890, 1892) (Fig. 2). Moberg (1910) provided an overview on the Silurian of Sweden (including the Cambrian and Ordovican), stating that 'By the Silurian is here understood all our deposits characterized by trilobites or graptolites' and discussed the historical development of the Silurian succession of Dalarna. He included in the Gotlandian of Dalarna the *Rastrites* Shale (1), *Retiolites* Shales (2), grey shales poor of fossils & *Bumastus* Limestone (3) and the Grindsandstone (4). Little progress has been made since the overview of Moberg (1910), largely in the detailed biostratigraphical investigations of early Silurian graptolite successions at Kallholn and Osmundsberget mentioned earlier.

Lehnert *et al.* (2012, fig. 5) presented the general lithological succession of the Mora 001 drill core and indicated a more than 220 m thick Silurian succession of shales and sandstones above a mid-Darriwilian unconformity, differentiated into six lithological members (Figs 1B, 2). Information on the dip of the strata and any tectonic deformation in the succession is not available, but a variable inclination of the strata is easily recognizable in the drill cores (cf. Fig. 3). Lehnert *et al.* (2012) indicated the presence of megaslumps, debris flows and turbidites in their lower shale member and Muhamad *et al.* (2015, 2017) and Muhamad (2017, p. 16) referred the deformation in the Mora 001 and Solberga 1 drill cores to Caledonian collision tectonics and considered the successions to be 'largely unaffected by faulting and impact-related deformation'. Biostratigraphical information to date the lithostratigraphical column was not provided. The authors suggested a major unconformity between the early Darriwilian Holen Limestone and the overlying 'siliciclastic succession' (Lehnert *et al.* 2012, fig. 7). The biostratigraphical investigation of the graptolite faunas found in the succession revises this interpretation.

The Holen Limestone

Lehnert *et al.* (2012) regarded the red limestone below the Kallholn Formation in the Mora 001 drill core (Figs 1B, 4) as the Holen Limestone, based on the known general lithologies of the Ordovician succession of Dalarna and Västergötland (see Ebbestad *et al.* 2007; Lindskog 2010). However, there are no palaeontological data available to support this suggestion and the age of this red limestone in the Mora 001 drill core remains unknown. The possible gap between the Holen Limestone and the Kallholn Formation has also not been investigated. Lehnert *et al.* (2012, p. 97) interpreted this gap as 'the result of the

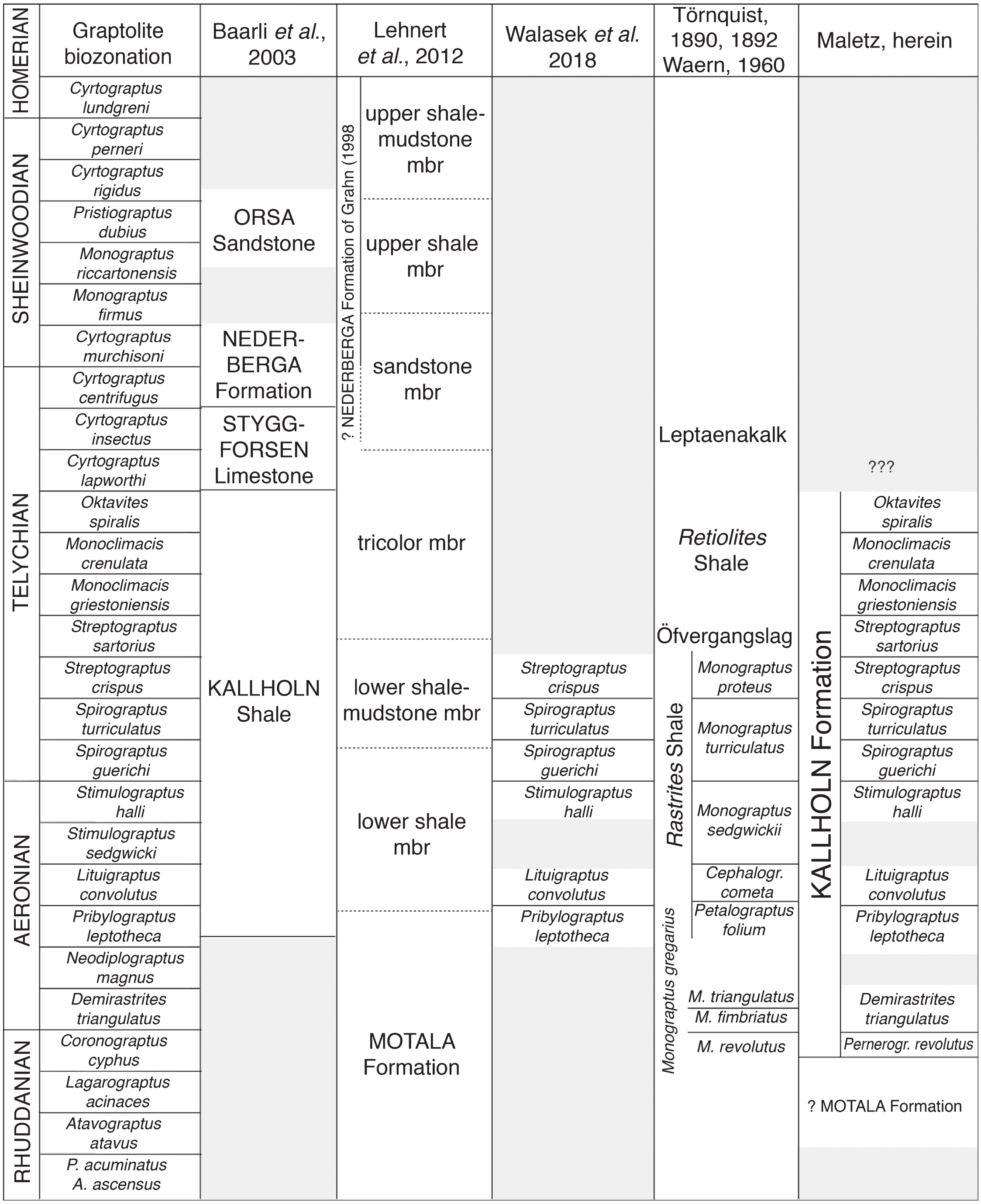

Fig. 2. Correlation of lithostratigraphical units and graptolite biostratigraphy of Dalarna. Silurian graptolite biostratigraphy based on Maletz (2021). Intervals marked in grey are not recognized or represent gaps in the succession.

passage of the Caledonian peripheral forebulge due to tectonic loading by thrust sheet to the west'. This interpretation may be rejected by the presence of a ca. 290-m thick Ordovician succession in the Mora VM2 drill core only 600 m to the north (Muhamad *et al.* 2015, 2018), suggesting that the variation in thickness may be based on impact tectonics.

The Motala Formation

Lehnert *et al.* (2012, fig. 4) indicated the presence of the Motala Formation in the Solberga 1 drill core based on the lithology of the interval (Fig. 2) underlain by the late Ordovician Loka Formation. The authors differentiated three members but did not

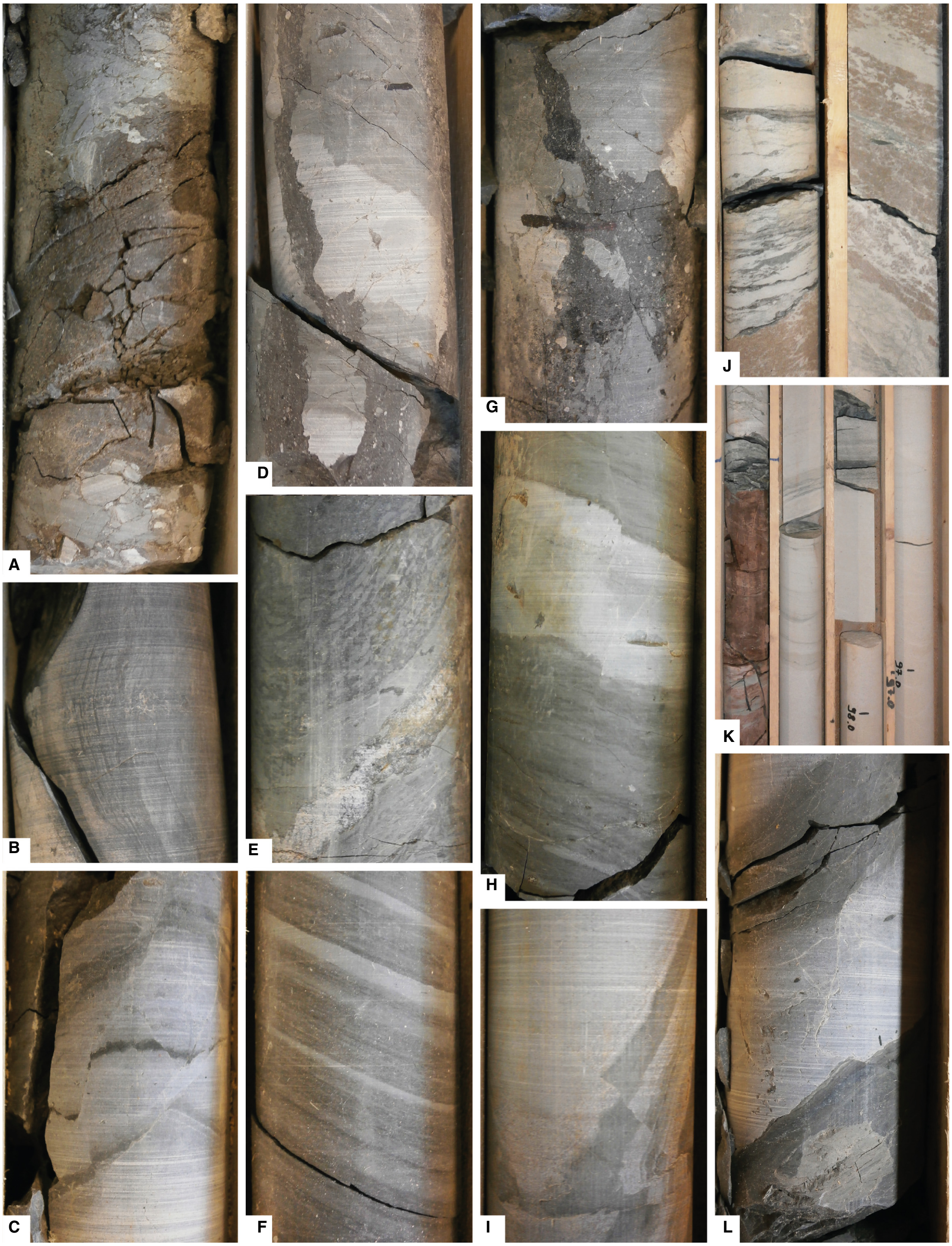

Fig. 3. Sedimentology and tectonic indications in the Mora 001 drill core. A, Mora box 5 (21.65–28.30 m), strongly brecciated limestone in upper interval of the Kallholn Formation. B, Mora box 19 (116.40–122.80 m), vertical position of Kallholn Formation siltstones. C, Mora box 22 (135.60–142.20 m), tectonic deformation of Kalholln Formation siltstones. D, Mora box 5 (21.65–28.30 m), impact injection breccia in Kallholn Formation. E, Mora box 18 (109.18–116.40 m), highly bioturbated interval of Kallholn Formation showing inclination of layers. F, Mora box 25 (157.50–164.25 m), lamination in Kallholn Formation. G, Mora box 4 (15.00–21.65 m), Kallholn Formation with injection breccia. H, Mora box 6 (28.30–34.80 m), green to brown Kallholn Formation shales with light coloured carbonate concretion. I, Mora box 18 (109.18–116.40 m), tectonic deformation in green shales and siltstones of Kallholn Formation. J, Mora box 12 (69.40–76.25 m), top of Orsa Sandstone Formation showing inclination of white sandstones and intercalated reddish mudstones. K, Mora box 16 (96.40–103.15 m), Orsa Sandstone Formation; left column was identified as the tricolor member in Lehnert *et al.* (2012). L, Mora box 34 (218.20–225.00 m), deformed limestone in Kallholn Formation. Diameter of the drill core ~4 cm.

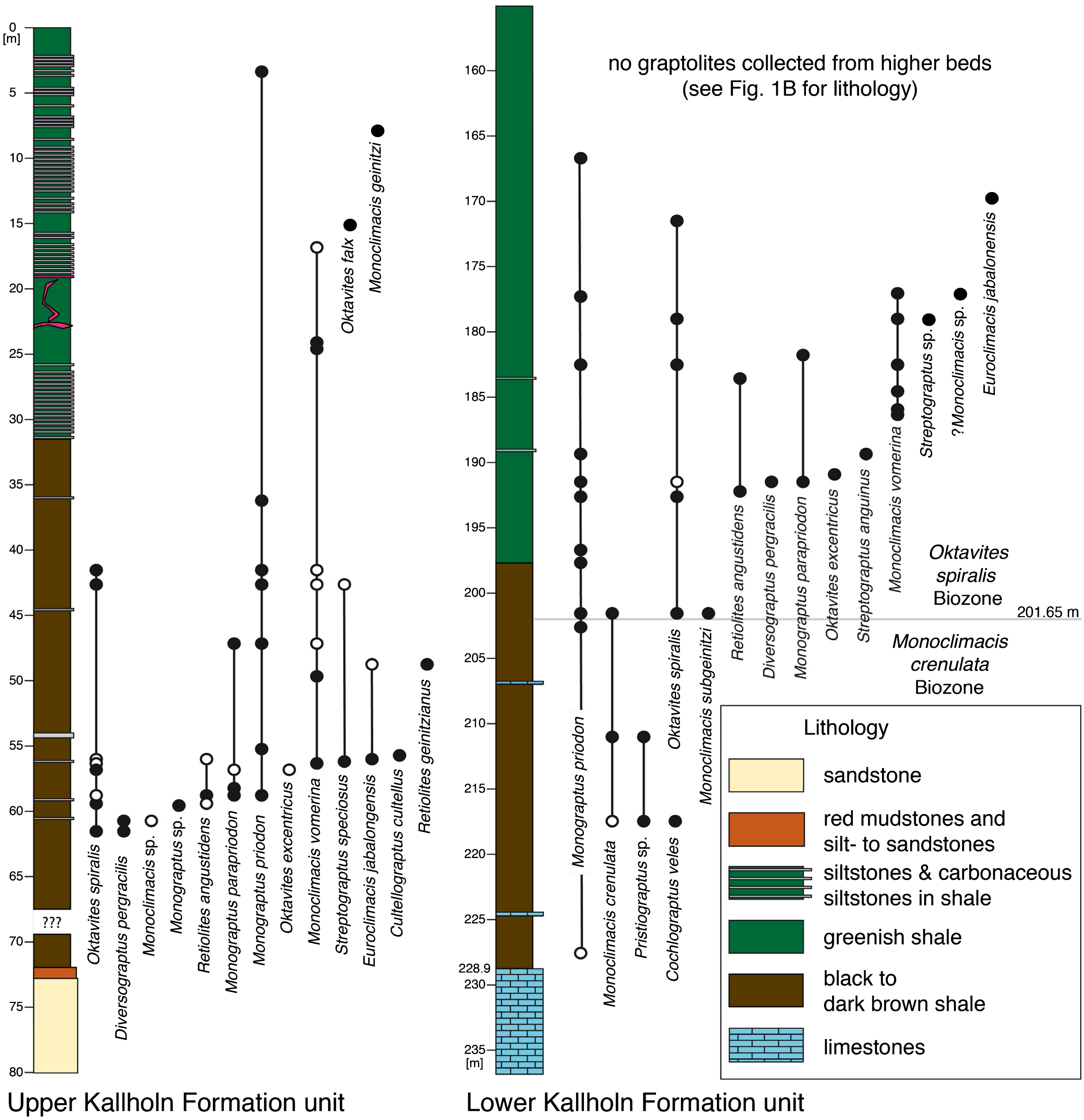

Fig. 4. Mora 001 drill core, graptolite ranges and biostratigraphy. Key to lithological column also for Figures 1 and 7. Empty circles indicate uncertain identifications.

provide any palaeontological evidence for the comparison with the Motala Formation described from Östergötland (Bergström & Bergström 1996). This is the first reference to the presence of the Motala Formation in Dalarna and a lithological description does not exist. Ebbestad *et al.* (2015; fig. 2) included the Motala Formation in their Siljan succession and indicated a gap to the underlying Glisstjärn Formation. The top-Hirnantian (uppermost Ordovician) Glistjärn Formation, however, was not recognized in the Solberga 1 drill core by Lehnert *et al.* (2012).

Bergström & Bergström (1996) did not differentiate any members in the Motala Formation of Östergötland and did not discuss any evidence of a wider palaeogeographical distribution of the unit. The topmost bed is a light-grey, fine-grained, pyrite-bearing limestone bed with a distinct discontinuity surface, suggesting a gap at the top of the unit in Östergötland. In the Solberga 1 drill core, the possible Motala Formation is overlain by ca. 60 m of Kallholn Formation. The basal contact of the Kallholn Formation with the Motala Formation has not been investigated.

Until identified through the fossil content, the presence of the Motala Formation in the Solberga 1 drill core has to be regarded as unproven and the age of the lithological unit referred to the Motala Formation in the drill core remains uncertain.

The Kallholn Formation

The intervals from ca. 0–72 m and 99–228.9 m of the Mora 001 drill core (Figs 1, 4) are here included in the Kallholn Formation, based on the lithology and the available graptolite faunas (Figs 5, 6). The *Monoclimacis crenulata* and *Oktavites spiralis* biozones have been recognized in the Mora 001 drill core. The Kallholn Formation of the Solberga 1 drill core is 60 m thick, but represents a largely different biostratigraphical interval, covering the *P. revolutus* Biozone to the basal *O. spiralis* Biozone (see discussion on biostratigraphy). The youngest biostratigraphical interval in the Solberga 1 drill core, the *O. spiralis* Biozone, is an interval also present in the Mora 001 drill core and indicates a biostratigraphical overlap of the lithological units in both cores.

Törnquist (1874) introduced the term Kallholn Shale for the graptolitic succession at Kallholn, but the term has not been used subsequently as the biostratigraphical terms *Rastrites* Shale and *Retiolites* Shale were more widely distributed (e.g. Törnquist 1883, 1890, 1892; Warburg 1910). Törnquist (1883, 1890, 1892) described a transitional layer ('öfvergångslag') between his *Rastrites* Shale and *Retiolites* Shale as a light, soft shale, bearing a rich graptolite fauna including elements from both intervals. This 'öfvergångslag' is based on faunal overlap, not on lithological differences. Törnquist (1892) listed *Cochlograptus veles* (Richter 1871) (his *Monograptus discus* Törnquist 1883) among the taxa, that may indicate the modern *Streptograptus sartorius* to *M. crenulata* Biozone interval (cf. Fig. 2). Nothing was known to Törnquist (1883) about the thickness of this interval.

Linnarsson (1881) identified comparable shales at Råssnäsudden, Östergötland as the Klubbudden Shale. Jaanusson (1982) referred the early Silurian shales to the Kallholn Formation, but did not provide a definition. Bergström & Bergström (1996) used the term Kallholn Shale for an interval of shales above 'the post-Motala shales in Östergötland and the Llandoverian dark shales and mudstones in Västergötland and Dalarna'.

Bergström *et al.* (1998, fig. 5) indicated an unconformity with the underlying Boda Limestone at the base of the Kallholn Formation at Kallholn, as the basal part of the Kallholn Formation was identified to represent the *Coronograptus gregarius* Biozone of Aeronian age. Muhamad *et al.* (2015) indicated that the boundary between the Ordovician and Silurian strata in the Mora 001 drill core has an erosional contact, following the interpretation of Lehnert & Meinhold (2011) and Lehnert *et al.* (2012) in which the Middle Ordovican (Darriwilian) Holen Limestone is overlain directly by the lower shale member. The contact between the two members has not been investigated or illustrated; thus, its development cannot be confirmed. A tectonic contact due to the impact in Devonian times and the resulting tectonic deformation of the strata is more likely.

The real lithological thickness of the Kallholn Formation in Dalarna is uncertain. Baarli *et al.* (2003) indicated a thickness of 50 m for the Kallholn Formation, overlain by the Styggforsen Limestone of uncertain thickness and a Nederberga Formation of more than 75 m (Fig. 2). Lehnert *et al.* (2012) and Muhamad *et al.* (2017) suggested over 200 m of Kallholn Formation in the Mora 001 drill core, but this investigation indicates a considerably lower thickness.

The Kallholn Formation in the Mora 001 drill core (Fig. 3A–I, L) includes dark brown to black and green shales and mudstones with a variable number of small and large limestone concretions and bentonite beds, spanning large parts of the Llandovery. Bioturbation is easily recognized in certain intervals (Fig. 3E, H) and appears to be common in the shales. The lower part of the Kallholn Formation is generally dark brown to black, grading into more greenish to greyish shales upwards. Pyrite filled burrows are present at some levels. The fossil content is represented by often well-preserved graptolites, sometimes found in full relief, filled by pyrite.

Lehnert *et al.* (2012) discussed synsedimentary deformation in the lower shale interval, but not in the upper one. The authors mentioned megaslumps, debris flows and turbidites and suggested the passage of a Caledonian forebulge from the west. Deformation features are common in the lower Kallholn Formation interval in the More 001 drill core (Fig. 3) and can also be found in the upper Kallholn Formation interval. Layers are commonly inclined (Fig. 3F) and even vertical laminations can be seen (Fig. 3B), which are associated with fractures (Fig. 3C, H). Brecciated beds (Fig. 3A) and injection breccias (Fig. 3D, G) showing angular fragments of the surrounding sediment incorporated in a dark grey matrix are present in the upper Kallholn Formation interval. These may be connected to the formation of the meteorite impact. Unfortunately, detailed investigations of the impact tectonics involving the Palaeozoic sediments of the Siljan area have not been undertaken so far.

Fig. 5. Mora 001, lower Kallholn Formation unit graptolites. A, *Cochlograptus veles*, relief specimen, PMU 37450, 217.40 m. B, *Oktavites spiralis*, PMU 37451A, 192.40–192.50 m. C-D, *Streptograptus* sp., note wide base of thecae, PMU 37452, 178.90 m. E, *Pristiograptus* sp., PMU 37453, 211.00 m. F, ? *Monoclimacis* sp., distal fragment, PMU 37454.1, 177.10 m. G, *Oktavites spiralis*, small stipe fragment, low relief, PMU 37455, 191.50 m. H, *Monoclimacis subgeinitzi* Fu in Fu & Song, 1986, PMU 37457, 201.60 m. I, *Euroclimacis jabalonensis*, poor proximal end showing hooded thecae, PMU 37458, 169.70 m. J, *Diversograptus pergracilis*, slender fragment, dry, PMU 37456, 191.50 m. K, ? *Streptograptus anguinus*, PMU 37459A, 189.35 m. L, *Monograptus priodon*, long flattened fragment, PMU 37460, 179.75 m. M, *Monoclimacis crenulata*, PMU 37461A, 211.00 m. N, *Monoclimacis crenulata*, PMU 37462, 201.65 m. O, *Monoclimacis vomerina*, distal fragment, PMU 37463A, 186.00 m. P, *Monograptus parapriodon*, PMU 37464, 191.50 m. Q, ? *Monoclimacis* sp., fragment without sicula, see lack of geniculum, PMU 37454.2, 177.10 m. R. *Diversograptus pergracilis*, in alcohol, PMU 37456, 191.50 m. S, *Retiolites angustidens*, PMU 37465A, 183.55 m. Scale bar 1 mm.

Lehnert *et al.* (2013, p. 121; 2014a,b) indicated that the absence of marine fossils in large parts of the siliciclastic succession of the More 001 drill core may be explained through the geochemical data, as these appear to indicate a deposition 'at either fully lacustrine to slightly brackish conditions', based on the investigation of Berner *et al.* (2013a,b). The palaeontological investigation here presented show rich graptolite faunas in most of the siliciclastic succession, but not all parts of the lithological column have been investigated in detail. The results indicate a fully marine environment for the sediments, as graptolites are invariably found in normal marine sediments and have never been documented from brackish or lacustrine environments.

The Styggforsen Limestone

Linnarsson (1871) described the Stygforsen Cementkalk, later the Styggforsen Limestone (Hede in Magnusson 1958) and indicated the presence of graptolites (*Graptolithus priodon* Bronn 1835, *Retiolites geinitzianus* Barrande 1850, *Graptolithus convolutus* = ? *O. spiralis* (Geinitz 1842)), trilobites and brachiopods. Törnquist (1874, p. 39) listed the Stygforskalk and Stygforsskiffer, overlain by the Osmundsbergets skiffer? and the Öfre Graptolitsskiffer. Schmalensee (1892) discussed the contact between the Slipsandsten (Orsa Sandstone) and the Retioliteslagren (cf. Cementkalk, Stygforsen Limestone) and mentioned the presence of graptolites in the latter at Styggforsen. Hadding (1958, fig. 19) and Lindström *et al.* (2008) provided photographs of the lithology of the Styggforsen Limestone unit. Magnusson (1958) listed the Styggforsen Limestone and described it as: 'thin layers of reddish-grey, yellowish or greenish-grey, dense, hard limestone alternating with more or less thick bands of grey to greenish-grey or reddish-grey shale' reaching a thickness of about 50 m. It is overlain, most probably unconformably, by the Orsa Sandstone (but see Schmalensee 1892). This interval appears to be exposed only at Styggforsen and a correlation with the sedimentary succession in other places of Dalarna is impossible.

The graptolite fauna already listed, but not described by Linnarsson (1871), may indicate an interval belonging to the *O. spiralis* Biozone, probably a lateral equivalent to the higher part of the Kallholn Formation as found in the Mora 001 drill core. Bulman (1932) described the graptolites from Styggforsen in great detail from chemically isolated material, including *Monograptus priodon*, *O. spiralis* and *Monograptus* sp. (now *Lapworthograptus grayae* (Lapworth 1876): see Zalasiewicz 1995). Schmalensee (1892) listed graptolites from the interval, but the material has not been described and illustrated. His identifications of *Monograpus scanicus* (Tullberg 1883) and *Cyrtograptus* sp. thus cannot be verified. The Styggforsen Limestone has not been discovered in the Mora 001 and Solberga 1 drill cores.

The Nederberga Formation

The Nederberga Formation has never been described or defined and is not listed in Magnusson (1958). Schmalensee (1884) found a new fauna in the Orsa area, supposedly from part of the upper graptolite shale (*Retiolites* Shale). Törnquist (1886) named the interval the *Bumastus* Limestone, which may be comparable to the interval Grahn (1998) identified as the Nederberga Formation. Grahn (1998) discussed what he identified as the type locality of the Nederberga Formation and described the chitinozoan record from the ditch. There is no accessible exposure left in the place. Grahn (1998) illustrated two sections, together ca. 130 m long, but did not provide any information on the dip of the strata and the precise thickness of the unit remains unknown. Most chitinozoan taxa range through the whole interval and the faunas can be included in the *Angochitina longicollis* Biozone (correlatable to the *O. spiralis* to *Cyrtograptus centrifugus* Biozone: Melchin *et al.* 2012, 2020). Grahn (1998) stated that the chitinozoan record indicates an age no younger than the *Cyrtograptus murchisoni* graptolite Zone and that there has been an exposure showing the contact between the Nederberga Formation and the Orsa Sandstone, but no details were provided. Wickström & Stephens (2020) stated that the Kallholn Formation is overlain by an argillaceous limestone and mudstone and referred to Grahn (1998), though did not name the unit. The validity of the Nederberga Formation still needs to be established. It may, however, be correlatable to the higher part of the Kallholn Formation in other localities. The identification of the 'upper shale member' and the 'upper shale-mudstone member' of the Mora 001 drill core (Lehnert *et al.* 2012) as the Nederberga Formation in the Mora 001 drill core (Fig. 1B) cannot be upheld based on the current information, even though it has been marked upon in a number of publications (e.g. Juhlin *et al.* 2012; Lehnert *et al.* 2012; Lu *et al.* 2015; Lu *et al.* 2017). The interval is here referred to the Kallholn Formation. The use of the name Nederberga Formation for a lithostratigraphical unit in the Siljan Ring area should be rejected.


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Fig. 6. Mora 001, upper Kallholn Formation unit graptolites. A, *Streptograptus speciosus*?, see long thecal overlap and development of apertures, PMU 37467.1, 42.60 m. B, *Streptograptus speciosus*?, see long thecal overlap and development of apertures, PMU 37467.2, 42.60 m. C–D, *Streptograptus speciosus*, fragment showing thecal style, PMU 37468.1a, b, 56.30 m. E–F, *Diversograptus pergracilis*, proximal end, counterparts, PMU 37469.1a, b, 61.25 m. G, *Streptograptus speciosus*?, see long thecal overlap, PMU 37466A, 42.60 m. H, *Diversograptus pergracilis*, fragment, PMU 37469A.2, 61.25 m. I, *Diversograptus pergracilis*, fragment, showing thecal apertures, PMU 37470, 60.80 m. J, *Monograptus parapriodon*, proximal end, PMU 37471A.1, 58.25 m. K, *Oktavites spiralis*, proximal end with sicula, PMU 37472, 61.25 m. L, *Monoclimacis geinitzi*, fragment, PMU 37473A, 7.85–7.90 m. M, *Monograptus parapriodon,* fragment, low relief, pyrite filled, PMU 37474A, 58.75–58.80 m. N, *Monograptus parapriodon*, fragment in relief, PMU 37475, 47.05 m. O, *Retiolites angustidens*, meshwork on ancora sleeve visible in upper right corner of specimen, PMU 37476A, 58.75–58.80 m. P, *Retiolites geinitzianus*, fragment showing thecal style, no ancora sleeve, PMU 37477, 48.70 m. Q, *Monoclimacis vomerina*, proximal end, PMU 37478A.1, 24.18–24.20 m. R, *Monoclimacis vomerina*, distal fragment, PMU 37478A.2, 24.18–24.20 m. S, *Streptograptus speciosus*, fragment, PMU 37468A.2, 56.30 m. T, *Monograptus parapriodon*, proximal end, flattened, PMU 37479, 58.75–58.80 m. U, *Oktavites spiralis*, fragment, PMU 37480A.1, 56.80–56.85 m. V, *Monoclimacis vomerina*, fragment, PMU 37481, 56.55 m. W, *Oktavites spiralis*, PMU 37482, 42.60 m. X, *Oktavites falx*, fragment, PMU 37483A, 15.00 m. Y, *Oktavites spiralis,* PMU 37484, 61.30 m. Z, *Oktavites excentricus*, fragment, PMU 37480B.2, 56.80–56.85 m. AA, *Monoclimacis vomerina*, fragment, PMU 37485A, 49.65 m. AB, *Cultellograptus cultellus*, PMU 37486A, 55.90 m. AC, *Monograptus priodon*, distal fragment, PMU 37487, 55.20–55.23 m. Scale bar 1 mm

The Orsa Sandstone Formation

The Orsa Sandstone (also identified as Slipsandsten and Grindsandstone: Magnusson 1958) is a loose, feldspatic sandstone of a white, grey or red colour, in the latter with or without light spots (Moberg 1910, p. 63). It may be conglomeratic or brecciated, with small flattened portions of red or green clay and shale embedded. The Orsa Sandstone is at least 58.9 m thick (Petalas 1985), but as more complete successions are not available the complete thickness of the unit is uncertain. Petalas (1985) described the Orsa Sandstone in some detail from numerous places and interpreted it as a deposit formed as inland dunes by the wind. Raindrop impressions and mud cracks are present, cross bedding is common, convolute bedding appears, clay layers and galls are observed. Thus, the sandstone is quite variable in its sedimentary composition and development.

Schmalensee (1892) suggests a concordant contact between the Orsa Sandstone and the Kallholn Formation, but most authors accepted a discordant contact (e.g. Moberg 1910; Warburg 1910; Thorslund & Jaanusson 1960). However, a detailed investigation of the contact does not exist. Already Nathorst (1885) regarded the slipsandsten (Orsa Sandstone) as the youngest Silurian stratigraphical unit. Warburg (1910) suggested that the Orsa Sandstone is younger than all the fossiliferous Silurian rocks of the Siljan and may be of late Silurian age, but also considered the possibility of a Devonian age. Thorslund & Jaanusson (1960) referred the Orsa Sandstone to the Ludlow (Upper Silurian) and correlated it with the Öved-Ramsåsa Group of Scania, southern Sweden. Baarli *et al.* (2003, fig. 5) indicated a possible Sheinwoodian age for the Orsa Sandstone. Andersen *et al.* (2011) identified it as a Silurian continental sandstone. Gee *et al.* (2013, table 2) discussed the Orsa Sandstone as the 'Old Red Sandstones' and the youngest strata in the Siljan Ring and referred to the sandstone at Styggforsen as of Middle Silurian (Wenlock) age. Ebbestad & Högström (2007, fig. 1) more carefully suggested a late Silurian to Devonian age of the Orsa Sandstone. A comparison with the Öved Sandstone in Scania (see Jeppsson & Laufeld 1986) may be reasonable, but fossils have not been discovered to date the unit and support any of the previous interpretations. Mehlqvist *et al.* (2015) indicated through a palynological investigation that the upper part Öved Sandstone Formation of Scania is Devonian (Lochkovian) in age, while the lower part is Pridoli (late Silurian) in age.

Lehnert *et al.* (2012, fig. 5) interpreted a sandstone unit in the Mora 001 drill core ('sandstone member') (Fig. 1B) as a regression of the shoreline in Wenlock times, followed by a rapid transgression. Lehnert *et al.* (2014b) discussed the deposition of the sandstone as the progradation of a delta system in the upper part of the succession, possibly due to a global sea-level drop during the Sheinwoodian (early Wenlock) glaciation. A Wenlock age of the sandstone member, however, is unlikely if it is found in an uninterrupted succession within the shales of the Kallholn Formation, but would be of a mid-Llandovery (*O. spiralis* Biozone) age. The 'tricolor member' and the 'sandstone member' of Lehnert *et al.* (2012) is here interpreted to represent a sliver of the Orsa Sandstone, tectonically introduced into the succession of the Mora 001 drill core (Fig. 3J, K). The Orsa Sandstone Formation is widely found in the region (see Lindström *et al.* 2008, fig. 4) and due to the impact tectonics it is unlikely that the unit in the Mora drill core represents a different, previously unrecognized sandstone unit. Lithologically, the sandstone is easily comparable with the Orsa Sandstone as described by Petalas (1985). Interestingly, Meinhold *et al.* (2013) made a geochemical comparison of the 'sandstone member' of the Mora 001 drill core with the Mesoproterozoic Dala Sandstone Formation, but not with the Orsa Sandstone. Due to the lack of any acceptable biostratigraphical dates, the Orsa Sandstone Formation is not shown in Fig. 2, as it may represent a unit younger than the Sheinwoodian (Wenlock, mid-Silurian).

Graptolite biostratigraphy

The graptolite biostratigraphy for the Silurian is based on Maletz (2021), providing the latest overview on the graptolite biostratigraphy of Scandinavia and their international correlation. All graptolite biozones used herein must be regarded as purely local and boundaries are tentative, as the graptolite record in these drill cores is not sufficient for a precise biozonation.

Törnquist (1883) provided the earlier concept for the graptolite biostratigraphy of the Silurian of Dalarna, differentiating the *Rastrites* Shale and the *Retiolites* Shale. Törnquist (1892) differentiated six graptolite zones in the *Rastrites* Shale and one in the *Retiolites* Shale, with another interval identified as the 'öfvergångslag' (Fig. 2). Walasek *et al.* (2018) provided the latest graptolite biostratigraphy for the lower part of the Kallholn Formation in the Kallholn locality that may be regarded as the type locality of this lithological unit. They discussed a thickness of about 22 m of the Kallholn Formation in the Kallholn S section and about 15 m in the Kallholn N section. Walasek *et al.* (2018) indicated the presence of the *Pribylograptus leptotheca* to *Streptograptus crispus* biozones in the Kallholn N section, but not all intervening biozones were recognized. The succession thus only exposes the lower part of the Kallholn Formation as understood here. The higher part of the Kallholn Formation has not been redescribed since the original graptolite descriptions by Törnquist (1890, 1892). Törnquist (1892) indicated the presence of *S. sartorius* in his öfvergångslag. Loydell & Maletz (2004, p. 68) identified the *S. sartorius* Biozone in the Solberga section of Maletz & Reich (1997), in which a rich radiolarian fauna was found (Noble & Maletz 2000). Based on the graptolite faunas of the Mora 001 and Solberga 1 drill cores, the higher part of the Kallholn Formation is here included in the *M. crenulata* and *O. spiralis* biozones (Fig. 2). Younger graptolites have not been reported from Dalarna.

All illustrated graptolite specimens from the two drill cores are preserved in the collection of the Museum of Evolution, Uppsala University, Uppsala, Sweden (PMU), including also additional, not illustrated material used to construct the range charts. Pyritic specimens are generally photographed under alcohol or water to increase the contrast of the pyrite to the surrounding sediment (see especially Fig. 6).

The Mora 001 graptolite faunas

The four shale and shale–mudstone members of Lehnert *et al.* (2012) are here identified as the Kallholn Formation and their graptolite faunas are documented (Fig. 4). These provide information on the age of the intervals. The lower shale member, initially regarded as of Middle Ordovician age (Lehnert & Meinhold 2011) was later interpreted as of Llandovery to Wenlock (Silurian) age based on preliminary graptolite identifications (Lehnert *et al.* 2012). However, palaeontological data for the succession are only provided in this paper. Unfortunately, the graptolite record for the succession is not very good, a result probably not based on the lack of graptolites in the succession, but on the time available to investigate the core and the need to keep the lithological column in shape for further investigation. Thus, fossils have been collected from relatively few levels where they were easily accessible without completely crushing the core (Fig. 4). Still, the results were highly useful for the understanding of the age and biostratigraphical correlation of the lithological intervals.

The lower Kallholn Formation unit (ca. 105–222 m: Lehnert *et al.* 2012, fig. 5: lower shale member and lower shale–mudstone member) provided graptolites only in the interval below 165 m (Fig. 4). No graptolites have been discovered in the lower shale-mudstone member of Lehnert *et al.* (2012), unfortunately. The reason may be the strong tectonic deformation of most of the interval and the unfavourable (silty) lithology. The lower interval, ca. 201.65–228.9 m, is here referred to the *M. crenulata* Biozone. The presence of *C. veles* (217.4 m) (Fig. 5 A) in this interval clearly indicates an interval below the *O. spiralis* Biozone. Bjerreskov (1975) indicated that the species is never found associated with *O. spiralis* and thus is restricted to the *S. crispus* and *Monoclimacis griestoniensis* biozones. *Monograptus priodon* (Fig. 5L) and *M. crenulata* Elles & Wood 1911 (Fig. 5M, N) occur in the interval, but are long-ranging species.

Oktavites spiralis (Fig. 5B, G) appears first at 201.65 m, defining the base of the *O. spiralis* Biozone, and is present at a number of levels higher up in the shales. The presence of *Oktavites excentricus* Bjerreskov 1975 at 191.00 m may represent the middle part of the *O. spiralis* Biozone (Loydell *et al.* 2009). The same species is present at 56.80–56.85 m in the upper Kallholn Formation unit. Several *Monoclimacis* species are present in the interval, of which *Monoclimacis vomerina* (Nicholson 1872) (Fig. 5O) is the most common one. A possible presence of *Euroclimacis jabalonensis* Loydell *et al.* 2009 (Fig. 5I) in the higher part of the interval may be the first record of this species in Scandinavia, but the material is poorly preserved. A relief fragment showing rounded genicula and a distinctly widening tubarium may belong to *Monoclimacis* sp., but the proximal end is lacking, and the specimen does not show any apertural hoods or hooks. It may alternately be identified as *Pristiograptus* sp. (Fig. 5Q).

A single fragment of *Streptograptus* sp. (Fig. 5C, D) shows wide bases of the metathecae, narrowing distally, typical of a species similar to *Streptograptus storchi* from the *Spirograptus guerichi* to *S. crispus* biozones (Loydell & Maletz 2004) and differs considerably from *Streptograptus anguinus* (Přibyl, 1941) (Fig. 5K). A number of slender fragments are identified as *Diversograptus pergracilis* (Bouček 1931) (Fig. 5J, R). Due to the preservation of largely flattened, pyrite filled tubaria, the characteristic thecal apertures (see Loydell & Nestor 2006) are difficult to see. A number of slender *Monograptus* specimens have been identified as *Monograptus parapriodon* Bouček 1931 (Fig. 5P). The thecal style is identical to that of *M. priodon*, but the tubarium does not widen much from the proximal end. *Monograptus parapriodon* may also be represented in the material illustrated by Bulman (1932, pl. 1, figs 5–11) from the *Retiolites* Shale of Stygforsen collected by von Schmalensee and prepared by Holm. Other specimens from Gotland (Bulman 1932, pl. 1, figs 1–4) are more robust and belong to *M. priodon*.

Slender biserial specimens showing a retiolitid meshwork and a considerable filling with pyrite are identified as *Retiolites angustidens* Elles & Wood 1908 (Fig. 5S) due to the dimensions (see Loydell *et al.* 1997). The meshwork of the ancora sleeve is recognizable only in small parts of the colony and most parts are filled with a thin layer of pyrite.

The upper Kallholn Formation unit (ca. 0–72 m: Lehnert *et al.* 2012, fig. 5: upper shale member and upper shale-mudstone member) can entirely be included in the *O. spiralis* Biozone (Fig. 4). Graptolites are more common in the lower part of the interval (ca. 34–61 m), the 'upper shale member' of Lehnert *et al.* (2012), and are rare in the 'upper shale-mudstone member' (ca. 0–34 m) showing considerable tectonic distortion. At the base of the upper interval of the Kallholn Formation a considerably fractured interval of shales can be seen, suggesting a tectonic basal contact. Graptolites are not uncommon, and many fragments of *O. spiralis* (Fig. 6K, U, W, Y) are present, but larger specimens have not been found. Several species of *Monoclimacis* have been differentiated (Fig. 6L, Q, R, V). A specimen of the biostratigraphically strongly restricted *Cultellograptus cultellus* (Törnquist 1881) at 55.90 m (Fig. 6AB) indicates the lower *O. spiralis* Biozone. A few specimens of *R. angustidens* (58.75 m) (Fig. 6O), barely showing any details of the ancora sleeve and a single fragment of *R. geinitzianus* (48.70 m) (Fig. 6 P) with evidence of the thecal style, but lacking most of the ancora sleeve meshwork, are found. Specimens referred here to *Streptograptus speciosus* (42.60 m, 56.30 m) (Fig. 6C, D, S) show the enrolled thecal apertures of a *Streptograptus* species and vaguely indicate the presence of cupulae. Specimens from the 42.60 m level (Fig. 6A, B, G) are preliminarily included in the same species, but show high thecal overlap. They either represent distal fragments of *S. speciosus* (Tullberg 1883) or another unrelated species. Specimens of *M. priodon* (Fig. 6AC), *M. parapriodon* (Fig. 6J, M–N, T), *M. vomerina* (Fig. 6Q, R, V), *Monoclimacis geinitzi* (Bouček 1932) (Fig. 6L) and *Oktavites falx* (Suess 1851) (Fig. 6X) are present, but are not informative for biostratigraphical purposes. The interval does not bear any biostratigraphially relevant taxa, except for indicating the *O. spiralis* Biozone.

The Solberga 1 graptolite faunas

The Solberga 1 drill core on the SE side of the Siljan Ring (Lehnert *et al.* 2012, fig. 2) shows a thick Ordovician succession of limestones overlain by the Kallholn Formation of Llandovery, lower Silurian age (Fig. 7). Biostratigraphical data exist only for the Kallholn Formation and the identification of units in the Ordovician succession is entirely based on lithological criteria. Still it is obvious that the Ordovician succession is strongly tectonized and repetition of lithological units is common as Lehnert *et al.* (2012, fig. 6) show through the presence of numerous thrust slices. Faulting was not indicated in the Silurian part of the succession, but intervals showing distortion of the layering and the presence of slickenslides indicate a certain amount of deformation of the succession.

A number of bentonite beds have been encountered in the Solberga 1 drill core and Lehnert *et al.* (2012, p. 92) provided the precise levels of these beds. The bed at 33.19–33.05 m was the thickest (14 cm) with the others only between two and five cm in thickness. The bentonites can be compared generally with the beds at Osmundsberget and Kallholn (e.g., Bergström *et al.* 1995; Bergström *et al.* 1998; Huff

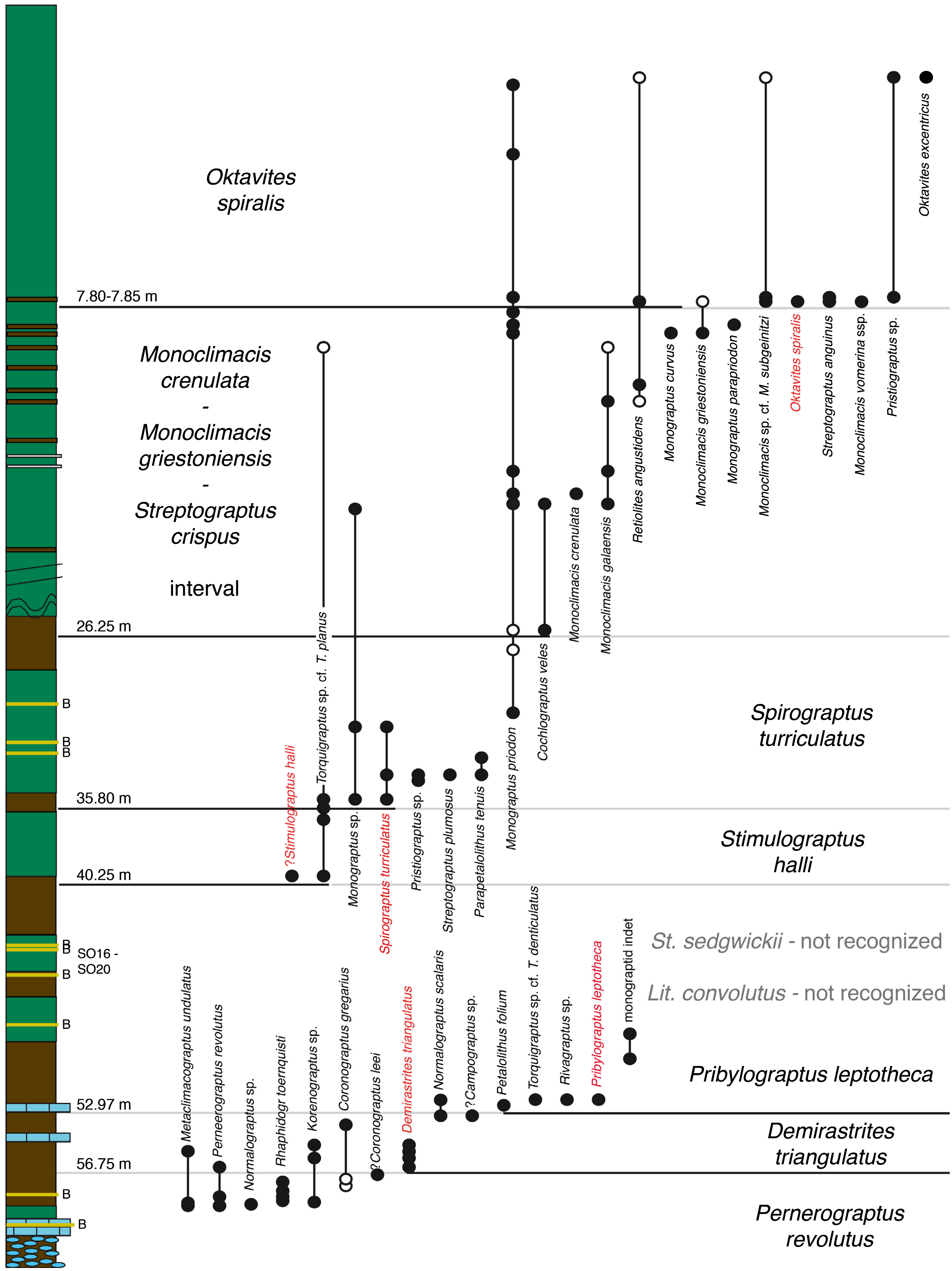

Fig. 7. Graptolite biostratigraphy of the Solberga 1 drill core. For lithological key see Figure 4; B indicates bentonite beds. Empty circles indicate uncertain identifications.

Fig. 8. Solberga 1, Kallholn Formation graptolites. A, *Rhaphidograptus toernquisti*, PMU 37488A, 58.50 m. B, *Demirastrites triangulatus*, proximal fragment, PMU 37489, 55.85–55.90 m. C, *Demirastrites triangulatus*, distal fragment, PMU 37490, 55.97 m. D, *Torquigraptus* sp. cf. *Torquigraptus planus*, proximal end, but sicula not preserved, PMU 37491A.1, 40.25 m. E, *Torquigraptus* sp. cf. *T. planus*, distal fragment, PMU 37491A.2, 40.25 m. F, *Petalolithus folium*, PMU 37492A, 52.97 m. G, *Streptograptus anguinus*, PMU 37493A, 7.80–7.85 m. H, *Torquigraptus* sp. cf. *Torquigraptus denticulatus* (Törnquist, 1899), PMU 37494A, 52.88–52.90 m. I, *Oktavites spiralis*, proximal end, PMU 37495A, 7.80–7.85 m. J, *Cochlograptus veles*, PMU 37496, 19.00–19.08 m. K, *Retiolites angustidens*, PMU 37497A, 7.80–7.85 m. L, *Parapetalolithus tenuis*, PMU 37498, 34.55 m. M, *Monoclimacis* sp. cf. *Monoclimacis vomerina*, PMU 37499, 7.80–7.85 m. N, *Monograptus priodon*, PMU 37500, 18.60–18.65 m. O, *Monograptus priodon*, proximal end, PMU 37501, 9.1 m. P, *Pristiograptus* sp., dorsal view, PMU 37502, +4.74 to 4.80 m. Q, *Monoclimacis griestoniensis*, poor proximal end, PMU 37503, 9.6 m. R, *Stimulograptus halli*, PMU 37504, 40.25 m. S, *Spirograptus turriculatus*, PMU 37505A, 31.75 m. Scale bar 1 mm.

et al. 1998, 2013; Walasek *et al.* 2018) being found in a supposedly biostratigraphically similar interval (*Stimulograptus halli* to *Spirograptus turriculatus* Biozone). A precise correlation of individual beds is, however, not possible. Huff *et al.* (2013) correlated the beds SO16-SO20 of the Solberga 1 drill core (possibly *Lituigraptus convolutus* Biozone) (Fig. 7) with the Osmundsberget bentonite at Osmundsberget (Bergström *et al.* 1998; Huff *et al.* 1998), but the Osmundsberget bentonite is found in the higher part of the *S. turriculatus* Biozone or even higher (cf. Loydell & Maletz 2004; Walasek *et al.* 2018), making the correlation unlikely to be correct.

The graptolite biostratigraphy is based on relatively few graptolites in a drill core with small diameter (ca. 4 cm) and, thus, may not be too precise (Fig. 7). At the base of the succession, *Rhaphidograptus toernquisti* (Elles & Wood 1906) (Fig. 8A) is the most common taxon. The species is easily recognizable in complete proximal ends with the initially uniserial development, but distal fragments may easily be misidentified as normalograptids.

A number of slender curved monograptids can be identified as *P. revolutus*, but thecal details are difficult to see in the flattened material. Flattened and fragmented specimens of *Metaclimacograptus undulatus* can also be observed. The interval is here referred to the *P. revolutus* Biozone following Waern (1960). It is overlain by the *Demirastrites triangulatus* Biozone based on the common occurrence of the index species (Fig. 8B–C). The base of the zone is taken at 56.75 m. The presence of a distal fragment of *Petalolithus folium* (Hisinger 1837) (Fig. 8F) is used to recognize the *P. leptotheca* Biozone interval in the drill core at 52.97 m, as further indicative taxa for this interval are not present. There is no fossil evidence of the *L. convolutus* Biozone and the *Stimulograptus sedgwickii* Biozone in the drill core (Fig. 7). A single specimen is referred to *Rivagraptus* sp. based on the proximal end, but apertural spines are not seen on the thecae. Thus it is uncertain, whether the specimen may be referred to the well-known *Rivagraptus bellulus*. There is a considerable interval, more than 10 m thick between the occurrence of *P. folium* and the presence of? *S. halli* (Barrande 1850) (Fig. 8R) and the first specimens of the genus *Torquigraptus* sp. cf. *Torquigraptus planus* (Barrande 1850) (Fig. 8D–E) at 40.25 m, in which barely any graptolites were found. A number of specimens of *S. turriculatus* (Barrande, 1850) at 35.80 m may indicate the biozone of this name, but the species has been reported from several additional levels (Fig. 8S), while the earlier *S. guerichi*, present in the Osmundsberget section (see Loydell & Maletz 2004), was not found. Poor specimens of *Parapetalolithus tenuis* (Barrande 1850) (Fig. 8L) are present in the *S. turriculatus* Biozone. As *S. turriculatus* ranges through its own interval and also the overlying *S. crispus* Biozone, the presence of *C. veles* at 26.25 m and higher up in the succession (Fig. 8J) may indicate the latter interval (Walasek *et al.* 2018, p. 8). *Cochlograptus veles* is common in the *S. crispus* to *M. crenulata* biozones, though does not reach into the *O. spiralis* Biozone (cf. Bjerreskov 1975; Loydell *et al.* 2017). A flattened proximal end of *M. griestoniensis* (Nicol 1850) (Fig. 8Q) was found at 9.60 m, indicating the *M. griestoniensis* Biozone or the overlying *M. crenulata* Biozone. *Oktavites spiralis* was found in a few fragments and proximal ends at 7.80–7.85 m (Fig. 8 I), indicating the *O. spiralis* Biozone. At the base of this interval also *S. anguinus* is present (Fig. 8G). Specimens probably belonging to the genus *Pristiograptus*, preserved in a dorsal view resembling a biserial colony, occur in the interval (Fig. 8P). In cases in which only the outline is visible, these may be identified as glyptograptids or similar biserial graptolites. Laterally preserved specimens of this taxon were not found. A well-preserved specimen with proximal end showing a number of distinctly hooked thecae is here referred to *Monoclimacis* sp. cf. *M. vomerina* (Fig. 8M). Bjerreskov (1975) described a similar form as *Monograptus vomerina* n. subsp. in which 3–4 proximal thecae are hooked from the basal *O. spiralis* Biozone.

Graptolite biostratigraphy of the Kallholn Formation

It is unclear how complete the Kallholn Formation succession in Dalarna is as the succession has to be pieced together from small outcrops providing only limited biostratigraphical information. A number of levels with graptolites indicate a late Rhuddanian to late Telychian succession. Graptolites of Sheinwoodian (Wenlock) age have not been described from Dalarna unless the record of *M. scanicus* and *Cyrtograptus* sp. by Schmalensee (1892) can be verified. There is no doubt that the *Rastrites* and *Retiolites* Shales of early authors can be incorporated into a single lithostratigraphical unit, the Kallholn Formation.

The existing information now provides a general idea on the completeness of the Llandovery Kallholn Formation (Fig. 2). The oldest parts have been discussed by Waern (1960), based on successions at Gulleråsen-Sanden and Silvberg, but the successions in both localities are somewhat different. The successions show the oldest recognized parts of the

Kallholn Formation, starting in the *P. revolutus* Biozone. The interval is followed by the *Demirastrites fimbriatus* and *D. triangulatus* zones at Silvberg, while at Gullerasen-Sanden, layers with *P. folium* are following on the *P. revolutus* interval and the *D. fimbriatus* and *D. triangulatus* intervals are not recognized. The identification of a lower *D. fimbriatus* interval and an upper *D. triangulatus* interval is unusual, as *D. fimbriatus* (Nicholson 1868) (a synonym of *Demirastrites pectinatus* (Richter 1853)) occurs above *D. triangulatus* (Harkness 1851) (see Štorch & Melchin 2018, fig. 2). Hutt *et al.* (1970) illustrated graptolites from the Silvberg section, including *R. toernquisti* and referred the material to the *Monograptus gregarius* Biozone.

The Silvberg section shows the *P. folium* interval followed by the *S. sedgwickii* and *Rastrites linnaei* intervals. In the Gullaerasen-Sanden section, a *Cephalograptus cometa* interval can be found between the *P. folium* and the *S. sedgwickii* intervals. The *P. folium* and *C. cometa* intervals may be correlated with the *L. convolutus* Biozone in other regions as the biostratigraphical distribution of these species indicates (cf. Štorch 1998). Unfortunately, the graptolite faunas of the successions have not been described. Waern (1960) indicated the presence of a number of bentonite beds, found in all graptolite zones. The lithologies vary considerably and cannot be correlated between the sections. Waern (1960) erected the Bollerup, Silvberg, Klubbudden and Kullatorp stages for Sweden based on his findings and defined these by the graptolite faunas.

Walasek *et al.* (2018) redescribed the Kallholn succession and recognized an interval from the Aeronian *P. leptotheca* Biozone to the Telychian *S. crispus* Biozone, but not all biostratigraphical intervals were found (Fig. 2). The base of the Kallholn Formation in the Kallholn N section was considered to be within the *P. leptotheca* Biozone, overlain by the *L. convolutus* Biozone (fauna described in Maletz 2003; Loydell & Maletz 2009). A considerable gap was detected above the *L. convolutus* Biozone, above which the *S. halli* Biozone was found. This gap, covering the *S. sedgwickii* Biozone previously discussed by Waern (1960), Thorslund & Jaanusson (1960) and Bergström *et al.* (1998), was not detected by Walasek *et al.* (2018). The following *S. guerichi* and *S. turriculatus* biozones could be differentiated (Loydell *et al.* 1993) and in the uppermost part of the succession the *S. crispus* Biozone is present. The authors illustrated only a few important graptolite species and did not cover the complete faunas. Loydell & Walasek (2019) described with *Pristiograptus paradoxus* and *Torquigraptus loveridgei* two new species from the lower *S. turriculatus* Biozone at Kallholn.

Loydell *et al.* (1993) described chemically isolated material of *S. guerichi* from a level ca. 4 m above the contact with the Upper Ordovician Boda Limestone in the Osmundsberget section. Bergström *et al.* (1998) discussed the Osmundsberget section and recognized the *S. sedgwickii* and *S. turriculatus* biozones, in which they found a number of bentonite beds. The largest bentonite bed was considered to be in the lower part of the *S. turriculatus* Biozone and measured 115 cm in thickness. Loydell & Maletz (2002, 2004) provided a section from the Osmundsberget quarry showing the position of their samples, but did not provide detailed information on the biostratigraphy. The youngest sample was indicated to be from the lower *S. turriculatus* Biozone, but most of the interval was referred to the *S. guerichi* Biozone. The base of the Kallholn Formation at Osmundsberget was considered to possibly be in the *S. halli* Biozone, but the lowermost faunas were not biostratigraphically significant (Loydell & Maletz 2004, p. 67).

A short section at Solberga (Maletz & Reich 1997), initially considered to represent the *S. turriculatus* Biozone, was later referred to the *S. sartorius* Biozone (Loydell & Maletz 2004) due to the common occurrence of the index species and of *C. veles*. The upper part of the section, in which a fault can be seen above the level with *S. sartorius*, may actually belong to the *M. crenulata* Biozone.

Graptolitic successions from the *M. griestoniensis* to the *O. spiralis* biozones have not been described from any outcrop so far. Törnquist (1880) described *R. geinitzianus* from Dalarna in some detail and, based on material from Stygforsen and Nittsjö, even differentiated the internal thecal style from the ancora sleeve development. Törnquist (1890) described the retiolitids *Retiolites obesus* (*Pseudoplegmatograptus obesus*), *Retiolites* cfr. *perlatus* (*Pseudoretiolites perlatus*) and *Stomatograptus grandis* (*Stomatograptus toernquisti*) from the *Retiolites* Shales of Dalarna. Törnquist (1890, 1892) described the graptolites of the Retiolites Shale from the localities Styggforsen and Nittsjö, but these localities were never described in detail and the biostratigraphical ranges of the faunal elements are unknown. The Mora 001 and Solberga 1 drill cores, thus represent the first biostratigraphical information on the *M. griestoniensis/crenulata* and *O. spiralis* biozone intervals of Dalarna. Younger strata are not proven, as specimens of *Cyrtograptus* have not been discovered in Dalarna. Thus, the top of the Kallholn Formation of Dalarna may be in the late Telychian (Llandovery, Silurian) *O. spiralis* Biozone. Cyrtograptids indicating the *Cyrtograptus lapworthi* Biozone of late Telychian age are present further south at Kinnekulle in Västergötland (Arveståls & Streng 2013).

Conclusions

The following conclusions can be drawn:

1 The Mora 001 and Solberga 1 drill cores provide the best and most complete information on the Llandovery (early Silurian) graptolite biostratigraphy of the Siljan impact region known so far.
2 The graptolite succession ranges from the *P. revolutus* Biozone (late Rhuddanian) through the Aeronian to the *O. spiralis* Biozone (late Telychian). Younger graptolite faunas are unknown from Dalarna.
3 The drill core successions are strongly affected by the Devonian meteorite impact as is shown by impact-related tectonic features like injection breccias and the insertion of lithological slivers into unrelated rocks sequences.
4 A sliver of the Orsa Sandstone is shown to be inserted tectonically (impact related) into the Kallholn Formation shales in the Mora 001 drill core.
5 The name Nederberga Formation should not be used in the Palaeozoic succession of Dalarna, as it is not defined and cannot be recognized.

Acknowledgements. – Oliver Lehnert and Guido Meinhold made this work possible by asking me to join them in their research on the sedimentary succession of the Siljan Impact and to sample the Mora 001 and Solberga 1 drill cores, deposited at IGRENE in Mora, Dalarna in autumn 2012. Per Ahlberg, Anders Lindskog (Lund, Sweden) and Jan Ove Ebbestad (Uppsala, Sweden) provided important historical literature concerning the investigation of the Silurian of Dalarna. Earlier fieldwork on the Silurian Kallholn Formation was supported by DFG project Ma 1269/5-1 (1999-2001). David Loydell (Portsmouth, UK) supported this earlier research with his knowledge on Silurian graptolites. This paper is a contribution to the IGCP 591 project 'The Early to Middle Paleozoic Revolution'. Open Access funding enabled and organized by Projekt DEAL.

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