

Miaolingian (Cambrian) trilobite biostratigraphy and carbon isotope chemostratigraphy in the Tingskullen drill core, Öland, Sweden

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Abstract. The Cambrian succession of the Tingskullen drill core from northern Öland comprises Cambrian Series 2 and Miaolingian (Wuliuan Stage) siliciclastic strata. The major portion of the succession is represented by the Miaolingian Borgholm Formation, which, in ascending order, is subdivided into the Mossberga, Bårstad and Åleklinta members. The Åleklinta Member is barren of body fossils, whereas the Mossberga and Bårstad members are moderately to highly fossiliferous and biostratigraphically reasonably well constrained. Trilobites and agnostoids from the Bårstad Member are indicative of the *Acadaparadoxides pinus* Zone. The Mossberga Member has not yielded any zonal guide fossils but is tentatively assigned to the *Eccaparadoxides insularis* Zone. A $\delta^{13}\text{C}_{\text{org}}$ curve throughout the Borgholm Formation shows a general positive trend up-section without any distinctive excursion, suggesting that the Wuliuan *Acadaparadoxides* (*Baltoparadoxides*) *oelandicus* Superzone (the ‘Oelandicus beds’) of Öland is younger than the negative Redlichiiid–Olenellid Extinction Carbon isotope Excursion (ROECE), which is known from near the top of Stage 4 and close to the traditional ‘Lower–Middle Cambrian boundary’ in several parts of the world.

Key words: biostratigraphy, carbon isotope stratigraphy, Miaolingian Series, Wuliuan Stage, Cambrian, Öland, Sweden.

INTRODUCTION

In most parts of the world, the Cambrian has traditionally been divided into lower, middle and upper parts (corresponding to series/epochs). The boundary of each series (epoch) was, however, placed at a chronostratigraphic level that varied from region to region (e.g. Robison et al. 1977; Geyer & Shergold 2000). In order to resolve this problem, the International Subcommission on Cambrian Stratigraphy is working towards a global subdivision of the Cambrian System into four series and ten stages (e.g. Babcock et al. 2005), as opposed to the traditional tripartite subdivision into three series. Hence, the chronostratigraphic subdivision of the Cambrian System is currently undergoing substantial changes and the traditional series ‘Lower’, ‘Middle’ and ‘Upper’ Cambrian will be abandoned (see Peng et al. 2012 for a

brief review). Each new global chronostratigraphic unit in the current conceptual model of the Cambrian System will have definitions based on the boundary-stratotype concept (Salvador 1994), in which a Global boundary Stratotype Section and Point (GSSP) is used to define the base of a series or stage.

So far, six Cambrian stages (Fortunian, Wuliuan, Drumian, Guzhangian, Paibian and Jiangshanian) and three series (Terreneuvian, Miaolingian and Furongian) have been defined and formally named (Peng et al. 2004, 2009, 2012; Babcock et al. 2007; Landing et al. 2007; Zhao et al. 2012, 2019; Geyer 2019). The remaining undefined series and stages have received provisional numerical designations. The Miaolingian Series was ratified in 2018 and is divided into three global stages, in ascending order, the Wuliuan, Drumian and Guzhangian stages. Although of considerably greater stratigraphic

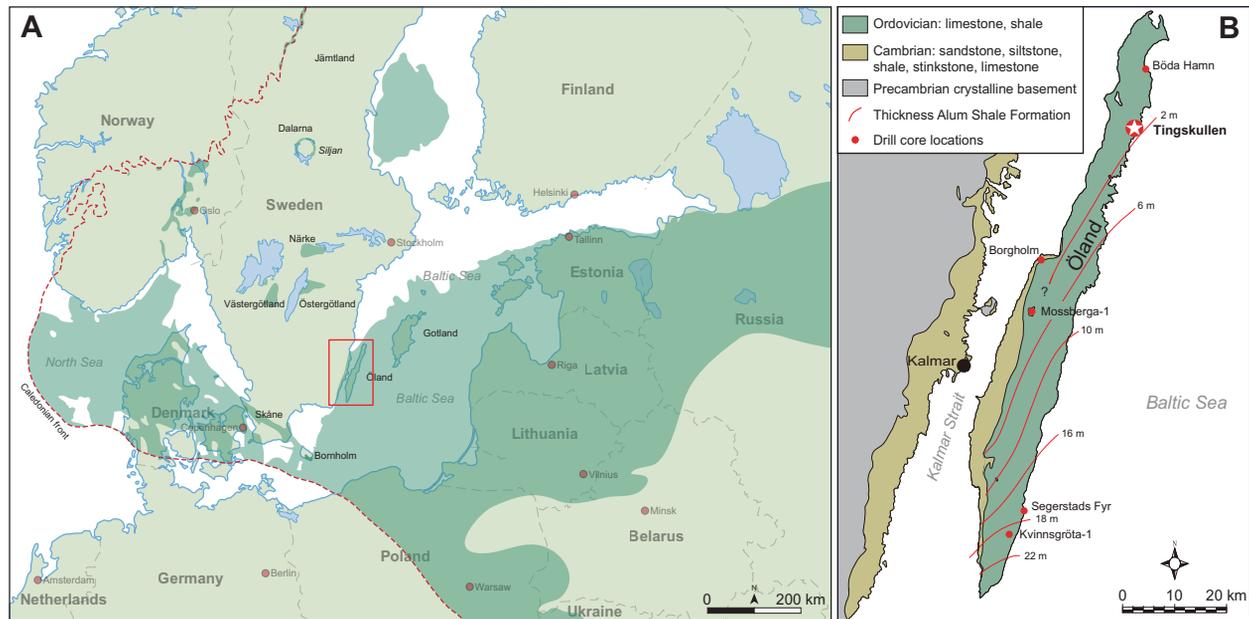


Fig. 2. A, map of southern Sweden and the surrounding Baltoscandian region showing the distribution of lower Palaeozoic rocks (green shading). Modified from Lindskog & Eriksson (2017, fig. 1). **B**, simplified geological map of Öland, southern Sweden, showing the location of the Tingskullen drill site and the location of other core drillings referred to in the text. Unbroken lines represent isopachytes for the Miaolingian through the Lower Ordovician (Tremadocian) Alum Shale Formation. Modified from Erlström (2016, fig. 1) and Ahlberg et al. (2019, fig. 1).

(Martinsson 1974; Nielsen & Schovsbo 2007; Erlström 2016). It comprises three formations, in ascending order: the File Haidar Formation (Cambrian Series 2), the Borgholm Formation (lower Miaolingian Series, Wuliuan Stage) and the Alum Shale Formation (middle Miaolingian through the Lower Ordovician, Tremadocian) (Hagenfeldt 1994; Nielsen & Schovsbo 2007).

The File Haidar Formation attains a thickness of 112 m (Hagenfeldt 1994; Nielsen & Schovsbo 2011) and is dominated by fine- to medium-grained, light grey quartz arenites with subordinate silt- and mudstone beds. The silt- and mudstone-dominated Borgholm Formation is 114 m thick on southern Öland and thins out to 43 m on northern Öland (Hessland 1955; Hagenfeldt 1994). It generally rests on the File Haidar Formation with the prominent ‘Hawke Bay’ unconformity (Nielsen & Schovsbo 2007, 2015). In the Öland–Gotland area, the Borgholm Formation is subdivided into four members, in ascending order: the Grötlingbo, Mossberga, Bårstad and Äleklinta members (Nielsen & Schovsbo 2007). Nielsen & Schovsbo (2015) and Nielsen & Ahlberg (2019) indicated the presence of the Grötlingbo Member on northern Öland, but that part of the Öland succession is herein assigned to the När Sandstone Member of the upper File Haidar Formation. The Mossberga Member consists of medium to dark grey siltstones with thin sandstone interbeds, whereas the Bårstad Member is generally more

fine-grained and dominated by greenish-grey siliciclastic mudstones alternating with thin siltstone beds (Nielsen & Schovsbo 2007). The Mossberga and Bårstad members were deposited in an intracratonic basin (see Nielsen & Schovsbo 2015, fig. 51) and are generally richly fossiliferous. The fossil faunas are dominated by trilobites, agnostoids (including condylopygids) and phosphatic-shelled brachiopods. In older literature, the Mossberga and Bårstad members have been referred to as shales with *Paradoxides oelandicus*, *Oelandicus* beds/shales or the *Oelandicus* Stage (e.g. Sjögren 1872; Linnarsson 1876a, 1877; Westergård 1936; Hessland 1955). Weidner et al. (2014) briefly discussed the depositional setting and faunal diversity of the Mossberga and Bårstad members and noted that the diversity is higher (~30 taxa) than in the equivalent outer shelf–shelf-edge deposits of Jämtland and Ångermanland, north-central Sweden.

The Äleklinta Member, in older literature referred to as the *Paradoxissimus* Siltstone or *Tessini* Sandstone (see Martinsson 1965, 1974; Weidner & Nielsen 2009), consists of grey siltstones with thin sandstone intercalations. It has a thickness of up to 70 m on southern Öland and thins out to ~1 m on northern Öland (Nielsen & Schovsbo 2007). The Äleklinta Member is unconformably overlain by the Alum Shale Formation, which is incomplete with several substantial gaps of variable magnitudes. The Alum Shale Formation gradually thins out towards the NNW of Öland

(Westergård 1944, 1947; Erlström 2016; Ahlberg et al. 2019; Fig. 2B herein).

The exposed Ordovician succession of Öland has a thickness of up to 46 m and consists predominantly of cool-water carbonates ('orthoceratite limestone') with numerous hardgrounds (Wu et al. 2017). It is highly condensed and a typical representative of the Central Baltoscandian Confacies Belt of Jaanusson (1976, 1979, 1995). The lowermost Ordovician (Tremadocian) consists of dark grey mudstones and shales belonging to the 0.35–2.80-m-thick Djupvik Formation, previously referred to as the *Ceratopyge* Shale (Stouge 2004), which reflects the end of siliciclastic sedimentation in the Central Baltoscandian Confacies Belt and is overlain by Lower–Middle Ordovician grey or red 'orthoceratite limestone'. The youngest exposed strata are of early Sandbian age and belong to the Dalby Limestone (Jaanusson 1960).

MATERIALS AND METHODS

The Tingskullen core drilling was performed in 2010 at a site (WGS coordinates N 57.116172, E 16.993013) approximately 700 m northeast of Källa Hamn and south of Tingskullsgatan on northeastern Öland (Fig. 2B). It was made by the Engineering Geology Group of the Department of Measurement Technology and Industrial Electrical Engineering, Lund University, with an Atlas Copco CT20 drill rig (*Riksriggen*). Drilling with continuous coring continued to a depth of ~107.0 m below the ground level, which corresponds to the bedrock surface, and ended within the upper part of the File Haidar Formation (provisional Cambrian Series 2; Dahlqvist et al. 2013). The drill core is currently housed at the Department of Geology, Lund University, and comprises Cambrian Series 2 (107.00–102.28 m), Miaolingian (102.28–46.50 m), ?Furongian (46.50–46.00 m) and Lower–Middle Ordovician (46.00–0 m) strata (Fig. 3). The core diameter is 39 mm and recovery of the tectonically undisturbed, essentially horizontal, core rock succession is close to 100%. The succession shows no major late diagenetic alteration and has not been buried below the oil window (cf. Buchardt et al. 1997, fig. 19). The pristine preservation of conodonts from the 46-m-thick Ordovician limestone succession strata overlying the Cambrian strata described in this paper showing a Colour Alteration Index (CAI of Epstein et al. 1977) of 1 is also indicative of shallow burial (Wu et al. 2017). The major portion of the Cambrian succession in the core is represented by the lower Miaolingian (Wuliuan Stage) Borgholm Formation. Middle and upper Miaolingian (Drumian–Guzhangian) strata are lacking in the core.

Dahlqvist et al. (2013) provided a brief first overview of the drill core and its lithostratigraphic succession.

Calner et al. (2014) and Wu et al. (2017) discussed the $\delta^{13}\text{C}_{\text{carb}}$ chemostratigraphy of the Ordovician portion of the drill core and its correlation with the conodont biostratigraphy.

The Cambrian and lowermost Ordovician (Tremadocian) succession of the Tingskullen core was split up and examined. Fossils were collected and specimens of characteristic taxa were painted with opaque matt black and then lightly coated with a sublimate of ammonium chloride prior to being photographed using a digital camera (Canon 550D) mounted on a table-set camera holder with four external light sources.

A total of 116 samples, most of which taken at 0.5-m or 1.0-m intervals, were collected from a 56.11 m thick rock interval (102.12–46.01 m) of the Tingskullen drill core. All samples were subjected to processing for $\delta^{13}\text{C}_{\text{org}}$ following the procedure described by Ahlberg et al. (2009) and Terfelt et al. (2014). Carbon isotope analyses of organic carbon were performed using a Flash EA 2000 elemental analyser connected online to a ThermoFinnigan Delta V Plus mass spectrometer at the Geocentre of Northern Bavaria, Friedrich-Alexander University of Erlangen-Nürnberg in Erlangen, Germany. All carbon isotope values are reported in the conventional δ -notation in per mil relative to V-PDB (Vienna-Pee Dee Belemnite). The accuracy and reproducibility of the analyses were monitored by replicate analyses of laboratory standards calibrated to the international standards USGS 40 and 41 and were ± 0.05 (1σ). The obtained $\delta^{13}\text{C}_{\text{org}}$ values are listed in Table 1 and used for the isotope curve described and discussed below.

LITHOLOGICAL SUCCESSION

The Cambrian succession of the Tingskullen core has a thickness of 61.00 m (Fig. 3). The lowermost 4.72 m (107.00–102.28 m) consists of light grey, fine-grained quartz arenites representing the upper När Sandstone Member of the File Haidar Formation. Mudstone intercalations are common at 106.30–106.12 and 105.30–105.15 m, and an intraformational conglomerate is present at 102.82–102.76 m (Fig. 4A). The När Sandstone Member is overlain by the Miaolingian Borgholm Formation. The lower half (102.28–70.40 m) of this formation belongs to the Mossberga Member, which consists of a basal conglomerate (102.28–102.14 m) and a succession of medium to dark grey, finely laminated mudstones with common thin siltstone interbeds and two thin calcareous levels (at 88.10–87.80 m and 73.10–72.90 m). The basal conglomerate contains clasts of fine-grained sandstone as well as variably rounded phosphoritic clasts in a greenish glauconitic matrix and rests disconformably on the När Sandstone Member.

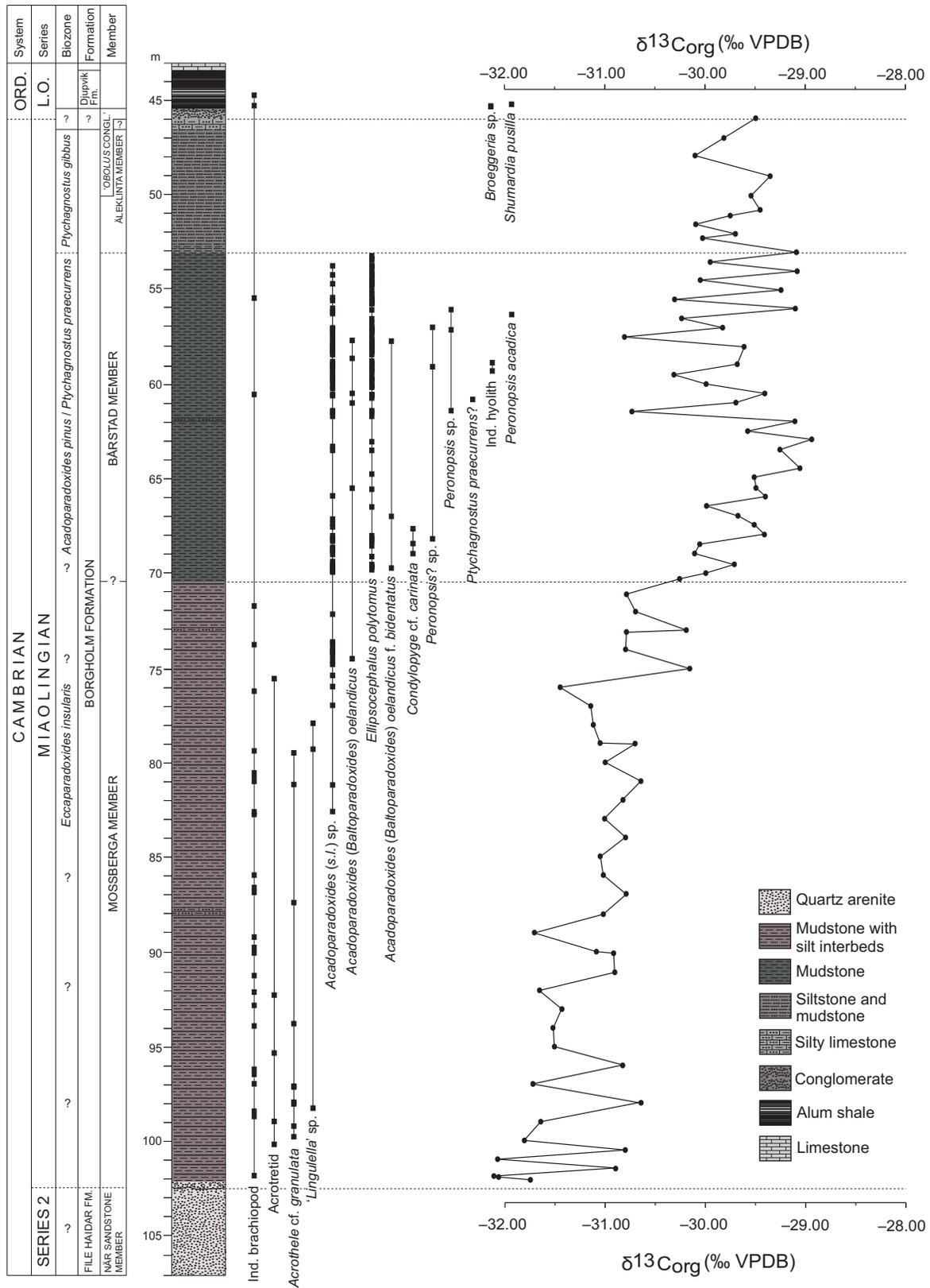


Fig. 3. Lithological succession, biostratigraphy and ranges of fossils in the Cambrian (Borgholm Formation) and lowermost Ordovician (Djupvik Formation), and the $\delta^{13}\text{C}_{\text{org}}$ record through the Miaolingian (Cambrian) of the Tingskullen drill core, Öland, Sweden. The m-figures to the left of the column refer to drilling depth. L.O., Lower Ordovician. Note the oscillating $\delta^{13}\text{C}_{\text{org}}$ values in the lowermost part of the Mossberga Member (core depth 102.1 to ~95.0 m) and upper Bårstad Member.

Table 1. Stable isotope data from organic matter ($\delta^{13}\text{C}_{\text{org}}$) from the Tingskullen drill core. All values are reported relative to Vienna-Pee Dee Belemnite (V-PDB). Sample series TK OC was taken in 2012, and sample series Ti was taken in 2017

| Sample | Core depth (m) | $\delta^{13}\text{C}_{\text{org}}$ (‰) | Biozone | Sample | Core depth (m) | $\delta^{13}\text{C}_{\text{org}}$ (‰) | Biozone |
|-----------|----------------|--|-------------------|----------|----------------|--|-----------------------|
| Ti 1 | 46.01 | -29.49 | <i>P. gibbus</i> | Ti 30 | 75.02 | -29.45 | ? |
| Ti 2 | 47.02 | -29.90 | <i>P. gibbus</i> | TK OC 55 | 75.02 | -30.86 | ? |
| TK OC 113 | 47.02 | -29.74 | <i>P. gibbus</i> | TK OC 53 | 76.00 | -31.59 | ? |
| Ti 3 | 48.00 | -30.05 | <i>P. gibbus</i> | Ti 31 | 76.00 | -31.28 | ? <i>E. insularis</i> |
| TK OC 111 | 48.00 | -30.14 | <i>P. gibbus</i> | Ti 32 | 77.00 | -31.11 | ? <i>E. insularis</i> |
| Ti 4 | 49.02 | -29.13 | <i>P. gibbus</i> | TK OC 51 | 77.00 | -31.17 | ? <i>E. insularis</i> |
| TK OC 109 | 49.02 | -29.56 | <i>P. gibbus</i> | Ti 33 | 78.00 | -30.95 | ? <i>E. insularis</i> |
| Ti 5 | 50.00 | -29.10 | <i>P. gibbus</i> | TK OC 49 | 78.00 | -31.28 | ? <i>E. insularis</i> |
| TK OC 107 | 50.00 | -29.98 | <i>P. gibbus</i> | TK OC 47 | 78.95 | -31.04 | ? <i>E. insularis</i> |
| TK OC 105 | 50.71 | -29.46 | <i>P. gibbus</i> | Ti 34 | 79.01 | -30.70 | ? <i>E. insularis</i> |
| Ti 6 | 51.01 | -29.75 | <i>P. gibbus</i> | Ti 35 | 80.00 | -31.17 | ? <i>E. insularis</i> |
| TK OC 103 | 51.50 | -30.09 | <i>P. gibbus</i> | TK OC 45 | 80.00 | -30.83 | ? <i>E. insularis</i> |
| Ti 7 | 52.02 | -29.69 | <i>P. gibbus</i> | TK OC 43 | 81.01 | -30.49 | ? <i>E. insularis</i> |
| TK OC 101 | 52.25 | -30.03 | <i>P. gibbus</i> | Ti 36 | 81.01 | -30.78 | ? <i>E. insularis</i> |
| Ti 8 | 53.01 | -29.09 | <i>A. pinus</i> | TK OC 41 | 81.99 | -30.95 | ? <i>E. insularis</i> |
| TK OC 99 | 53.52 | -29.96 | <i>A. pinus</i> | Ti 37 | 81.99 | -30.68 | ? <i>E. insularis</i> |
| Ti 9 | 54.00 | -29.08 | <i>A. pinus</i> | Ti 38 | 83.00 | -30.90 | Not zoned |
| TK OC 97 | 54.47 | -30.05 | <i>A. pinus</i> | TK OC 39 | 83.00 | -31.05 | Not zoned |
| Ti 10 | 55.01 | -29.24 | <i>A. pinus</i> | TK OC 37 | 83.99 | -30.75 | Not zoned |
| TK OC 95 | 55.48 | -30.31 | <i>A. pinus</i> | Ti 39 | 83.99 | -30.83 | Not zoned |
| Ti 11 | 56.00 | -29.10 | <i>A. pinus</i> | TK OC 35 | 84.98 | -30.89 | Not zoned |
| TK OC 93 | 56.52 | -30.24 | <i>A. pinus</i> | Ti 40 | 84.98 | -31.19 | Not zoned |
| Ti 12 | 57.00 | -29.83 | <i>A. pinus</i> | TK OC 33 | 86.00 | -30.86 | Not zoned |
| TK OC 91 | 57.51 | -30.81 | <i>A. pinus</i> | Ti 41 | 86.00 | -31.18 | Not zoned |
| Ti 13 | 58.04 | -29.62 | <i>A. pinus</i> | TK OC 31 | 86.99 | -30.78 | Not zoned |
| Ti 14 | 58.97 | -29.68 | <i>A. pinus</i> | Ti 43 | 88.09 | -31.16 | Not zoned |
| TK OC 87 | 59.49 | -30.32 | <i>A. pinus</i> | TK OC 29 | 88.09 | -30.88 | Not zoned |
| Ti 15 | 60.00 | -29.98 | <i>A. pinus</i> | Ti 44 | 88.99 | -31.91 | Not zoned |
| TK OC 85 | 60.51 | -29.41 | <i>A. pinus</i> | TK OC 27 | 88.99 | -31.48 | Not zoned |
| Ti 16 | 61.00 | -29.69 | <i>A. pinus</i> | Ti 45 | 89.99 | -31.08 | Not zoned |
| TK OC 83 | 61.48 | -30.73 | <i>A. pinus</i> | TK OC 25 | 90.02 | -30.92 | Not zoned |
| Ti 17 | 62.01 | -29.11 | <i>A. pinus</i> | TK OC 23 | 91.00 | -30.47 | Not zoned |
| TK OC 81 | 62.51 | -29.57 | <i>A. pinus</i> | Ti 46 | 91.00 | -31.32 | Not zoned |
| Ti 18 | 62.97 | -28.93 | <i>A. pinus</i> | Ti 47 | 91.98 | -31.34 | Not zoned |
| TK OC 79 | 63.51 | -29.26 | <i>A. pinus</i> | TK OC 21 | 91.98 | -31.98 | Not zoned |
| Ti 19 | 64.01 | -26.60 | <i>A. pinus</i> | Ti 48 | 93.01 | -31.33 | Not zoned |
| TK OC 77 | 64.48 | -29.06 | <i>A. pinus</i> | TK OC 19 | 93.01 | -31.53 | Not zoned |
| Ti 20 | 64.98 | -29.52 | <i>A. pinus</i> | Ti 49 | 94.01 | -31.70 | Not zoned |
| TK OC 75 | 65.54 | -29.48 | <i>A. pinus</i> | TK OC 17 | 94.01 | -31.35 | Not zoned |
| Ti 21 | 66.01 | -29.40 | <i>A. pinus</i> | Ti 50 | 95.00 | -31.41 | Not zoned |
| TK OC 73 | 66.50 | -29.98 | <i>A. pinus</i> | TK OC 15 | 95.00 | -31.61 | Not zoned |
| Ti 22 | 67.00 | -29.67 | <i>A. pinus</i> | TK OC 13 | 95.99 | -31.03 | Not zoned |
| TK OC 71 | 67.53 | -29.53 | <i>A. pinus</i> | Ti 51 | 95.99 | -30.61 | Not zoned |
| Ti 23 | 68.00 | -29.41 | <i>A. pinus</i> | Ti 52 | 97.00 | -31.69 | Not zoned |
| TK OC 69 | 68.51 | -30.06 | <i>A. pinus</i> | TK OC 11 | 97.00 | -31.74 | Not zoned |
| Ti 24 | 68.99 | -30.11 | <i>A. pinus</i> | Ti 53 | 97.99 | -30.45 | Not zoned |
| TK OC 67 | 69.52 | -29.62 | <i>A. pinus</i> | TK OC 9 | 97.99 | -30.81 | Not zoned |
| Ti 25 | 69.96 | -29.99 | ? <i>A. pinus</i> | Ti 54 | 99.00 | -31.53 | Not zoned |
| TK OC 65 | 70.25 | -30.26 | ? | TK OC 7 | 99.00 | -31.74 | Not zoned |
| Ti 26 | 71.00 | -30.48 | ? | Ti 55 | 100.00 | -31.85 | Not zoned |
| TK OC 63 | 71.00 | -31.06 | ? | TK OC 5 | 100.00 | -31.76 | Not zoned |
| TK OC 61 | 71.98 | -30.78 | ? | Ti 56 | 100.51 | -30.79 | Not zoned |
| Ti 27 | 71.98 | -30.60 | ? | Ti 57 | 101.00 | -31.97 | Not zoned |
| TK OC 59 | 72.96 | -30.47 | ? | TK OC 3 | 101.00 | -32.17 | Not zoned |
| TK OC 59 | 72.96 | -29.89 | ? | Ti 58 | 101.49 | -30.89 | Not zoned |
| Ti 28 | 73.08 | -30.77 | ? | TK OC 1 | 101.90 | -32.13 | Not zoned |
| Ti 29 | 74.00 | -30.91 | ? | Ti 59 | 101.98 | -32.06 | Not zoned |
| TK OC 57 | 74.00 | -30.67 | ? | Ti 60 | 102.12 | -31.73 | Not zoned |

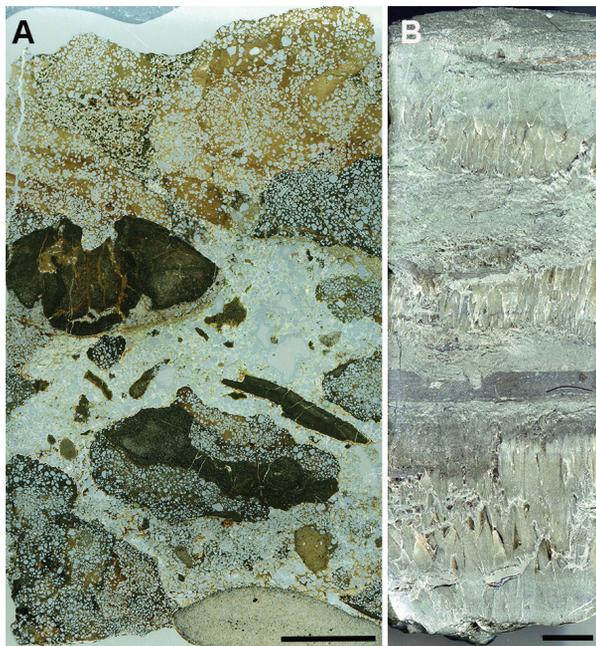


Fig. 4. **A**, thin-section macrograph of conglomerate with sandstone and phosphoritic clasts at the base of the Mossberga Member. Core depth: 102.19–102.14 m. **B**, polished section through the limestone-dominated succession with three 1–2-cm-thick intervals containing well-preserved palisadic crystals of calcite. Core depth: 46.50–46.40 m. Scale bars represent 1 cm.

The Mossberga Member is succeeded by a 17.25-m-thick interval (70.40–53.15 m) with medium to dark greenish-grey, bioturbated siliciclastic mudstones alternating with thin siltstone beds. This interval is assigned to the Bårstad Member. The boundary between the Mossberga Member and the Bårstad Member is tentatively placed at ~70.40 m, where there is a fairly abrupt shift to more greenish and generally darker mudstones. The Bårstad Member is overlain, probably conformably, by an interval (53.15–46.50 m) comprising light grey finely laminated silt- to very fine-grained sandstones alternating with medium greenish-grey mudstones. Bioturbation and small-scale cross-lamination occur frequently throughout this interval, which is assigned to the Äleklinta Member. It is in turn overlain by a 0.5-m-thick light grey, limestone-dominated succession (46.50–46.00 m) with three 1–2-cm-thick intervals with well-preserved palisadic crystals of calcite in the lowermost part (46.50–46.40 m; Fig. 4B) and a light grey crystalline limestone in the upper part. It is covered by a succession of variegated greenish to dark grey, in part very coarsely sparitic limestone, which has a thickness of 0.60 m (46.00–45.40 m) and shows palaeokarst structures (Dahlqvist et al. 2013; Calner et al. 2014; Wu et al. 2017). This interval is interpreted as an equivalent to the lower

Tremadocian ‘*Obolus* conglomerate’ (e.g. Westergård 1922, 1947; Tjernvik 1956). It is overlain by dark grey to black, finely laminated shales (45.40–43.37 m) belonging to the middle–upper Tremadocian Djupvik Formation (in older literature referred to as the Ceratopyge Shale; Stouge 2004).

DEPOSITIONAL ENVIRONMENTS AND RELATIVE SEA-LEVEL

The cored part of the När Sandstone Member is a massive to faintly laminated quartz arenite that represents rapid deposition in an inner shelf environment. The predominance of planar to slightly undulating lamination and inclusions of mudstone suggests deposition below the influence of daily wave action (shoreface) and more likely in the most shallow part of the lower shoreface. The upper unconformable boundary of this unit and the associated conglomerate (Fig. 4A) imply the shallowing of the depositional environment followed by prolonged exposure of the succession and reworking of already lithified sandstone. No obvious shallowing upward succession (i.e. shoreface deposits) is preserved in the core, indicating rapid regression and a substantial erosion of the succession. The presence of phosphoritic clasts in a glauconite-rich matrix in the boundary-conglomerate, as well as the immediately overlying dark and organic-rich mudstones, further implies sediment starvation and low depositional rates in this area during the ensuing transgression. Based on the temporal shift from sandstone, reworked subaerially and in the shoreline environment, to mudstone deposited well below the wave-base (see below), the transgression likely changed depositional depth with several tens of metres. This major regressive–transgressive cycle can partly be attributed to the ‘Hawke Bay Event’ (cf. Nielsen & Schovsbo 2007, p. 78, 2015).

The relatively minor facies changes and conformable transitions through the overlying Mossberga, Bårstad and Äleklinta members exclude more abrupt changes to relative sea-level and instead continuous sedimentation in deep to moderately shallow waters through the remainder of the Wuliuan Age. It is worth noting, however, that the Bårstad Member is unconformably overlain by the Äleklinta Member in most other areas of Öland (Nielsen & Schovsbo 2007, p. 80, 2015).

The thin and finely laminated siltstone interbeds in the Mossberga Member were deposited through low-density currents and interpreted as the distal expression of storm-reworked sediments. The laminated beds are common and well preserved due to the absence of bioturbation and infauna during deposition, which in turn may reflect relatively low levels of oxygenation in the sediment pore waters in the outer shelf areas. The transition to the overlying Bårstad Member is fairly distinct but con-

formable in the Tingskullen succession. This member lacks the finely laminated siltstone beds typical of the underlying Mossberga Member, suggesting continuous drowning of source areas during the peak of the post-‘Hawke Bay’ transgression (cf. Nielsen & Schovsbo 2015). The transition to the overlying Äleklinta Member also appears to be conformable. The facies of this member is distinct with abundant laminated or cross-laminated siltstone beds, interbedded with greenish mudstone, and abundant bioturbation. The Äleklinta Member marks a renewed shallowing of the environment and deposition in the lower shoreface. The upper portion of the Äleklinta Member is exposed at Äleklinta approximately 22 km southwest of the Tingskullen drill site. Here abundant sedimentary structures and the overall sedimentary facies imply deposition in a wave- and storm-dominated inner shelf setting. The Äleklinta Member is truncated by a major unconformity (sequence boundary).

BIOSTRATIGRAPHY

The Terreneuvian and Cambrian Series 2 succession of Scandinavia is generally unfossiliferous or poorly fossiliferous except in its uppermost part. By contrast, the Miaolingian and Furongian strata of Scandinavia are generally richly fossiliferous with faunas commonly dominated by polymerid trilobites and agnostoid arthropods. Both groups have been widely applied as the principal tools for biostratigraphical and chronostratigraphical classification of Miaolingian through Furongian strata of Scandinavia since at least the 1870s. The Miaolingian of Scandinavia is currently subdivided into three superzones, which in ascending order are the *Acadoparadoxides oelandicus*, *Paradoxides paradoxissimus* and *P. forchhammeri* superzones (Nielsen et al. 2014; Babcock et al. 2017). These superzones were considered to represent regional stages by Westergård (1946). The *A. oelandicus* Superzone corresponds to the Bödän regional Stage, and the *P. paradoxissimus* Superzone corresponds to the Almbackenian regional Stage (Nielsen & Schovsbo 2015). The Wuliuan Stage of Scandinavia is now being subdivided into three polymerid trilobite zones, in ascending order: the *Eccaparadoxides insularis*, *Acadoparadoxides pinus* and *Ctenocephalus exsulans* zones (e.g. Nielsen et al. 2014). The *A. pinus* and *C. exsulans* zones are equivalent to the *Ptychagnostus praecurrens* and *P. gibbus* agnostoid zones, respectively (Ahlberg 1989; Nielsen et al. 2014).

The Borgholm Formation (Wuliuan Stage) of Öland has yielded a fairly diverse shelly fauna. Together, Sjögren (1871, 1872) and Linnarsson (1876a, 1876b, 1877) listed about 20 taxa, including trilobites, agnostoids, brachiopods and hyoliths. Since then, not only the biostratigraphy

has been revised, but also the trilobite and agnostoid ranges have been more firmly established. The succession and ranges of trilobites and agnostoids in the Borgholm Formation of Öland have been studied, for example, by Westergård (1929, 1936, 1944, 1946, 1947), Wærn (1952) and Weidner & Nielsen (2009). The hyoliths described from the Borgholm Formation by Holm (1893) were revised by Malinky & Berg-Madsen (1999).

The När Sandstone Member in the Tingskullen core is unfossiliferous and not biostratigraphically constrained. The overlying Borgholm Formation is partly bioturbated with horizontal and oblique burrows in several intervals (Fig. 5A). Indeterminate pyritized or carbonaceous filaments are common in both the Mossberga and the Bårstad members. Body fossils collected from these members include phosphatic-shelled brachiopods, trilobites, agnostoids and a few hyoliths. The Mossberga Member is generally poorly fossiliferous, especially in its lower half, whereas the Bårstad Member has yielded a rich and fairly diverse shelly fauna. Brachiopods are most common in the Mossberga Member and represented by obolids, acrotretids and acrothelids (Fig. 5B–D). *Acrothele* cf. *granulata* Linnarsson, 1876 (Fig. 5B) was recorded in the core interval 99.78–79.49 m.

The lowest observed occurrence of trilobites is in the upper half of the Mossberga Member at 82.59 m. Polymerid trilobites are very common in the Bårstad Member, but the fauna is of low diversity and restricted to paradoxidids and *Ellipsocephalus polytomus* Linnarsson, 1877. The latter species appears at 69.82 m and ranges throughout the entire Bårstad Member. All paradoxidid trilobites belong to the genus *Acadoparadoxides* (*s.l.*) and the most common species is seemingly *A. (Baltoparadoxides) oelandicus* (Sjögren, 1872) *s.l.* In the Bårstad Member, the trilobites are accompanied by generally rare agnostoids of four taxa: *Condylopyge* cf. *carinata* Westergård, 1936 (68.97–67.64 m), *Ptychagnostus praecurrens* (Westergård, 1936)? (60.79 m), *Peronopsis acadica* (Hartt in Dawson, 1868) (56.39–56.37 m) and *Peronopsis* sp. (68.18–56.10 m).

The Äleklinta Member in the Tingskullen succession is largely unfossiliferous except for trace fossils, but following Weidner & Nielsen (2009) it is assigned to the *Ptychagnostus gibbus* Zone. The overlying 0.5-m-thick light grey, carbonate-dominated succession (46.50–46.00 m) with well-preserved palisadic crystals of calcite is unfossiliferous, but may represent a thin wedge of the uppermost Miaolingian and/or Furongian (Dahlqvist et al. 2013). The top of the studied interval, i.e. the Tremadocian Djupvik Formation, is poorly fossiliferous but phosphatic-shelled brachiopods (*Broeggeria* sp.; Fig. 5E, F) were observed at 45.31 and 45.30–45.28 m, and two cranidia of the small trilobite *Shumardia (Conophrys) pusilla* (Sars, 1835) were recorded at 45.20 m (Fig. 6O, P).

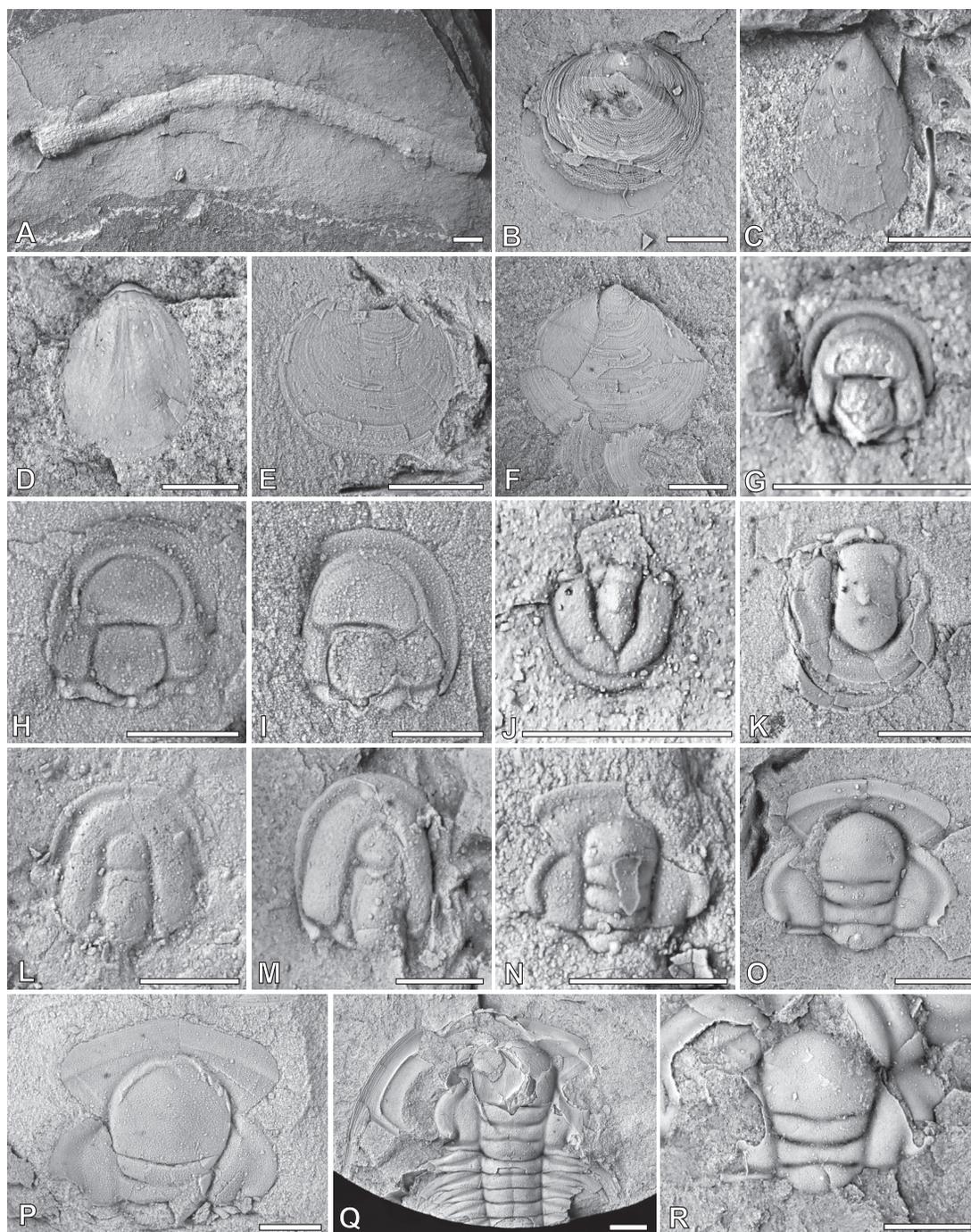


Fig. 5. Fossils from the Miaolingian and Lower Ordovician in the Tingskullen drill core. Scale bars correspond to 2 mm. **A**, gently curved annulated burrow with a subcircular cross section, tentatively assigned to *Planolites*, PMU 36493, Bårstad Member (56.76 m). **B**, *Acrothele* cf. *granulata* Linnarsson, 1876, ventral valve, exterior, PMU 36494, Mossberga Member (97.12 m). **C**, **D**, '*Lingulella*' sp., Mossberga Member: **C**, ventral valve, exterior, PMU 36495, 79.28 m; **D**, internal mould of dorsal valve, PMU 36496, 77.89 m. **E**, **F**, *Broeggeria* sp., Djupvik Formation: **E**, indeterminate valve, PMU 36497, 45.31 m; **F**, ventral valve, exterior, PMU 36498, 45.30–45.28 m. **G–I**, *Condylopyge* cf. *carinata* Westergård, 1936, Bårstad Member: **G**, small cephalon, PMU 36499, 68.97 m; **H**, cephalon, PMU 36500, 68.43 m; **I**, cephalon, PMU 36501, 67.64 m. **J**, *Ptychagnostus praecurrens* (Westergård, 1936)?, small pygidium, PMU 36502, Bårstad Member (60.79 m). **K**, *Peronopsis* sp., pygidium, PMU 36503, Bårstad Member (68.18 m). **L**, **M**, *Peronopsis acadica* (Hartt in Dawson, 1868), Bårstad Member: **L**, cephalon, PMU 36504, 56.39–56.37 m; **M**, cephalon, PMU 36505, 56.39–56.37 m. **N–P**, *Acadoparadoxides* (*s.l.*) sp., Bårstad Member: **N**, juvenile cranium, PMU 36506, 56.23–56.22 m; **O**, juvenile cranium, PMU 36507, 56.05 m; **P**, juvenile cranium, PMU 36508, 63.27 m. **Q**, **R**, *Acadoparadoxides* (*Baltoparadoxides*) *oelandicus* (Sjögren, 1872), Bårstad Member: **Q**, cranium with five articulated thoracic tergites and detached left librigena, PMU 36509, 69.78 m; **R**, incomplete cranium, PMU 36510, 58.74 m.

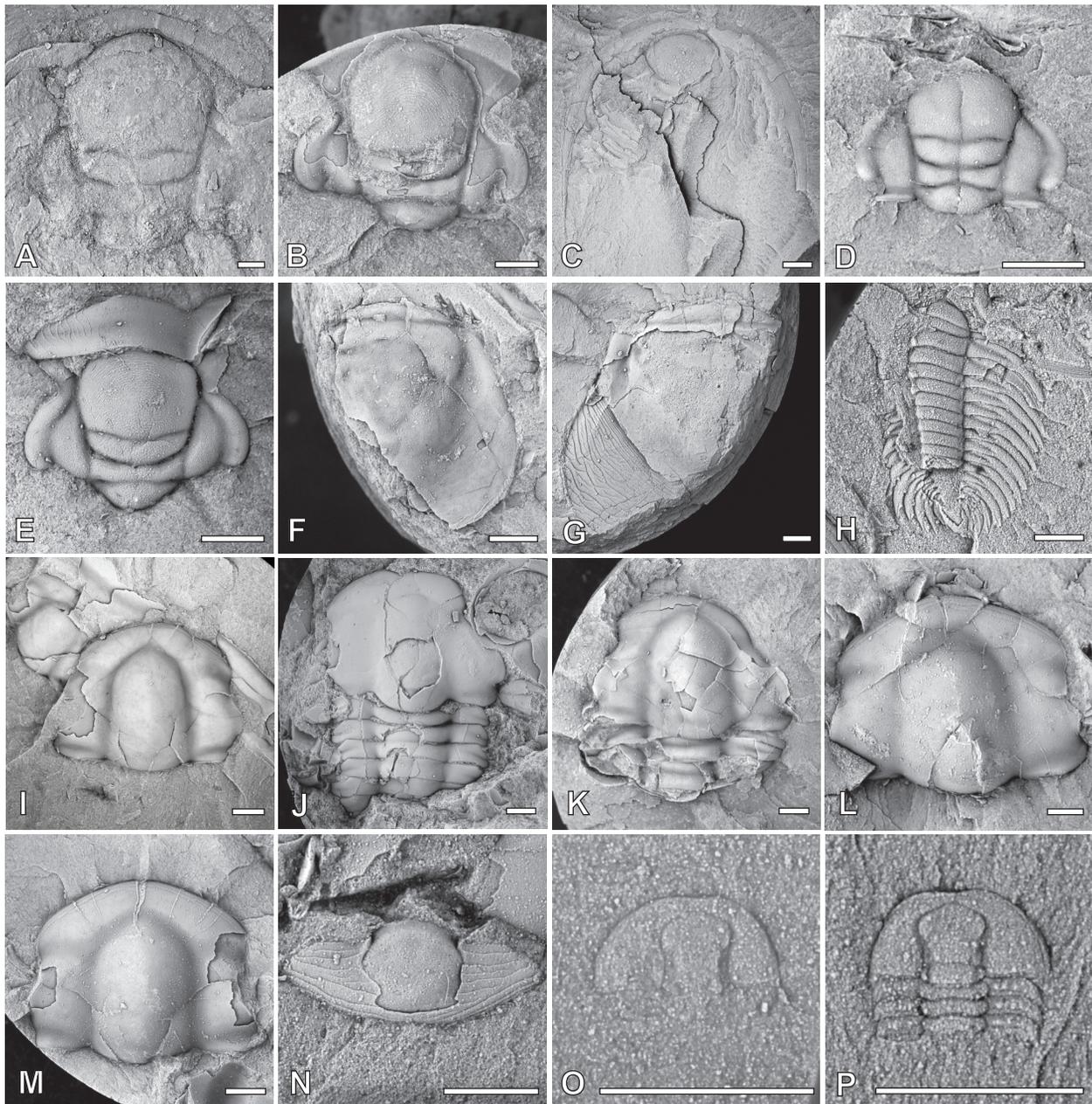


Fig. 6. Trilobites from the Miaolingian and Lower Ordovician in the Tingskullen drill core. Scale bars correspond to 2 mm. **A, B**, *Acadoparadoxides (Baltoparadoxides) oelandicus* (Sjögren, 1872): A, cranidium, PMU 36511, Mossberga Member (77.22 m); B, cranidium, PMU 36512, Bårstad Member (65.50–65.46 m). **C**, *Acadoparadoxides (s.l.)* sp., cephalon with hypostome, ventral view, PMU 36513, Mossberga Member (73.61 m). **D, E**, *Acadoparadoxides (Baltoparadoxides) oelandicus* (Sjögren, 1872), Bårstad Member: D, cranidium, PMU 36514, 60.46–60.43 m; E, cranidium, PMU 36515, 57.74–57.72 m. **F, G**, *Acadoparadoxides (Baltoparadoxides) oelandicus* forma *bidentatus* (Westergård, 1936), Bårstad Member: F, incomplete pygidium, PMU 36516, 67.00–66.97 m; G, incomplete pygidium, PMU 36517, 69.74 m. **H**, *Acadoparadoxides (s.l.)* sp., small incomplete thoracopygon, PMU 36518, Bårstad Member (57.74–57.72 m). **I–N**, *Ellipsocephalus polytomus* Linnarsson, 1877, Bårstad Member: I, cranidium, PMU 36519, 69.65 m; J, cranidium with six articulated thoracic tergites, PMU 36520, 69.12 m; K, cranidium with three articulated thoracic tergites, PMU 36521, 63.02 m; L, cranidium, PMU 36522, 59.19–59.18 m; M, cranidium, PMU 36523, 57.26 m; N, pygidium, PMU 36524, 54.20 m. **O, P**, *Shumardia (Conophrys) pusilla* (Sars, 1835), Djupvik Formation (45.20 m): O, cephalon, PMU 36525; P, cephalon with three articulated thoracic tergites, PMU 36526.

On the basis of the succession on Öland, Westergård (1936) subdivided the ‘Oelandicus beds/stage’, comprising the Mossberga and Bårstad members, into a lower zone with *Paradoxides* (now *Eccaparadoxides*) *insularis* Westergård, 1936 and an upper zone with *Paradoxides* (now *Acadoparadoxides*) *pinus* Westergård, 1936. The *E. insularis* Zone is also characterized by the occurrence of *Bailiella emarginata* (Linnarsson, 1877) and *Condylopyge regia* (Sjögren, 1872) (Westergård 1936, 1953). The trilobite and agnostoid fauna in the *A. pinus* Zone is more diverse and, in addition to the eponymous species and forms of the *A. oelandicus* plexus, it includes, among others, *Acadoparadoxides torelli* (Westergård in Asklund & Thorslund, 1935), *Burlingia laevis* Westergård, 1936, *Ptychagnostus praecurrens* and *Condylopyge carinata* (e.g. Westergård 1936, 1946, 1953; Weidner et al. 2014; Weidner & Ebbestad 2014; Geyer & Corbacho 2015). In the Öland–Gotland area, the *E. insularis* Zone grades downwards into a fairly thick succession with no other body fossils than linguliformean brachiopods. This succession has generally been assigned to the *E. insularis* Zone (e.g. Westergård 1936), but should rather be regarded as unzoned (cf. Nielsen & Ahlberg 2019).

The zonal index fossils have not been identified in the Tingskullen core and the biostratigraphical data are inadequate for subdividing the ‘Oelandicus beds/stage’ into biozones. The record of *Acadoparadoxides* (*Balto-paradoxides*) *oelandicus* forma *bidentatus* (Westergård, 1936), *Condylopyge* cf. *carinata* and *Ptychagnostus praecurrens*? in the Bårstad Member suggests, however, that this member belongs to the *Acadoparadoxides pinus* Zone (Fig. 3). The Mossberga Member has not yielded any zonal guide fossils, but its upper trilobite-bearing part (82.59 to ~70.40 m) is tentatively assigned to the *Eccaparadoxides insularis* Zone. The only shelly fossils recorded from the lower half of the Mossberga Member are phosphatic-shelled brachiopods.

SYSTEMATIC NOTES

All illustrated specimens are stored in the Palaeontological collections of the Museum of Evolution, Uppsala University, Sweden (PMU).

Family ACROTHELIDAE Walcott & Schuchert in
Walcott, 1908

Genus *Acrothele* Linnarsson, 1876

Acrothele cf. *granulata* Linnarsson, 1876
Figure 5B

Remarks. Circular to subcircular valves with concentric growth lines and a granulated external surface from the Mossberga Member (99.78–79.49 m) are identified as

Acrothele cf. *granulata* Linnarsson, 1876. The ventral valve is virtually flat to gently convex with a prominent raised umbo and a foramen situated excentrically, adjacent to posterior margin.

Acrothele granulata was originally described from the ‘Oelandicus beds/stage’ (probably the *A. pinus* Zone) cropping out at Lillviken and Hackås in Jämtland, central Sweden. It has subsequently been described from the ‘Oelandicus beds/stage’ and younger Miaolingian strata in various parts of Scandinavia, e.g. on Öland (Linnarsson 1877) and in southwestern Norway (e.g. Henningsmoen 1952; Bruton & Harper 2000).

Family CONDYLOPYGIDAE Raymond, 1913
Genus *Condylopyge* Hawle & Corda, 1847

Remarks. *Condylopyge* is a distinctive and geographically widely distributed genus characterized by a very large, expanded and almost semicircular anterior glabellar lobe and a cylindrical posterior glabellar lobe. It ranges from the upper part of Cambrian Series 2 through the Miaolingian and was most recently discussed by Fatka et al. (2015) and Naimark & Pegel (2017). The former authors assigned 16 species to the genus. Miaolingian representatives of *Condylopyge* seem to be most common in inner shelf settings that were located at high latitudes and they are largely restricted to West Gondwana, Avalonia and Baltica, albeit with a few occurrences in Siberia (Conway Morris & Rushton 1988; Fatka et al. 2015; Naimark & Pegel 2017).

Condylopyge cf. *carinata* Westergård, 1936
Figure 5G–I

Remarks. Westergård (1936, 1946) described two species of *Condylopyge* from the ‘Oelandicus beds/stage’ of Öland: *C. regia* (Sjögren, 1872) from the *E. insularis* Zone and *C. carinata* Westergård, 1936 from the *A. pinus* Zone. The cephalae of these species are more or less indistinguishable, whereas the pygidium of *C. carinata* differs from *C. regia* in having unfurrowed pleural fields and a longer axial node (see Westergård 1936; Rushton 1966; Rushton & Weidner 2007).

Three condylopygid cephalae were recorded from the lower Bårstad Member (68.97–67.64 m) in the Tingskullen core. They are identified under open nomenclature as *C. cf. carinata*. A slightly distorted pygidium from 68.18 m may also represent this species, but it has a short axial node and is herein referred to as *Peronopsis*? sp.

Family PTYCHAGNOSTIDAE Kobayashi, 1939
Genus *Ptychagnostus* Jaekel, 1909

Ptychagnostus praecurrens (Westergård, 1936)?
Figure 5J

Remarks. One small, non-spinose and non-scribulate pygidium from the middle Bårstad Member in the

Tingskullen core (60.79 m) has a prominent postaxial median furrow, a lanceolate posteroaxis and an unconstricted acrolobe. The median node is of moderate size and slightly deflects the posterior axial furrow (F2). The pygidium appears to represent an early holaspid and seems to fall within the range of variation seen in juveniles of *P. praecurrens* illustrated by Weidner & Ebbestad (2014). The posteroaxis is, however, more sharply pointed and the pygidium at hand is therefore questionably assigned to *P. praecurrens*.

Family PERONOPSIDAE Westergård, 1936
Genus *Peronopsis* Hawle & Corda, 1847

Peronopsis acadica (Hartt in Dawson, 1868)
Figure 5L, M

Remarks. Two cephalons from the Bårstad Member in the Tingskullen core (56.39–56.37 m) agree in all essential features with *Peronopsis fallax* (Linnarsson, 1869) as described by, for instance, Westergård (1936, 1946) and Robison (1982). *Peronopsis fallax* was originally described from the *Ptychagnostus gibbus* Zone at Djupadalen in Västergötland, south-central Sweden, and it has been regarded as a morphologically variable species ranging from the *Ptychagnostus praecurrens* Zone upwards into the *P. punctuosus* Zone (e.g. Westergård 1946; Robison 1982; Axheimer & Ahlberg 2003). Robison (1982) reviewed in some detail the taxonomy of *P. fallax*, and in a subsequent paper (Robison 1995) he suppressed this species as a junior subjective synonymy of *Peronopsis acadica* (Hartt in Dawson, 1868). This view is followed herein (cf. Naimark & Pegel 2017). The concept of *P. acadica* was recently discussed by Weidner & Nielsen (2014), who also provided an extensive list of synonyms.

Family PARADOXIDIDAE Hawle & Corda, 1847
Genus *Acadoparadoxides* Šnajdr, 1957

Remarks. *Acadoparadoxides* (type species *Paradoxides sacheri* Barrande, 1852) is difficult to diagnose and the concept of the genus has been widely discussed in the literature (e.g. Fletcher et al. 2005; Żylińska & Masiak 2007; Esteve 2014; Weidner et al. 2014; Geyer & Vincent 2015; Nowicki & Żylińska 2019). We follow the concept of *Acadoparadoxides* discussed by Weidner et al. (2014) and Geyer & Vincent (2015), who listed junior synonyms. The nominate subgenus is characterized by a well-marked frontal border, transglabellar S1 and S2 furrows, weakly developed or obsolete S3 and S4 furrows, recurved palpebral lobes, 19 thoracic segments (in adults) with relatively short pleural furrows, and a weakly segmented pygidium that is subequal in length and width or slightly wider than long and has a rounded or subangular posterior margin without spines. Species assigned to the subgenus *Acadoparadoxides* (*Baltoparadoxides*) (type species *Paradoxides oelandicus*

Sjögren, 1872) differ in having a more broadly oval exoskeletal outline, a medially well-incised S2, 17 thoracic segments in adults and a hexagonal pygidium with 2–4 pairs of short marginal spines (Geyer & Vincent 2015).

Paradoxidid and ellipsocephalid trilobites are by far the most common trilobites in the Borgholm Formation of the Tingskullen drill core. The paradoxidids are, however, almost exclusively represented by dissociated sclerites. Most of the sclerites are too incomplete for a confident identification and are left in open nomenclature as *Acadoparadoxides* (*s.l.*) sp. (Figs 5N–P, 6C, H). Six almost complete and well preserved cranidia are identified as *A. (B.) oelandicus* (Figs 5Q, R, 6A, B, D, E), and three pygidia with a fairly long axis are classified as *A. (B.) oelandicus* forma *bidentatus* (Westergård, 1936) (cf. Ahlberg 1989; Fig. 6F, G herein). Their posterior pygidial margin is broadly rounded and one of the pygidia exhibits a pair of short marginal spines. The zonal index paradoxidines for the *Eccaparadoxides insularis* and *Acadoparadoxides pinus* zones were not identified in the Tingskullen core.

Family ELLIPSOCEPHALIDAE Matthew, 1887
Genus *Ellipsocephalus* Zenker, 1833

Ellipsocephalus polytomus Linnarsson, 1877
Figure 6I–N

Remarks. *Ellipsocephalus polytomus* was described in some detail by Linnarsson (1877), Westergård (1936, 1950) and Ahlberg (1989). It is one of the most common and most widely distributed trilobites in the *Acadoparadoxides oelandicus* Superzone of Sweden, in which it ranges from the lower–middle part of the *E. insularis* Zone to the top of the *A. pinus* Zone (Westergård 1936). Possibly reworked specimens were reported by Westergård (1936, 1950) from the overlying Granulata Conglomerate Bed (Nielsen & Schovsbo 2007) of the basal *Paradoxides paradoxissimus* Superzone. *Ellipsocephalus polytomus* is very common in the Tingskullen core, but appears to be confined to an interval (69.82–53.23 m) assigned to the *A. pinus* Zone.

CARBON ISOTOPE CHEMOSTRATIGRAPHY

Studies during the past three decades have demonstrated the great value of $\delta^{13}\text{C}$ for both intercontinental and intracontinental correlation of Cambrian successions (e.g. Peng et al. 2012 and references therein; Zhu et al. 2019). Most of these studies have focused on $\delta^{13}\text{C}_{\text{carb}}$ using samples from carbonate-dominated successions. During recent years, however, $\delta^{13}\text{C}_{\text{org}}$ has been utilized for Cambrian successions dominated by shales and siliciclastic mudstones, and it has been shown that $\delta^{13}\text{C}_{\text{org}}$

chemostratigraphy is useful for approximate correlations between organic-rich siliciclastic-dominated and carbonate successions (e.g. Ahlberg et al. 2009, 2019 and references therein; Saltzman et al. 2011; Woods et al. 2011). Although $\delta^{13}\text{C}$ chemostratigraphy has emerged as an increasingly powerful tool for regional and global correlation of Cambrian strata, it has become evident that the stratigraphical pattern of carbon isotope curves can vary laterally (e.g. Edwards & Saltzman 2016; Henderson et al. 2018; Lindskog & Young 2019) and $\delta^{13}\text{C}$ events may be facies dependent and diachronous (Schiffbauer et al. 2017; Barili et al. 2018).

Zhu et al. (2006) compiled previous studies on Cambrian $\delta^{13}\text{C}$ chemostratigraphy and provided a composite $\delta^{13}\text{C}$ curve with ten distinct and named excursions, most of which seem to coincide with important biotic events (see also Babcock et al. 2015). The negative Redlichiiid–Olenellid Extinction Carbon isotope Excursion (ROECE; Zhu et al. 2006) is associated with the extinction of redlichiiid and olenellid trilobites at the end of Stage 4 (Fan et al. 2011; Wotte et al. 2011; Faggetter et al. 2017, 2018; Lin et al. 2019; Zhu et al. 2019). Although considered as one of the largest negative carbon isotope excursions known from the Cambrian (Zhu et al. 2006; Peng et al. 2012), isotopic data from vastly different regions provide inconclusive evidence as to the precise definition and placement of the ROECE (cf. Lin et al. 2019) and further studies are needed to establish if it is a globally identified perturbation in the Cambrian isotope curve.

A $\delta^{13}\text{C}_{\text{org}}$ curve based on 116 samples from the Mossberga, Bårstad and Äleklinta members in the Tingskullen drill core shows values between -32.1‰ and -28.9‰ (Table 1, Fig. 3). The high value of -26.6‰ at 64.01 m is explained by incomplete decarbonization prior to analysis or by the source and type of organic matter. This anomalously high value is excluded from the curve. Despite some scatter in the $\delta^{13}\text{C}_{\text{org}}$ values, a trend to higher $\delta^{13}\text{C}_{\text{org}}$ values is recorded up-section without any distinctive excursion.

The isotope curve can be broadly divided into two segments, one restricted to the Mossberga Member and the other largely to the Bårstad and Äleklinta members. The lowermost part of the Mossberga Member (core depth 102.1 to ~ 95.0 m) shows $\delta^{13}\text{C}_{\text{org}}$ values varying between -32.1‰ and -30.6‰ . It is followed by an interval (95–76 m) with values between -31.7 and -30.6‰ . Although the $\delta^{13}\text{C}_{\text{org}}$ values exhibit a considerable scatter, the isotope curve from near the top of the Mossberga Member to the top of the Bårstad Member (76–52 m) shows an overall positive trend (c. $+1.5\text{‰}$). The consistent shift to more positive values starts near the base of the Bårstad Member (at c. 70.25 m). Maximum $\delta^{13}\text{C}_{\text{org}}$ values of around 29.0‰ are measured in the lower half of the member (at 64.5–

62.9 m) and are followed by a shift to more negative values in the middle part of the Bårstad Member. Thus, though not well expressed, a minor positive excursion with an amplitude of c. $+1\text{‰}$ seems to be present in the lower–middle Bårstad Member (lower *Acadoparadoxides pinus*–*Ptychagnostus praecurrens* Zone). The isotope values from the Äleklinta Member are variable and range from -30.1‰ to 29.4‰ .

No distinctive negative excursion was captured, suggesting that the entire *Acadoparadoxides* (*Baltoparadoxides*) *oelandicus* Superzone of Scandinavia, including the lower non-trilobitic part of the Mossberga Member, is younger than the ROECE event, which is known in many areas from near the top of Cambrian Stage 4 and close to the traditional ‘Lower–Middle Cambrian boundary’. The absence of the ROECE in the Wuliuan succession of the Tingskullen core was expected because studies during the past two decades have shown that the *Acadoparadoxides* (*Baltoparadoxides*) *oelandicus* Superzone of Scandinavia is younger than the oldest paradoxidid-bearing strata in West Gondwana (Morocco and Spain) and Poland (Żylińska & Masiak 2007; Nowicki & Żylińska 2019; Sundberg et al. 2020).

DISCUSSION

The Wuliuan succession (the Borgholm Formation) in the Tingskullen drill core is lithologically and stratigraphically similar to coeval intervals in other drill cores from Öland (e.g. Westergård 1929, 1936; Wærn 1952; Hessland 1955; Erlström 2016; Ahlberg et al. 2019). The succession has a thickness of at least 100 m on southern Öland (114 m in the Kvinnsgröta-1 well and 106 m in the Segerstads Fyr drill core; Hagenfeldt 1994; Nielsen & Schovsbo 2007; Erlström 2016), and thins out to the north of Öland (55.8 m in the Tingskullen core and 43.2 m in the Böda Hamn core; Wærn 1952; Hessland 1955). On Öland, the maximum recorded thickness of the Mossberga Member is 26 m in the Kvinnsgröta-1 well (Nielsen & Schovsbo 2007). This member is, however, thicker (31.9 m) in the Tingskullen core. The thickness of the Bårstad Member in the Tingskullen and Böda Hamn cores is remarkably similar (~ 17 m). The Äleklinta Member is up to 68 m thick on southern Öland (Hagenfeldt 1994; Nielsen & Schovsbo 2007, 2015) and thins out towards the north. In the Tingskullen and Böda Hamn cores it is 6.65 and 1.50 m thick, respectively. The Äleklinta Member of Öland is generally dominated by a succession of light grey siltstones with thin interbeds of sandstone and rests unconformably on the Bårstad Member (Martinsson 1965; Nielsen & Schovsbo 2007). In the Tingskullen core, this member rests conformably on the Bårstad Member and is dominated by light grey siltstones

alternating with medium grey mudstones. A thin conglomerate (the Granulata Conglomerate Bed of Nielsen & Schovsbo 2007) suggestive of an unconformity was, however, described from the base of the Äleklinta Member (42.45 m) in the Böda Hamn core (Wærn 1952). This conglomerate is inferred to reflect a rapid sea-level rise, the Forsemölla Drowning, at the beginning of the *Ptychagnostus gibbus* Chron (Nielsen & Schovsbo 2015).

Locally on northern Öland, the Borgholm Formation is taken to include a silt- and mudstone succession that rests conformably on the File Haidar Formation and is truncated at the top by the ‘Hawke Bay’ unconformity (Nielsen & Schovsbo 2007). This succession is recognized as the Grötlingbo Member and inferred to be latest Cambrian Epoch 2 in age (Hagenfeldt 1994; Nielsen & Schovsbo 2011, 2015). However, the Grötlingbo Member cannot be identified in the Tingskullen core. Nielsen & Schovsbo (2007, p. 77) suggested that the Grötlingbo Member is disconformably overlain by the Mossberga Member and has a thickness of ~7 m in the Böda Hamn core (90.8–84.1 m). The succession below the basal conglomerate of the Mossberga Member in the Böda Hamn core is, however, dominated by a fine-grained, whitish sandstone with mudstone interbeds (Hessland 1955), and it agrees in all essential lithological characteristics with the När Sandstone Member of the File Haidar Formation. Thus, the Grötlingbo Member cannot be positively identified on Öland.

Nielsen & Schovsbo (2015, fig. 60) presented a general sea-level curve for the Borgholm Formation with a transgression at the base of the Mossberga Member and a renewed and prominent transgression (the Oelandic Drowning) at the base of the Bårstad Member. In the Tingskullen succession, the Bårstad Member facies indicates deposition in distinctly deeper waters than the Mossberga Member and provides confirming evidence for the renewed transgression during the deposition of the Bårstad Member.

On Öland, the lower half of the Mossberga Member, corresponding to subsequence MC3-2A of Nielsen & Schovsbo (2015), is non-trilobitic, but has yielded various phosphatic-shelled brachiopods. Nielsen & Schovsbo (2015) speculated that the dissolution of sclerites due to variable syngene dysoxic/oxic conditions on the sea floor (cf. Schovsbo 2001) might be responsible for the absence of trilobites in this interval. However, redox proxies and the oxic-dysoxic conditions on the sea-floor have not been investigated, and it is also worth noting that the lower, non-trilobitic Mossberga Member is lithologically closely comparable to the trilobite-bearing upper part of the Mossberga Member. Thus, the reason for the absence of trilobites in the lower Mossberga Member remains unknown.

CONCLUSIONS

The Cambrian succession of Öland, southern Sweden, records several facies changes, largely because of prominent sea-level changes during deposition. The recent Tingskullen core drilling penetrated 60.50 m of Cambrian Series 2 and Miaolingian (Wuliuan Stage) siliciclastic strata. The lowermost part of the drill core belongs to the upper När Sandstone Member (File Haidar Formation; provisional Cambrian Series 2), which is disconformably overlain by the Miaolingian Borgholm Formation. In ascending order, the Borgholm Formation is subdivided into the Mossberga, Bårstad and Äleklinta members. The Äleklinta Member is barren of body fossils, whereas the Mossberga and Bårstad members are moderately to richly fossiliferous with a shelly fauna largely represented by linguliformean brachiopods, paradoxidid and ellipsocephalid trilobites, and agnostoids. Trilobites and agnostoids from the Bårstad Member are indicative of the *Acadoparadoxides pinus* Zone. The Mossberga Member has not yielded any zonal guide fossils but its upper trilobite-bearing part is tentatively assigned to the *Eccaparadoxides insularis* Zone.

The Tingskullen drill core offers a unique opportunity to calibrate the Wuliuan $\delta^{13}\text{C}_{\text{org}}$ curve with the Wuliuan trilobite and agnostoid zone succession of Baltoscandia. Although the data exhibit some scatter, $\delta^{13}\text{C}_{\text{org}}$ values through the Borgholm Formation show a positive trend up-section without any characteristic excursion. This suggests that the Wuliuan *A. oelandicus* Superzone is younger than the negative Redlichiiid–Olenellid Extinction Carbon isotope Excursion (ROECE), which is known from near the top of Stage 4 and close to the traditional ‘Lower–Middle Cambrian boundary’ in several parts of the world.

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Miaolingi ladestiku (Kambrium) trilobiitide biostratigraafia ja süsiniku kemostratigraafia Tingskulleni puuraugus Rootsis Ölandi saarel

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Kambriumi läbilõike Tingskulleni puuraugus Ölandi saarel sisaldab 2. ladestiku ja Miaolingi (Wuliu lade) ränipurdkivimeid. Läbilõike põhiosa moodustab Miaolingi Borgholmi kihistu, mis on jagatud Mossberga, Bårstadi ja Äleklinta kihistikuks. Äleklinta kihistik ei sisalda fossiile, kuid Mossberga ja Bårstadi kihistikud on fossiilirikkad ning biostratigraafiliselt küllalt hästi esindatud. Bårstadi kihistiku trilobiidid ja agnostiidid määravad selle kuulumise *Acadoparadoxides pinus*'e biotsooni. Mossberga kihistik ei sisalda indeksfossiile, kuid on tinglikult arvatud *Eccaparadoxides insularis*'e biotsooni kuuluvaks. Borgholmi kihistu $\delta^{13}\text{C}_{\text{org}}$ profiili iseloomustab üldine positiivne trend ja selgete isotoopsündmuste puudumine. See näitab, et Wuliu lademesse kuuluva *Acadoparadoxides (Baltoparadoxides) oelandicus*'e ülembiotsoon (Oelandicuse kihid) Ölandil on noorem kui redlihiidide-olenelliidide väljasuremine ja negatiivne süsiniku isotoophälve (ROECE). Viimane on teada Kambriumi 4. lademe ülaosast ja asub lähedal traditsioonilisele Alam- ning Kesk-Kambriumi piirile maailma eri piirkondades.