Cambrian stratigraphy and depositional dynamics based on the Tomten-1 drill core, Falbygden, Västergötland, Sweden

Frans Lundberg

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Cover Picture: Tomten quarry, Västergötland, Sweden. Photo: Frans Lundberg, 2015.

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Abstract: The Tomten-1 drilling at Torbjörntorp in Västergötland, southern Sweden, penetrated 29.85 m of Cambrian Series 2 and 3, Furongian, and Lower and Middle Ordovician strata. The biostratigraphy, sedimentology and carbon isotope ($\delta^{13}C_{org}$) stratigraphy of the core have been analysed. The succession is interrupted by numerous stratigraphic gaps (i.e. hiatuses) of variable magnitudes. There also appear to be several stratigraphic gaps within the Exsulans Limestone Bed. In the Cambrian Series 3 through Furongian Alum Shale Formation, agnostoids and trilobites have been identified to species level and the succession is subdivided into nine biozones (in ascending order): the *Ptychagnostus gibbus*, *P. atavus*, *Lejopyge laevigata*, *Agnostus pisiformis*, *Olenus gibbosus*, *Parabolina spinulosa*, *Ctenopyge tumida*, *C. bisculata* and *C. linnarssoni* zones. Lithological characteristics have been studied macroscopically as well as microscopically through thin section petrography, allowing for identification of unconformities and general depositional environments. The characteristics of the strata have rendered it possible to divide the drill core into important lithostratigraphic units that reflect sea level changes and allow for a correlation with other drill cores in Sweden. Two negative $\delta^{13}C_{org}$ excursions have been recorded from the lowermost part of the Alum Shale Formation. The most distinctive of these has a net shift of 2.14 ‰ and occurs below the Exsulans Limestone Bed, in strata that seem to be equivalent to the *Ptychagnostus gibbus* Zone. It may correspond to an unnamed excursion that has been recorded from the Cambrian Stage 5 in Scania, southern Sweden, and South China, but in the absence of useful biostratigraphic evidence, this identification is problematic. Another, but very poorly developed excursion in the lower *P. atavus* Zone possibly represents the Drumian Carbon Isotope Excursion (DICE) as described from the GSSP section at Drum Mountains in Utah, western United States. However, the values are not low enough to be considered diagnostic for the DICE. Detailed and dense sampling is required in order to delimit the range and amplitude of this minor excursion in the Tomten-1 drill core. The Steptoean Positive Carbon Isotope Excursion (SPICE) has not been recorded, largely because of lack of $\delta^{13}C_{carb}$-sampling in the lithologically highly variable Kakeled Limestone Bed and the incompleteness of the lower Furongian (Paibian Stage). Collectively, the data suggest that the Tomten area was shallow enough to be exposed at low sea-level and that Västergötland was subaerial during long periods of time.

Keywords: Cambrian, biostratigraphy, carbon isotope stratigraphy, δ^{13} excursion (DICE), trilobites, agnostoids, drill core, Västergötland, Sweden.

Supervisors: Per Ahlberg, Mats Eriksson

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Frans Lundberg, Department of Geology, Lund University, Sölvegatan 12, SE-223 62 Lund, Sweden. E-mail: frans.a.lundberg@gmail.com

Kambrisk stratigrafi och depositionsdynamik baserad på Tomtenkärnan från Falbygden, Västergötland, Sverige

FRANS LUNDBERG

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Sammanfattning: Tomten-1 borrkärnan från Västergötland i södra Sverige omfattar en 29.85 m mäktig lagerföljd från kambrium serie 2 och 3, furongium och undre och mellersta ordovicium. Borrkärnan har studerats med avseende på bio- och kolisotopstratigrafi ($\delta^{13}C_{org}$) samt sedimentologi. Lagerföljden innehåller många stratigrafiska luckor av olika omfattning. Agnostider och trilobiter i alunskifferformationen från kambrium serie 3 och furongium har identifierats till artnivå, vilket resulterat i att nio biozoner har identifierats (i stigande ordning): zonerna med *Ptychagnostus gibbus*, *P. atavus*, *Lejopyge laevigata*, *Agnostus pisiformis*, *Olenus gibbosus*, *Parabolina spinulosa*, *Ctenopyge tumida*, *C. bisculata* och *C. linnarssoni*. Litologiska egenskaper har studerats på såväl makroskopisk som mikroskopisk nivå för att identifiera faunaförändringar, diskontinuitetsytor och depositionsmiljöer. Litologierna i borrkärnan har gjort det möjligt att dela in borrkärnan i viktiga litostratigrafiska enheter som speglar havsnivåförändringar och som i sin tur är korrelerbara med enheter från andra borrkärnor i Sverige. Två negativa kolisotopexkursioner har påvisats i den understa delen av alunskifferformationen. Den undre av dessa är distinkt och förekommer i ett fossilfattigt intervall med alunskiffer under exsulanskalkstenen. Detta intervall kan förmodligen räknas till *Ptychagnostus gibbus*-zonen. En motsvarande, inte namngiven exkursion har beskrivits från kambrium etage 5 i Skåne och södra Kina. En annan exkursion förekommer i den undre delen av *O. atavus*-zonen. Denna exkursion är inte lika distinkt, men kan åtminstone delvis motsvara Drumian Carbon Isotope Excursion (DICE) såsom den har beskrivits från Drum Mountains i Utah, västra USA. Tätare och mer detaljerad provtagning av Tomten-1-kärnan krävs emellertid för att säkert fastställa om det rör sig om DICE. Steptoean Positive Carbon Isotope Excursion (SPICE) har inte identifierats, men delar av denna finns troligen i kakeledskalkstenen. Den sammantagna bilden av Tomtenborrkärnan är att avlagringarna avsatts under relativt grunda förhållanden. Periodvis utgjorde Västergötland ett landområde som utsattes för denudation med borttransport av sediment.

Nyckelord: Kambrium, biostratigrafi, kolisotopstratigrafi, δ^{13}-exkursion (DICE), trilobiter, agnostider, borrkärna, Västergötland, Sverige.

Frans Lundberg, Geologiska institutionen, Lunds universitet, Sölvegatan 12, 223 62 Lund, Sverige. E-post: frans.a.lundberg@gmail.com

1 Introduction

The Cambrian Period was characterized by rather stable conditions with regards to the Baltoscandian platform, with no known volcanic activity within the continent. However, the margins surrounding the palaeocontinent were affected by violent tectonic processes during this time (Bergström & Gee 1985; Cocks & Torsvik 2005). During the Cambrian, Baltica was geographically situated 30–60° south of the palaeoequator and inverted relative to its present configuration (Torsvik & Rehnström 2001), and large areas were submerged, resulting in shallow shelf environments during most of the period (Cocks & Torsvik 2005). The entire Cambrian Period and most of the Ordovician witnessed a global rise in sea-level (Martinsson 1974; Haq & Schutter 2008). However, several karst horizons have recently been identified in the "middle" Cambrian through Early Ordovician Alum Shale Formation, suggesting that subaerial conditions were present at times (Lehnert et al. 2012; Newby 2012).

The basal Cambrian succession of Scandinavia was largely deposited on a Precambrian peneplain (i.e. planar subsurface) which in parts of Scandinavia was rather well developed following an extensive period of weathering and erosion (Martinsson 1974). The lowermost part of the succession is of early Cambrian age (provisional Cambrian epochs 1 and 2) and dominated by siliciclastic deposits (Andersson et al. 1985). These sediments had a proximal origin (Karlsson 2001).

The environmental conditions during Cambrian Epoch 3 in Scandinavia were characterized by vast areas with low topography and mostly with influx of fine-grained sediments (Cocks & Torsvik 2005). The lowermost part of Cambrian Series 3 consists of relatively coarse-grained sediments and is overlain by distinctly greyish and greenish shales and siltstones. Upwards in the stratigraphy these grade into darker and more kerogen-rich shales that form the Cambrian Series 3 through lower Tremadocian Alum Shale Formation (Bergström & Gee 1985).

During the Ordovician, Baltica continued its movement towards the north. The paleolatitude of the central parts of Baltica was, however, almost the same as during the Cambrian, although considerable rotation of the continent had effect on local areas. In the Ordovician there was significant deposition of limestone on Baltica (Cocks & Torsvik 2005).

The Alum Shale Formation consists of black to dark grey shale with subordinate limestone beds and lenses, colloquially referred to as 'Orsten' or stinkstone (Andersson et al. 1985). The formation crops out in many areas of Scandinavia and ranges stratigraphically from Cambrian Series 3 to the Lower Ordovician (Buchardt et al. 1997; Nielsen & Schovsbo 2011). The thickness of the Alum Shale Formation is varying; normally it is 20–30 m thick, whereas the Oslo area, Norway, and Scania, the southernmost province of Sweden, have approximately 100 m thick successions (Buchardt et al. 1997; Bergström & Gee 1985). The Alum Shale was predominantly deposited under dysoxic conditions, with sedimentation rates as low as 1–10 mm/1000 years (Thickpenny 1987; Buchardt et al. 1997). The presence of local hiatuses, wide areal extension and the relative thinness of the alum shale suggest deposition on a stable platform, with only minor vertical movements (Bergström & Gee 1985).

The biostratigraphy of the Cambrian Series 3 and Furongian of Scandinavia is based on agnostoids and polymerid trilobites. These series are divided into superzones which are further divided into zones. In the province of Västergötland, south-central Sweden, several of these are lacking or are incomplete, forming hiatuses in the succession.

The Cambrian Series 3 of Scandinavia embraces three superzones (in ascending order): the *Acadoparadoxides oelandicus*, *Paradoxides paradoxissimus* and *Paradoxides forchhammeri* superzones. The *A. oelandicus* Superzone is largely absent in Västergötland, and the latter two are incomplete. The Furongian Series includes the six superzones (in ascending order): the *Olenus, Parabolina, Leptoplastus, Protopeltura, Peltura* and *Acerocarina* superzones. In Västergötland the upper *Acerocarina* Superzone is absent, whereas the other five are partially incomplete (Nielsen et al. 2014). The Alum Shale Formation is generally richly fossilferous, and the faunas consist mainly of polymerid trilobites and agnostoids.

The purpose of this thesis is to present a high-resolution biostratigraphy of the Alum Shale Formation of the Tomten-1 drill core from Västergötland. Moreover, the succession is correlated with other coeval ones in Sweden. The biostratigraphic investigation also allows for hiatuses to be identified. Carbon isotope ($\delta^{13}C_{org}$) stratigraphy is made for further correlation, by identifying excursions occurring globally. Studies of lithological characteristics, microfacies and the microfossil content are done in order to interpret the depositional environment, taphonomy and biota.

2 Location and general remarks

The Tomten-1 drill core was retrieved in 2005 from the now abandoned Tomten Quarry, situated approximately 1.5 km northeast of the municipality of Torbjörntorp, Västergötland, southern Sweden (Fig. 1). The drilling was made by Skårby Kärnborrning AB on behalf of the Department of Geology, Lund University, Sweden. The purpose of the drilling was to obtain information from the exposed Furongian and the unquarried Cambrian Series 3 strata. Westergård (1922) described the upper part of the interval in the Tomten quarry, mainly with regards to the fossil content and ranges of biostratigraphically important taxa.

The drilling reached a depth of 29.85 m and recovered strata of, from top to bottom, the Lower Ordovician (0−1.5 m), Furongian (1.5−11.55 m), Cambrian Series 3 (11.55−26.45 m) and Cambrian Series 2 (26.45−29.85 m) (Appendix A).

The major portion of the drill core is represented

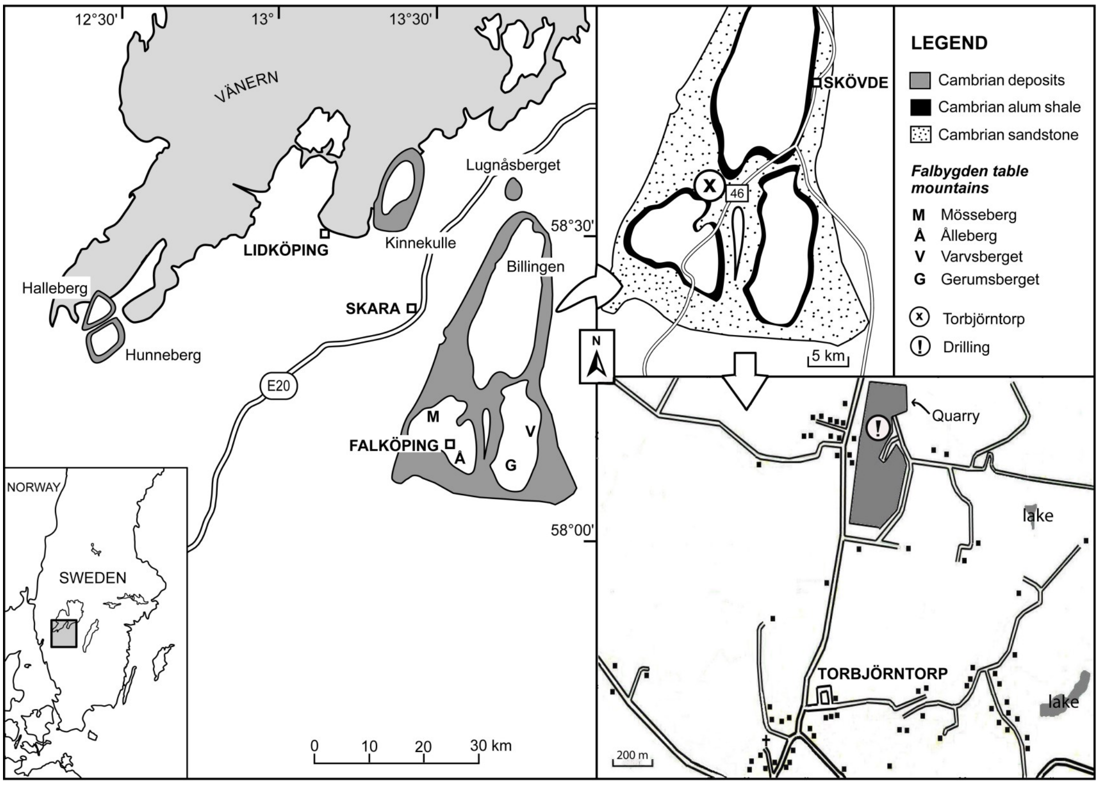


Fig. 1. Map of Västergötland, Sweden, showing Cambrian outcrop areas and the location of Tomten-1 drill site close to the municipality of Torbjörntorp. Modified from Axheimer et al. 2006, fig. 3.

by the Alum Shale Formation, mainly consisting of dark shale and generally subordinate black bituminous limestone. The Alum Shale Formation in Västergötland has been studied by, for instance, Westergård (1922, 1946), Ahlberg & Ahlgren (1996) and Terfelt (2003). The Furongian successions have been extensively studied with regards to biostratigraphy (e.g. Westergård 1922) and their potential as economic resources (Andersson et al. 1985).

3 Materials and methods

3.1 Lithology and facies

The Tomten-1 drill core was studied lithologically, i.e., with regards to texture, particle size, colour changes and presence of pyrite. Hydrochloric acid (5–10%) was applied to several parts of the drill core in order to identify carbonate intervals. A lithological succession was subsequently generated based on the available information. Both overview and detail photographs were taken (with a digital Nikon L29 camera) prior to sampling and splitting of the drill core.

Nineteen levels were sampled for more detailed studies of lithology and (micro) facies. Samples were selected in order to cover the complete range of different lithologies and facies types represented in the drill core. The samples were cut vertically with a rock saw and subsequently polished with a diamond paste. Images of the polished slabs were generated using a computer flatbed scanner. In addition, twenty-nine petrographic thin sections were produced from the polished slabs. These were examined in an optical binocular light microscope in order to further assess the mineralogy, lithological characteristics and faunal composition. Photomicrographs were taken of representative thin sections.

3.2 Fossil content and biostratigraphy

In order to evaluate the fossil content and biostratigraphy of the drill core, the shale intervals were split up approximately every centimeter, using a chisel and hammer. The limestone intervals were split up approximately every 5 cm. Higher resolution splitting of the limestones was not feasible due to the harder lithology. The top and bottom surface of each core slab were examined in a stereo microscope and all fossils were marked with a coloured pencil for more detailed observation and their occurrence was noted in a spread sheet. Subsequently each fossil was thoroughly studied and identified as accurately as possible using relevant published literature (e.g. Westergård 1922; 1946; 1947; Henningsmoen 1957; Robison 1984; Axheimer & Ahlberg 2003; Terfelt 2003, Høyberget & Bruton 2012 & Weidner & Nielsen 2014). Still, several specimens had to be left in open nomenclature because of their poor state of preservation. Selected representative specimens were coated with ammonium chloride in order to enhance the contrast, contours and detailed morphology, prior to being photographed using a digital Canon 550D camera mounted on a table set camera holder with four external light sources.

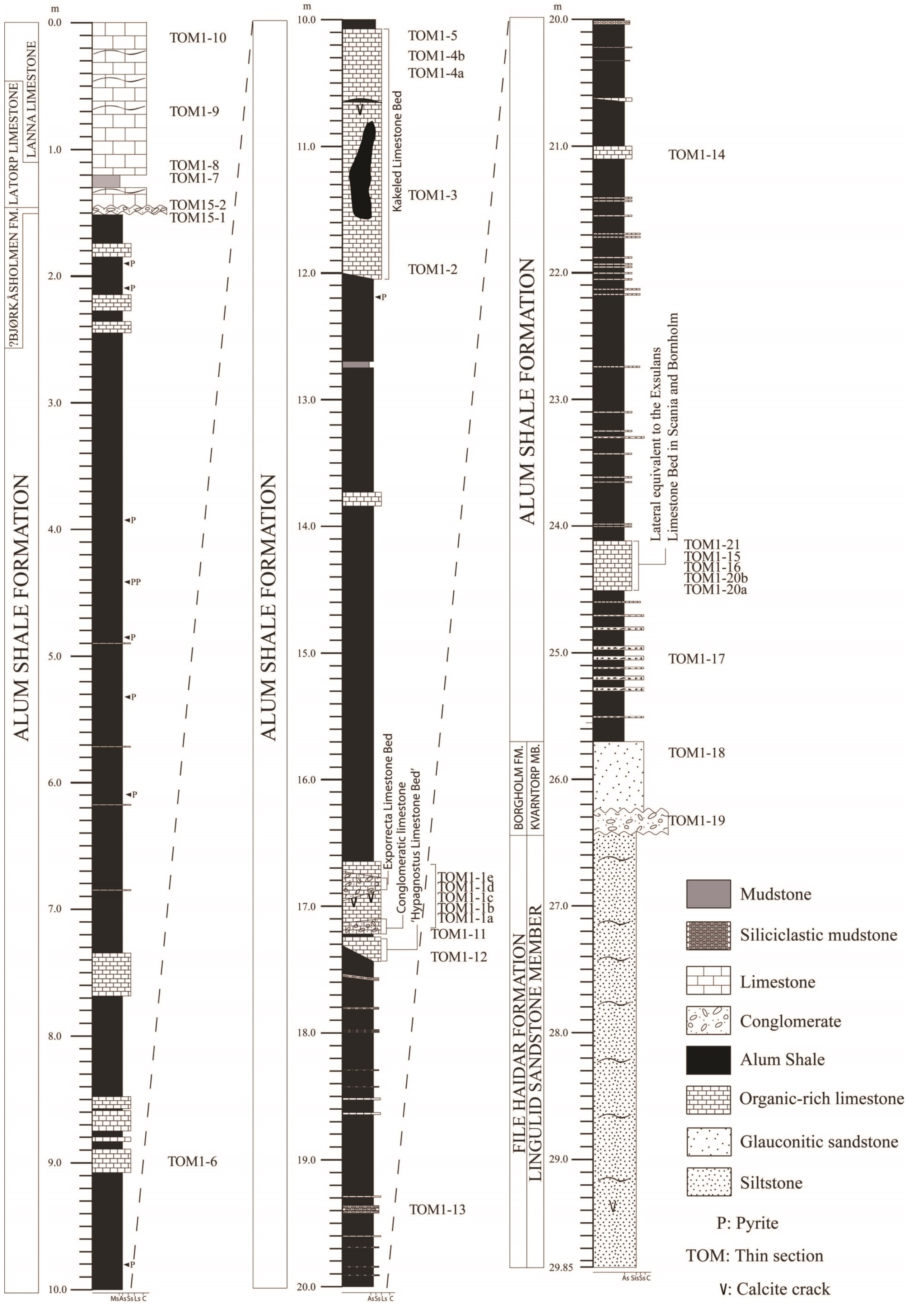


Fig. 2. Lithological succession of the Tomten-1 drill core, Torbjörntorp, Västergötland, Sweden.

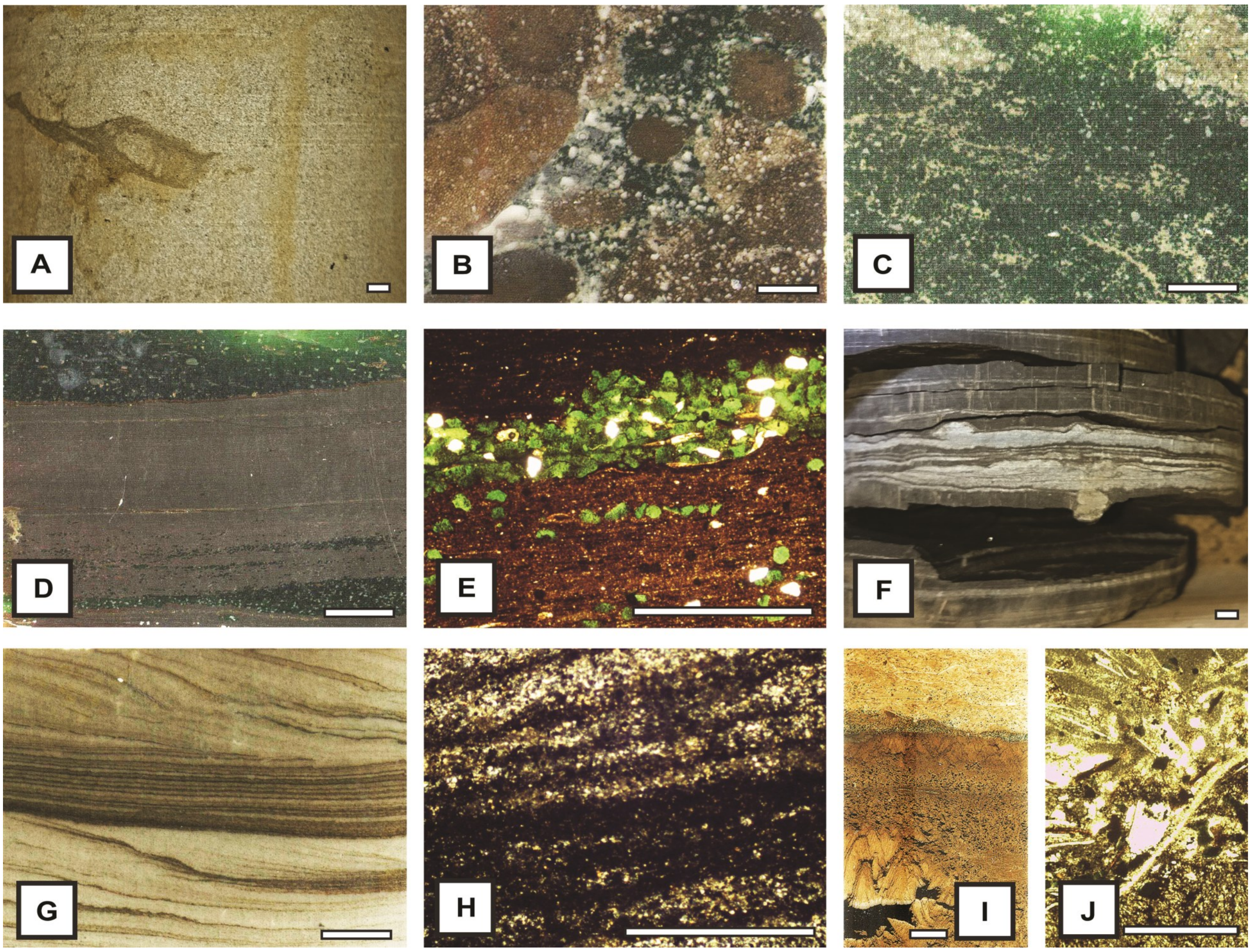


Fig. 3. Photos and photomicrographs from the lower part of the Tomten-1 drill core. Scale bars correspond to 5 mm. **A.** Lingulid sandstone with shale and intraclasts of surronunding sandstone. **B.** Pyrite-rich glauconitic conglomerate with large intraclasts resembling the underlying Lingulid Sandstone. Kvarntorp Member, Borgholm Formation (TOM1-19). **C.** Dark green, glauconitic mud rich sandstone of the Kvarntorp Member, Borgholm Formation (TOM1-18). **D.** Unconformable shift from shale to glauconite bed. Alum Shale Formation (TOM1-17). **E.** Close-up of (D) showing thin laminae of glauconite occurring in the shale. Alum Shale Formation (TOM1-17). **F.** White sandstone without any distinct bedding of the Alum Shale Formation. **G.** Siliclastic mudstone, with thin dark laminae. In the lower part it has mud drapes whereas in the upper part of the mudstone it becomes cross laminated. Alum Shale Formation (TOM1-13). **H.** Close-up of (G) showing possible microbial mats. Alum Shale Formation (TOM1-13). **I.** Crystallized limestone in the basal part whereas the upper part consists of pack/wackstone. Alum Shale Formation (TOM1-14). **J.** Close-up of (I) showing transition from orsten to skeletal rich packstone. Alum Shale Formation (TOM1-14).

3.3 Acid resistant microfossils

Microfossil samples were collected from five intervals in the drill core (24.20–24.26 m, 16.65–16.70 m, 11.07–11.15 m, 7.52–7.59 m and 1.00–1.09 m). The limestone samples were sawed vertically out of the drill core, crushed into cm-sized pieces with a hammer and subsequently dissolved in c. 10% acetic acid in accordance with standard methods for retrieving acid resistant microfossils (e.g. Jeppsson et al. 1999). The remaining acid resistant residue was then washed in deionized water, dried and then put in formic acid in order to get rid of possible dolomite prior to heavy liquid separation. After another cleaning in deionized water the sample residues were dried and picked for microfossils with a fine brush under a binocular light microscope.

3.4 Chemostratigraphy

Forty-four samples were taken from the Alum Shale Formation in the drill core, at intervals of approximately every half meter. In order to extract $^{13}C_{org}$, sample levels were identified in respect to shale, and avoiding limestones, pyrite and calcite. The samples were crushed into a fine powder using an agate mortar. In order to remove carbonate material, the samples were put in 10% formic acid and heated to 60 °C. The samples were then washed with deionized water several times until a pH level of approximately 6 was reached and subsequently dried in an oven (50 °C). They were thereafter pulverized with an agate mortar until a fine, homogeneous, powder was produced. The sample powder was put in vial and shipped off to an external laboratory for analysis (for a more detailed

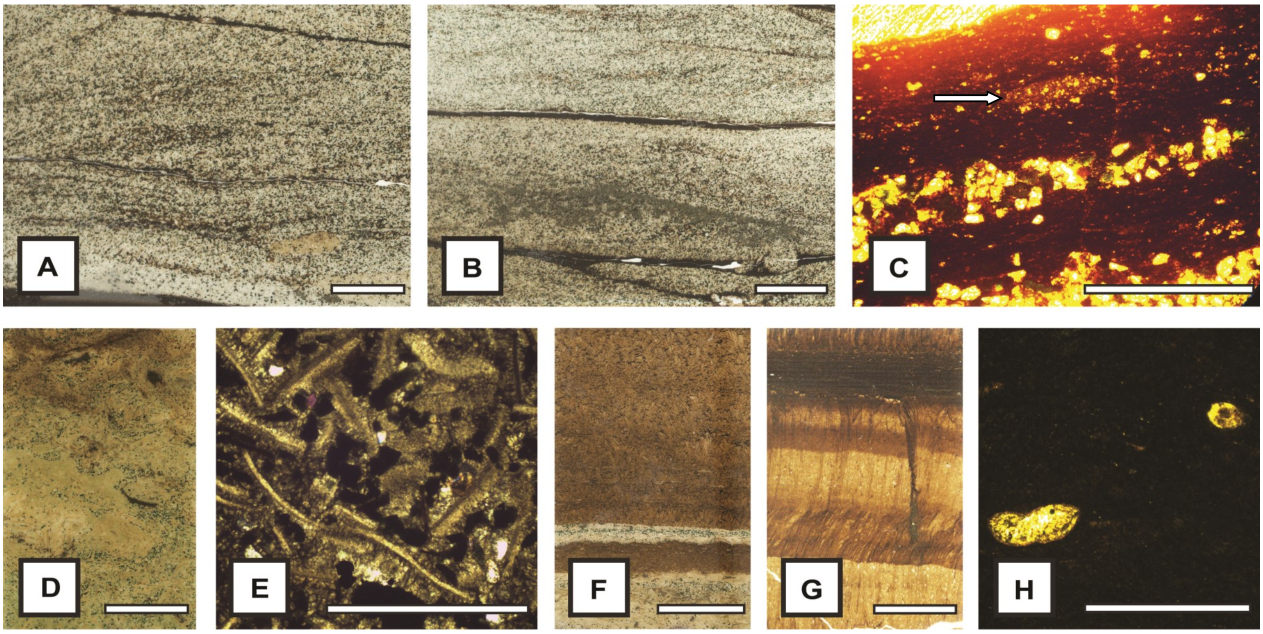


Fig. 4. Photomicrographs from the Exsulans Limestone Bed. Scale bar correspond to 5 mm. **A.** Basal part with unconformable lower part. Crossbedding occurs (TOM1-20a). **B.** Unconformities with fillings of alum shale (TOM1-20b). **C.** Close-up of (B) showing irregular fabric within the shale (TOM1-20b). **D.** Reworked interval (TOM1-16). **E.** Close-up of (D) showing calcite walled brachiopods (TOM1-16). **F.** Different facies of limestone (TOM1-15). **G.** The uppermost part with several facies shifts. A fault occurs immediately below a possible karst horizon (TOM1-21). **H.** Close-up of (G) showing skeletal remains c. 10 mm from the top (TOM1-21).

technical description of the methods used, see Bergström et al. 2014).

4 Lithostratigraphy

4.1 Lingulid Sandstone Member, File Haidar Formation (29.85−26.43 m)

The 3.42 m Lingulid Sandstone Member of the File Haidar Formation is distinctly bedded in the lower part and becomes more coarse-grained and massive in the upper part (cf. Nielsen & Schovsbo 2007). Some intervals are dark grey in colour.

Grains of pyrite occur throughout the Lingulid Sandstone. The pyrite grains sometimes reach a few centimetres in diameter and weathered pyrite has stained the surrounding sandstone. Thin irregular, 1−2 mm thick, shale horizons occur throughout the Lingulid Sandstone. At two levels (28.07 and 27.31 m), these shale horizons are 3−5 mm thick, with intraclasts of the surrounding sandstone (Fig. 3A). The drill core easily splits up along the shale horizons. A possible trilobite fragment, preserved upside down with regards to its living position, has been recorded at 27.70 m. Throughout the Lingulid Sandstone vertical cracks occur that sometimes are filled with calcite.

In the Billingen-Falbygden area, the Lingulid Sandstone Member of the File Haidar Formation has a thickness of 28−34 m (Martinsson 1974). This implies the 3.42 m thick sandstone in the Tomten-1 drill core represents approximately the uppermost tenth part of the Lingulid Sandstone Member in Västergötland. According to Nielsen & Schovsbo (2015), the Lingulid Sandstone in the Tomten-1 drill core would correspond to the basal upper Vergalian-Rausvian Stage. Martinsson (1974) noted the presence of trace fossils and brachiopods in the Lingulid Sandstone, and Ahlberg et al. (1986) described fragmentary trilobites from a few levels in the sandstone. Beds or lenses of impure carbonates occur in the Lingulid Sandstone (Hagström 1987). These may be derived from shelly marine organisms.

4.2 Kvarntorp Member, Borgholm Formation (26.43−25.70 m)

The 73 cm thick Kvarntorp Member of the Borgholm Formation is represented by glauconitic sandstone and conglomerate. Its lowermost part (26.43−26.29 m) consists of a pyrite-rich glauconitic conglomerate with large intraclasts ranging in diameter from 1 to 3 cm (Fig. 3B). The intraclasts are grey and have the lithological characteristics of the underlying Lingulid Sandstone Member. The lower boundary of the conglomerate forms an irregular erosional surface, inferably representing the Hawke Bay unconformity (see Nielsen & Schovsbo 2007, 2015).

The interval 26.29−25.75 m comprises dark green, glauconitic mud-rich sandstone (Fig. 3C). At two levels (26.13 m and 26.06 m), 2 cm large, grey clasts occur. These consist of either large pyrite crystals or sandstone fragments from the Lingulid Sandstone. Pyrite occurs throughout the Kvarntorp Member, with large centimeter-sized concretions at 25.90 m.

Fragments of indeterminate fossils have been found in the core. Acritarchs and brachiopods have been de-

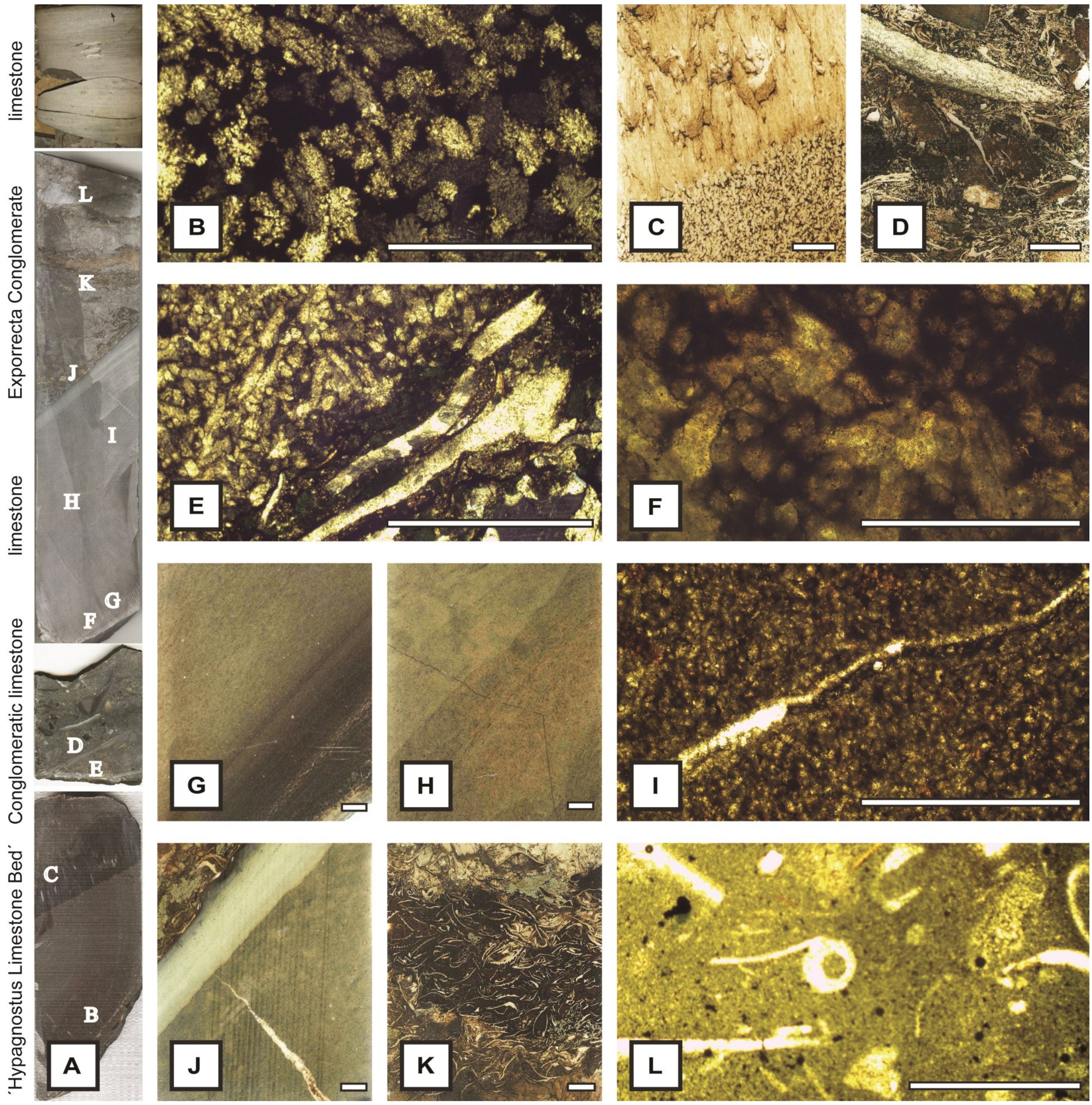


Fig. 5. **A.** Polished slabs of the 'Hypagnostus Limestone Bed', Conglomeratic Limestone, Limestone bed with Exporrecta Conglomerate and a photograph of an overlying limestone. The width of the drill core is 70 mm. **B–I.** Photomicrographs. Scale bars correspond to 5 mm. **B.** Showing the basal 'Hypagnostus Limestone Bed' with sharp transition from light to dark colour (TOM1-12). **C.** Upper part of the 'Hypagnostus Limestone Bed' with transition from fine grained to cone in cone limestone (TOM1-12). **D.** Conglomeratic Limestone with varied sized fragments, including beach pebbles (TOM1-11). **E.** Close-up of (D) showing brachiopods skeletal (TOM1-11). **F.** Cone in cone structure in the basal part of the limestone (TOM1-1a). **G.** Laminated limestone with colour shift (TOM1-1a). **H.** Middle part of the limestone (TOM1-1b). **I.** Close-up of (H) showing calcite crack within the limestone (TOM1-1b). **J.** Karst horizon and calcite crack (TOM1-1c). **K.** Abundant brachiopods in the Exporrecta Conglomerate (TOM1-1d). **L.** Close-up of (K) showing echinoderms, hyoliths and brachiopods in the Exporrecta Conglomerate (TOM1-1d).

scribed from the Kvarntorp Member in Östergötland and Närke (Westergård 1940; Eklund 1990).

4.3 Alum Shale Formation (25.70−1.55 m)

4.3.1 Alum Shale

In the Tomten-1 drill core, the unconformity at the top of the Borgholm Formation is overlain by a 24.15 m thick succession of dark grey and black shales of the Alum Shale Formation.

Glauconitic beds are present at 25.52−23.31 m, most of them in the lower 80 cm of this interval, where the individual bed thickness varies from 3−5 cm. The transition between the glauconite beds and the shale are often sharp (Fig. 3D). Sporadic glauconitic laminae

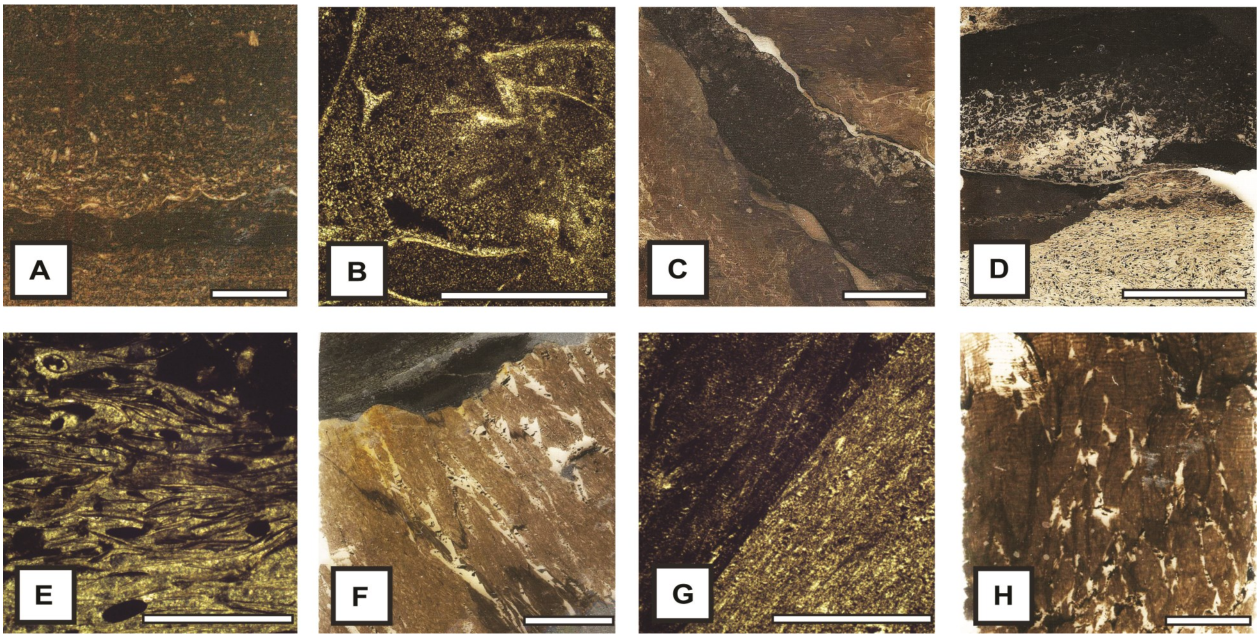


Fig. 6. Photomicrographs of the Kakeled Limestone Bed. Scale bar correspond to 5 mm. **A.** Basal part with mud-wackstone (TOM1-2). **B.** Close-up of (A) showing abundant trilobite skeletals (TOM1-2). **C.** Wackestone with surrounding cave filling of alum shale (TOM1-3). **D.** Crystalline limestone (TOM1-4a). **E.** Close-up of (D) showing cocqonid grainstone (TOM1-4a). **F.** Angled crystalline limestone (TOM1-4b). **G.** Close-up of (F) (TOM1-4b). **H.** Coarse-grained crystalline limestone (TOM1-5).

of various thicknesses (Fig. 3E) are present within the shale. The colour and textural characteristics resemble those of the underlying glauconitic sandstone of the Borgholm Formation. This glauconitic interval appears to represent a transitional shift from the Borgholm to the Alum Shale Formation. At some areas in Västergötland, the boundary between these formations appears to be gradual (Nielsen & Schovsbo 2007). In the Tomten-1 drill core, however, there is sharp unconformity at the top of the Borgholm Formation.

The characteristics of the Alum Shale vary. The lower part (25.70−17.40 m) of the Alum Shale Formation is largely composed of grey shale, often forming hard planar laminated packages with mud. In the upper middle part of the *Ptychagnostus atavus* Zone white sandstone occurs without any distinct bedding (Fig. 3F). In the upper half of the *P. atavus* Zone sometimes distinctive light grey packages of siltstone occur (Fig. 3G). These siltstones are laminated with a dark material (Fig. 3H) and sometimes cross bedding occurs (Fig. 3G).

In the upper parts of the Tomten-1 drill core the colour shifts from grey to black. The shift to darker shales is due to deposition of more organic material (Bergström & Gee 1985; this paper, Table 1). The Alum Shale is normally planar laminated, however, at proximity to lens-shaped limestone concretions the shale may have the same gradient as the adjacent limestone concretion. At several levels, the shale is extremely fragmented and brittle.

Thin (1–2 mm) white and yellow laminae representing pyrite and phosphate are present throughout the drill core. In the Furongian they appear to be more frequent. The weathered pyrite has stained the surface of large parts of the surrounding shale.

4.3.2 Limestone

The lowermost limestone bed in the Tomten-1 drill core is at 24.50−24.12 m. In the interval 24.01−21.31 m limestone also occur as millimeter-thick laminae. These show parallel bedding or are massive. At 21.10−1.73 m the limestone intervals become thicker with individual beds reaching several centimeters to decimeters in thickness.

Dworatzek (1987) described two types of limestone in the Alum Shale Formation of Västergötland. The first type occurs mainly on Mount Kinnekulle, whereas the second type is dominating in Mount Billingen, south-east of Kinnekulle. The first type is characterized by continuous layers and a complex composition, whereas the second type is characterized by horizontal lamination and large lenses known as 'stinkstones'. The Tomten-1 drill core has several intervals of limestone with different characteristics. In the middle *P. atavus* Zone, a limestone occurs that is mainly crystalline in the lower part. In the middle it is truncated by an erosional surface with overlying light grey packstone with abundant glauconite and shell fragments (Fig. 3I−J).

In the Alum Shale Formation several prominent limestone marker beds occur, which can be correlated throughout Sweden (Nielsen & Schovsbo 2007).

An unconformity marks the basal part of a limestone bed (24.49−24.12 m) described here as a lateral equivalent of the Exsulans Limestone Bed of Scania and Bornholm. The lowermost 10 cm comprises grey coloured quartzitic sandstone. In the basal part cross

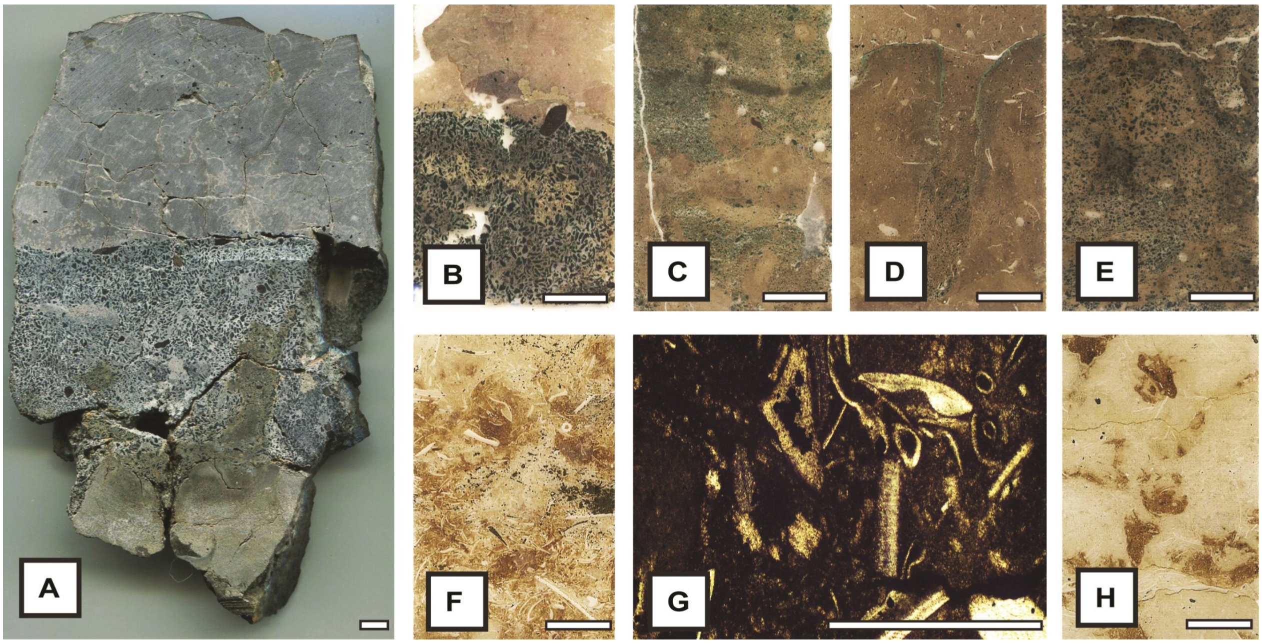


Fig. 7. Polished slab and microphotographs of Ordovician lithologies. Scale bars correspond to 5 mm. **A-C.** Bjørkåsholmen Formation **A.** Polished slab. **B.** Coarse-grained glauconitic packstone that transists to a recrystallized mud-wackstone. The fauna is dominated by arthropods. Horizontal cracks of calcite are present (TOM15-1). **C.** Pack-wackestone that grades to glauconitic packstone (TOM15-2). **D-E.** Latorp Limestone **D.** Large boring (TOM1-7). **E.** Highly glauconitic packstone (TOM1-8). **F-H.** Lanna Limestone **F.** Coarse-grained pack/wackestone (TOM1-9). **G.** Close-up of (F) showing abundant faunal remains (TOM1-9). **H.** Arthropod-dominated wackestone. Top of the Lanna Limestone (TOM1-10).

bedding is abundant (Fig. 4A), whereas higher up several unconformities with fillings of mm-thick alum shale occur with sometimes irregular fabric (Fig. 4B−C). Throughout the Exsulans Limestone Bed there is an abundance of glauconite and pyrite. The bed is frequently highly reworked (Fig 4D), with abundant brachiopod remains. In the upper part it grades (Fig. 4E) from a planar laminated, coquinoid limestone with occurrences of echinoderms and brachiopods (Fig. 4F) to a limestone of a crystalline character. In the uppermost part there are several colour shifts within a crystalline structure. Ten mm from the top there is an irregular surface. Below this surface a fault occurs (Fig. 4G) with glauconite occurring within a crack. There is planar laminated limestone with abundant shell fragments 10−5 mm below the top (Fig. 4H). The uppermost 5 mm of the Exsulans Limestone Bed again has an interval of crystalline structure. The top of the Exsulans Limestone Bed has a black irregular surface resembling dolomitization.

At 17.42 m, the dip of the bedding of the alum shale is gradually increasing. The 'Hypagnostus Limestone Bed' (Fig. 5A) distinctly overlies the shale with a dip of 39°. The dip gradually decreases within the limestone bed and in the middle there is a sharp transition also to a darker colour (Fig. 5B−C). At the top of the limestone there is a 1 cm thick horizontal package of Alum Shale. This lithology grades into an overlying conglomeratic limestone, containing abundant large shale clasts, resembling beach pebbles and brachiopod fragments (Fig. 5D−E). Above the conglomeratic limestone an unconformity occurs with an overlying limestone (Fig. 5F−G). Throughout the limestone there is distinct internal bedding with a dip of 45−50° (Fig. 5H). The limestone has a large vertical crack with a surrounding light grey zone and filling of the overlying Exporrecta Conglomerate (Fig. 5I), however, also smaller calcite cracks of almost vertical to 45° dip occur.

The limestone has an approximately 1 cm light grey zone in both its lower and upper boundary (Fig. 5J). The upper boundary has a dip of 50° relative to the horizontal plane. The overlying Exporrecta Conglomerate has abundant brachiopod remains (Fig. 5K) and fillings of shale and echinoderm fragments (Fig. 5L). A 19° disconformable boundary separates the Exporrecta Conglomerate and an overlying limestone unit. The upper part of the overlying limestone contains brachiopods.

The limestone occurring immediately below the Exporrecta conglomerate in the Tomten-1 drill core has previously been reported from Västergötland (cf. Weidner et al. 2004). However, the limestone occurring above the Exporrecta conglomerate only display brachiopod fragments from the acid residue sample. Thus, this limestone does not display the fossil richness that is characteristic of the Andrarum Limestone normally occurring at corresponding stratigraphic level (Berg-Madsen 1985).

The Kakeled Limestone Bed (12.05−10.08 m) is a massive grey limestone in its lower part (Fig. 6A−B) but gradually becomes frequently conglomeratic with fillings of shale in the upper part (Fig. 6C). Crystalline limestone occurs at some levels (Fig. 6D). Large and mature intraclasts resembling rounded beach pebbles are also present. There are frequent vertical cracks of calcite below light grey zones (1 cm). In the upper part of the limestone bed there are coquinoid horizons (Fig. 6E) with mass occurrence of the brachiopod *Orusia lenticularis*. Also crystallized limestones are present (Figs. 6F−G). Further up in the Furongian succession abundant limestone concretions occur, some of which are crystallized (Fig. 6H)

4.4 ?Bjørkåsholmen Formation (1.55−1.53 m)

The basal Ordovician bed consists of a 1–2 cm thick, glauconitic packstone unit situated between two disconformities here considered to represent the Bjørkåsholmen Formation (Fig. 7A–B). Pyrite is common in the lowermost part. The assemblage of the unit is dominated by arthropods and calcite cracks are present. In the lowermost part shell fragments are sparse, whereas in the upper part shell fragments become abundant (Fig. 7B−C). The internal structure indicates a karren system (karst weathered limestone), similar to folding structures (Lehnert et al. 2012, 2013a). The disconformities represent karst horizons indicating subaerial exposure during regressions (Lehnert et al. 2012, 2013a).

The Bjørkåsholmen Formation conglomerate is very thin in the Tomten-1 drill core compared to Norway and Öland (Egenhoff et al. 2010) (see Appendix B). This clearly illustrates the substantial weathering Västergötland was exposed to. Judging from the conodont data of Olgun (1987), the Bjørkåsholmen Formation as defined biostratigraphically by Egenhoff et al. (2010) does not appear to be represented in the Tomten-1 drill core. The conodont zonation of Olgun (1987) places it in the *P. proteus* conodont zone, corresponding to the *M. planilimbata* trilobite Zone. Lehnert et al. (2012), however, placed it in the upper *P. deltifer* conodont Zone.

4.5 Latorp Limestone (1.53−1.10 m)

The Latorp Limestone comprises a 43 cm thick succession that is dark grey in colour. Glauconite occurs

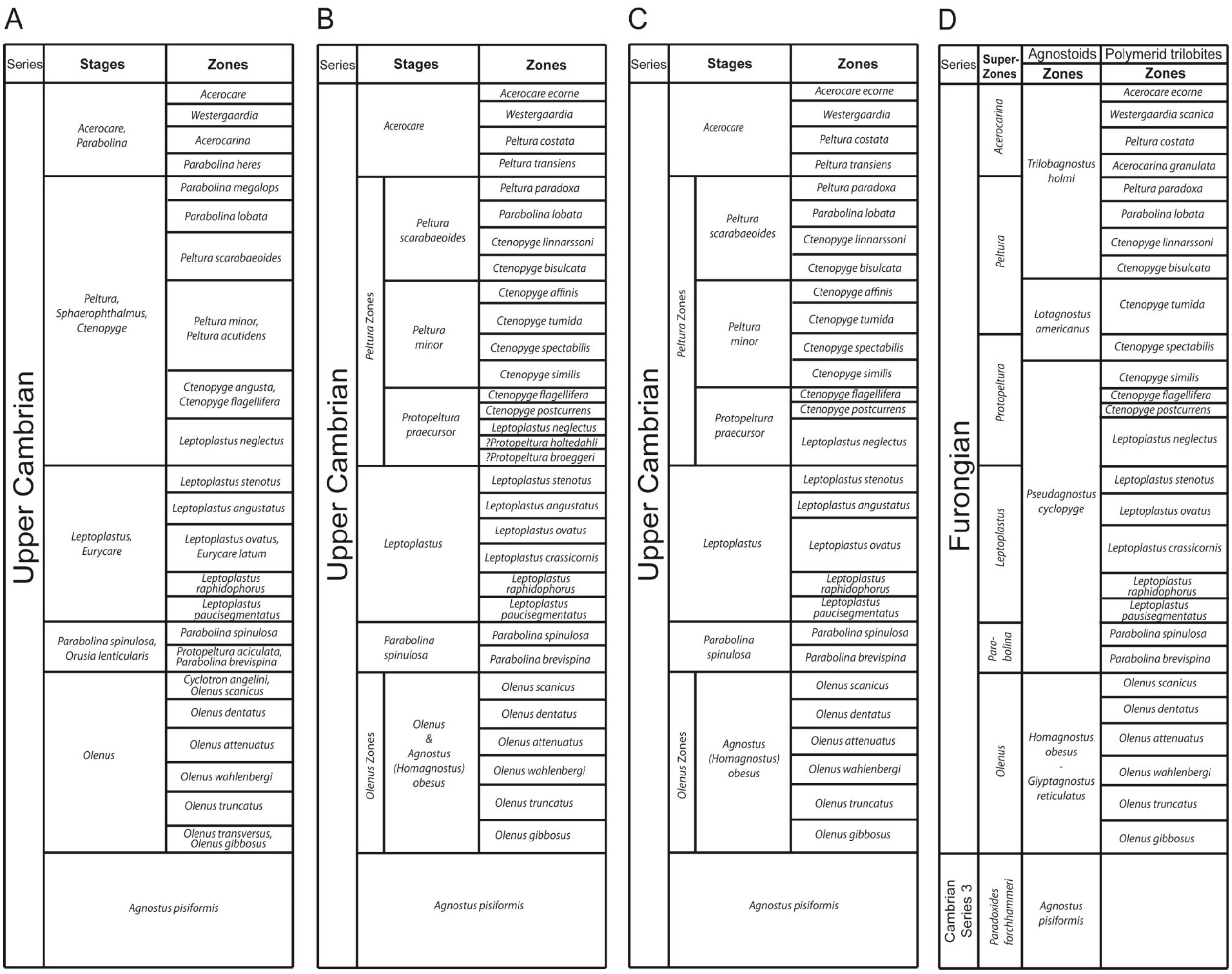


Fig. 8. Comparison of the Furongian biostratigraphy of Scandinavia as based on various authors. **A.** Westergård (1947). **B.** Henningsmoen (1957). **C.** Ahlberg (2003). **D.** Terfelt et al. (2008), Høyberget & Bruton (2012), Nielsen et al. (2014), and Weidner & Nielsen (2014).

throughout the interval (Fig. 7D–E), however, in the lower and upper parts glauconite grains are more common. Pyrite occurs in abundance at 1.20−1.10 m. A 5 mm thick distinctive whitish layer occurs at 1.25 m.

Calner et al. (2013) suggested this interval was coeval with the Holen Limestone, however, according to Thorslund (1937) and Olgun (1987) this unit corresponds to the Floian Latorp Limestone.

4.6 Lanna Limestone (1.10−0 m)

The uppermost part of the Tomten-1 drill core is represented by a 1.10 m thick succession of grey, often bioturbated 'orthoceratite limestone' of Mid Ordovician age. Lehnert et al. (2013a) assigned this limestone succession to the Darriwilian Holen Limestone. However, the lithological characteristics and its position in the sequence rather suggest that it represents the Dapingian Lanna Limestone.

The Lanna Limestone is light grey in colour. Pyrite is common in the lowermost part of the interval. Individual limestone beds are separated by corrosional hardgrounds and thin mud horizons. Bioturbation is common and appears to be increasing upwards (Fig. 7F–H). Shelly fossil fragments occur throughout the Lanna Limestone (Fig. 7G). At 0.95 m a large *Megalaspis* sp. occur. At 0.25 m an indeterminate fossil occur and a large indeterminate fossil occurs at 1.10 m.

The Lanna Limestone is approximately 4.5 m thick in the Tomten quarry, whereas the 1.10 m of the Lanna Limestone in the Tomten-1 drill core represents approximately one fourth of the lower part of the unit.

5 Furongian and Cambrian Series 3 biostratigraphy of Scandinavia

5.1 Furongian

The Furongian (roughly corresponding to the traditional 'Upper Cambrian', excluding the *A. pisiformis* Zone) of Scandinavia was extensively studied in the 19th century (e.g. Linnarsson 1868; Nathorst 1869). Current knowledge is largely based on the work of Westergård (1922) who comprehensively described trilobites and agnostoids stratigraphically and geographically of Sweden. He divided the 'Upper Cambrian' into the following six zones (in ascending order): the *Agnostus pisiformis, Olenus*, *Parabolina spinulosa* and *Orusia lenticularis*, *Leptoplastus* and *Eurycare*, *Peltura*, *Sphaeropthalmus* and *Ctenopyge*, and *Acerocare*, *Cyclognathus* and *Parabolina* zones. Westergård (1947) subdivided the 'Upper Cambrian' into six zones and 24 subzones (Fig. 8A). Henningsmoen (1957) continued this work and subdivided the Upper Cambrian into eight zones (in ascending order): the *Agnostus pisiformis, Olenus* and *Agnostus (Homagnostus) obesus*, *Parabolina spinulosa*, *Leptoplastus*, *Protopletura praecursor*, *Peltura minor*, *Peltura scarabaeoides* and *Acerocare* zones. Henningsmoen (1957) also increased the number of subzones to 32 (Fig. 8B). Nielsen & Schovsbo (1999) discarded three of these zones, resulting in 29 zones altogether. Also Ahlberg (2003) described 29 zones (Fig. 8C).

Terfelt et al. (2008) divided the Furongian into two parallel zonations (Fig. 8D) based on agnostoids and polymerids, respectively. The main reason for the agnostoid zonation was to provide a scheme for global correlation. The four agnostoid zones were (in ascending order): *Glypagnostus reticulatus*, *Pseudagnostus cyclopyge*, *Lotagnostus americanus* and *Trilobagnostus holmi*. The zones were retained from Ahlberg (2003), although the nomenclature of three zones was modified. The *Agnostus pisiformis* Zone was excluded from the Furongian, and the base of the latter was characterized by FAD of *G. reticulatus*. The traditional term 'Upper Cambrian' was replaced with Furongian (Peng & Babcock 2003; Peng et al. 2004) and the *Agnostus pisiformis* Zone was subsequently attributed to the *Paradoxides forchhammeri* Superzone of the Cambrian Series 3.

Høyberget & Bruton (2012) replaced the *Ctenopyge affinis* Zone with the broadened *Ctenopyge tumida* Zone (Fig. 8D). Weidner & Nielsen (2013) changed

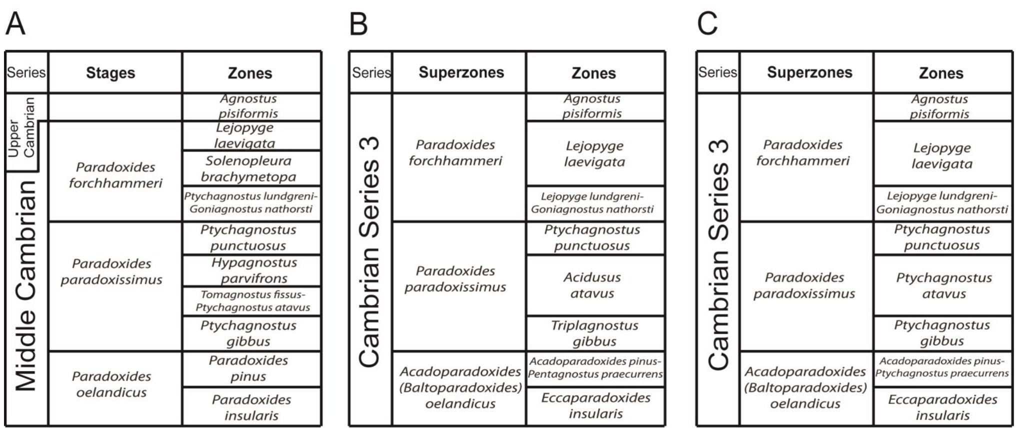


Fig. 9. Comparison of the Cambrian Series 3 biostratigraphy of Scandinavia as based on various authors. **A.** Westergård (1946). **B.** Nielsen et al. (2014) and Weidner & Ebbestad (2014). **C.** This study.

the name of the uppermost zone (Fig. 8D) from *Acerocare* to *Acerocarina*. Nielsen et al. (2014) modified the nomenclature of the Furongian of Scandinavia (Fig. 8D) and (re)introduced the concept of superzones. They retained the 27 polymerid zones and five agnostoid zones from Terfelt et al. (2008), although changing the name of the lowest agnostoid zone from *Glypagnostus reticulatus* to the *Homagnostus obesus* and *Glypagnostus reticulatus* Zone. The three polymerid zones of *Protopletura praecursor*, *Peltura minor* and *Peltura scarabaeoides*, were replaced with the two zones *Protopeltura* and *Peltura*. The *Parabolina spinulosa* Zone was replaced by the *Spinulosa* Superzone and the lowest zone, the *Agnostus* (*Homagnostus*) *obesus* Zone, was replaced by the *Olenus* Superzone. The Furongian of Scandinavia is hence divided into (in ascending order): the *Olenus, Parabolina, Leptoplastus, Protopeltura, Peltura* and *Acerocarina* superzones. Rasmussen et al. (2015) replaced the *L. angustatus* and *L. ovatus* zones with the *L. crassicornis*-*L. angustatus* Zone.

5.2 Cambrian Series 3

The subdivision of Cambrian Series 3 (roughly corresponding to the traditional 'Middle Cambrian') in Scandinavia is largely based on the work of Westergård (1946) (Fig. 9A), who divided the 'Middle Cambrian' of Sweden into three stages (the *Paradoxides oelandicus*, *P. paradoxissimus* and *P. forchhammeri* stages) and nine zones (in ascending order): the *Paradoxides insularis*, *Paradoxides pinus*, *Ptychagnostus gibbus*, *Tomagnostus fissus–Ptychagnostus atavus*, *Hypagnostus parvifrons*, *Ptychagnostus punctuosus*, *Ptychagnostus lundgreni–Goniagnostus nathorsti*, *Solenopleura brachymetopa* and *Lejopyge laevigata* zones.

Robison (1984) identified five global agnostoid zones (in ascending order): the *Ptychagnostus praecurrens, Ptychagnostus gibbus, Ptychagnostus atavus, Ptychagnostus punctuosus* and *Lejopyge laevigata* zones. Ahlberg (1989) suppressed the *Eccaparadoxides pinus* Zone of Scandinavia with the more widely recognizable *Ptychagnostus praecurrens* Zone.

Peng & Robison (2000) divided the 'middle' Cambrian into seven global agnostoid zones (in ascending order): the *Ptychagnostus praecurrens*, *Ptychagnostus gibbus*, *Ptychagnostus atavus*, *Ptychagnostus punctuosus*, *Goniagnostus nathorsti*, *Lejopyge laevigata* and *Proagnostus bulbus* zones. The base of each zone was defined by the first appearance of a selected, geographically widespread species, and the top by the base of the succeeding zone (Peng & Robison (2000). The global agnostoid zonation proposed by Peng & Robison (2000) has been widely adopted and can be applied also to Scandinavian strata (e.g. Axheimer & Ahlberg 2003; Weidner et al. 2004). The agnostoid zonation of Peng & Robison is used in this paper.

The *Agnostus pisiformis* Zone now forms the uppermost zone in the Cambrian Series 3 of Scandinavia. It was previously regarded as the basal zone of the traditional 'Upper Cambrian' (Axheimer et al. 2006). The strongly facies controlled *Solenopleura*? (or *Erratojincella*) *brachymetopa* Zone was incorporated in the *Lejopyge laevigata* Zone by Axheimer et al. (2006).

Weidner & Nielsen (2014) combined Westergård's (1946) *Tomagnostus fissus*-*Ptychagnostus atavus* and *Hypagnostus parvifrons* zones and named it the *Acidusus atavus* Zone. It was subdivided into a lower and an upper part. Nielsen & Weidner (2014) favoured the usage of three Scandinavian superzones in Cambrian Series 3 (in ascending order): the *Acadoparadoxides oelandicus, Paradoxides paradoxissimus* and *Paradoxides forchhammeri* zones (Fig. 9B). Weidner & Ebbestad (2014) subdivided the Cambrian Series 3 of Scandinavia into eight zones (in ascending order): the *Eccaparadoxides insularis*, *Ptychagnostus praecurrens* (published as *Acadoparadoxides pinus - Pentagnostus praecurrens*), *Ptychagnostus gibbus* (published as *Triplagnostus gibbus*), *Ptychagnostus atavus* (published as *Acidusus atavus*), *Ptychagnostus punctuosus, Lejopyge lundgreni - Goniagnostus nathorsti, Lejopyge laevigata* and *Agnostus pisiformis* zones (Fig. 9B).

For correlation this paper uses nomenclature of Weidner & Ebbestad (2014), however, using the globally accepted *Ptychagnostus gibbus* (published as *Triplagnostus gibbus*), *Ptychagnostus atavus* (published as *Acidusus atavus*) and *Ptychagnostus praecurrens* (published as *Acadoparadoxides pinus - Pentagnostus praecurrens*) zones (Fig. 9C).

6 Systematic notes

Terminology. – Morphological terms adopted are those described by Robison (1984), Whittington (*in* Kaesler 1997) and Peng & Robison (2000).

Repository. – Discussed and illustrated specimens are stored at the Department of Geology, Lund University, Sweden.

Class uncertain
Order Agnostida Salter, 1864
Family Agnostidae M´Coy, 1849
Genus *Agnostus* Brongniart, 1822

Agnostus pisiformis (Wahlenberg, 1818)

Figs. 10A–B

Material. – Hundreds of disarticulated specimens.

Remarks. – In the lower, shale-dominated part of the *A. pisiformis* Zone of the Tomten-1 drill core, *A. pisiformis* is not as well preserved as in the upper, limestone-dominated part. The species has been discussed in detail by, e.g., Westergård (1922, pp. 115–116, pl. 1, figs. 1–4, Westergård 1946, pp. 85–86, pl. 13, figs. 10–14), Ahlberg & Ahlgren (1996, pp. 130–131) and Høyberget & Bruton (2008). Müller & Walossek

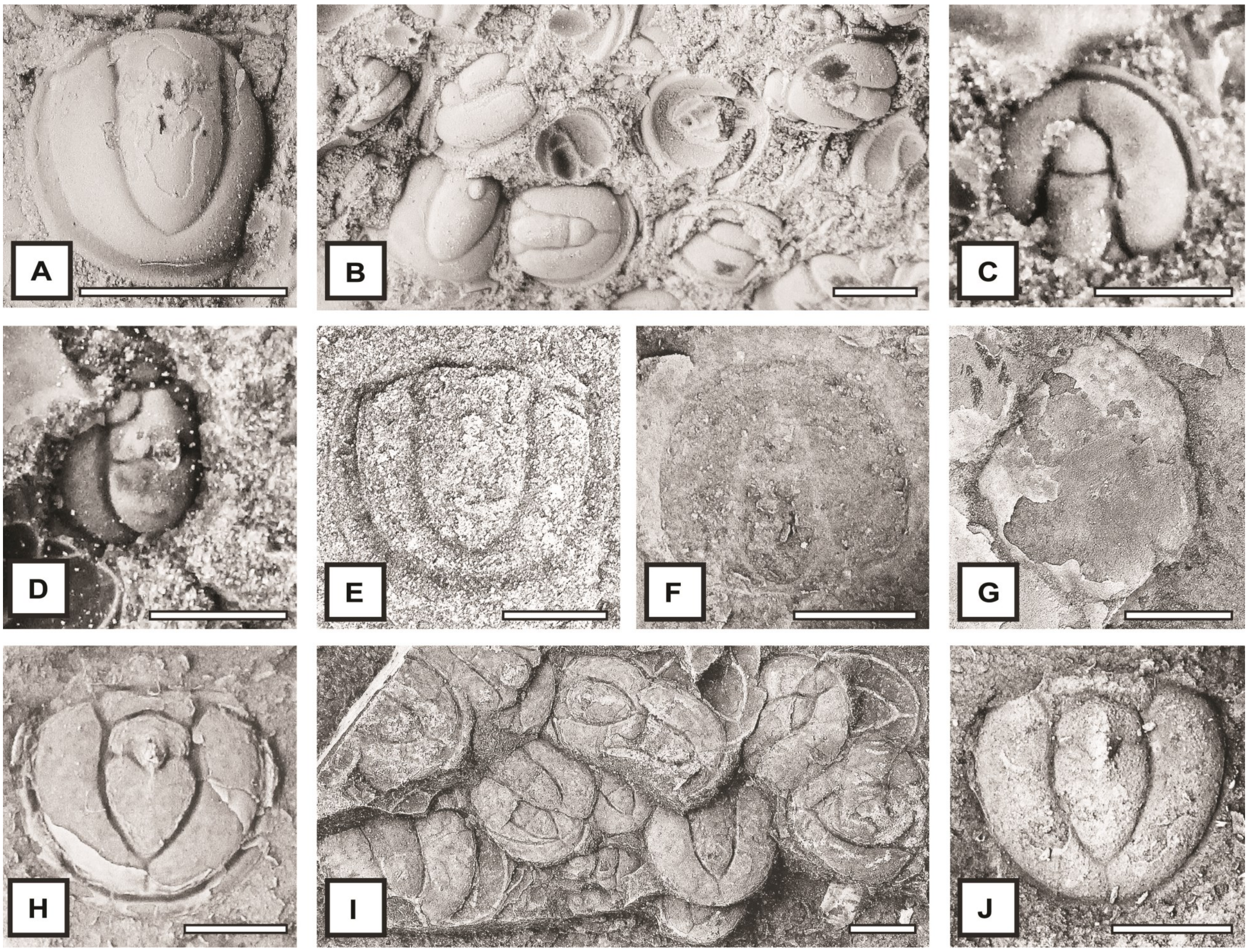


Fig. 10. Agnostoids from the Tomten-1 drill core. Scale bars correspond to 2 mm. **A–B.** *Agnostus pisiformis* (Wahlenberg, 1818) from the *A. pisiformis* Zone. **A.** Pygidium (11.92 m). **B.** Mass occurrence (11.62 m). **C–D.** *Agnostus* (*Homagnostus*) *obesus* (Belt, 1867) from the *O. gibbosus* Zone. **C.** Cephalon (11.14 m). **D.** Pygidium (11.14 m). **E.** *Peronopsis* cf. *insignis* (Wallerius, 1895), pygidium from the *L. laevigata* Zone (12.90 m). **F.** *Peronopsis* sp., cephalon from the *L. laevigata* Zone (13.02 m). **G.** *Lejopyge* sp., cephalon from the *L. laevigata* Zone (15.31 m). **H–I.** *Ptychagnostus atavus* (Tullberg, 1880) from the *P. atavus* Zone. **H.** Pygidium (23.67 m). **I.** Mass occurrence (24.04–24.01 m). **J.** *Ptychagnostus* cf. *atavus*, pygidium from the *P. atavus* Zone (24.09 m).

(1987) described exceptionally well preserved (phosphatized) specimens from the 'Orsten' type fauna of Västergötland.

Occurrence. – *Agnostus pisiformis* occurs throughout the *A. pisiformis* Zone in the Tomten-1 drill core. In the uppermost sampled level of the zone the index fossil is associated with a brachiopod and an indeterminate polymerid trilobite.

Agnostus (*Homagnostus*) *obesus* (Belt, 1867)

Figs. 10C–D

Material. – 12 cephala and 3 pygidia.

Remarks. – The specimens are rather well preserved. Westergård (1922, p. 116, pl. 1, fig. 4) described it as a subspecies of *A. pisiformis*. It has been described also by Westergård (1947, pp. 3–4, pl. 1, figs. 10–11) and Ahlberg & Ahlgren (1996, p. 131, figs. 3A–F). It ranges throughout the five lower zones of the *Olenus* Superzone and is used for intra- and interregional correlations (Ahlberg & Terfelt 2012).

Occurrence. – It appears in the lower part of the *O. gibbosus* Zone in the Tomten-1 drill core.
Associated fossils are *Olenus* sp., *O. gibbosus* and an indeterminate polymerid trilobite. It occurs throughout Scandinavia (Ahlberg & Ahlgren 1996).

Family Peronopsidae Westergård, 1936
Genus Peronopsis Hawle & Corda, 1847

Peronopsis cf. *insignis* (Wallerius, 1895)

Fig. 10E

Material. – One cephalon and nine pygidia.

Remarks. – The specimens at hand most closely resemble *P. insignis*, as described by Westergård (1946, p. 43, figs. 10–15). The specimens in the Tomten-1 drill core have vestigial marginal spines.

Occurrence. – *P.* cf. *insignis* occur in the upper part of the *L. laevigata* Zone in the Tomten-1 drill core. No associated species are present. *P. insignis* occurs throughout Västergötland (Westergård 1946) and has also been reported from the Oslo Region of Norway

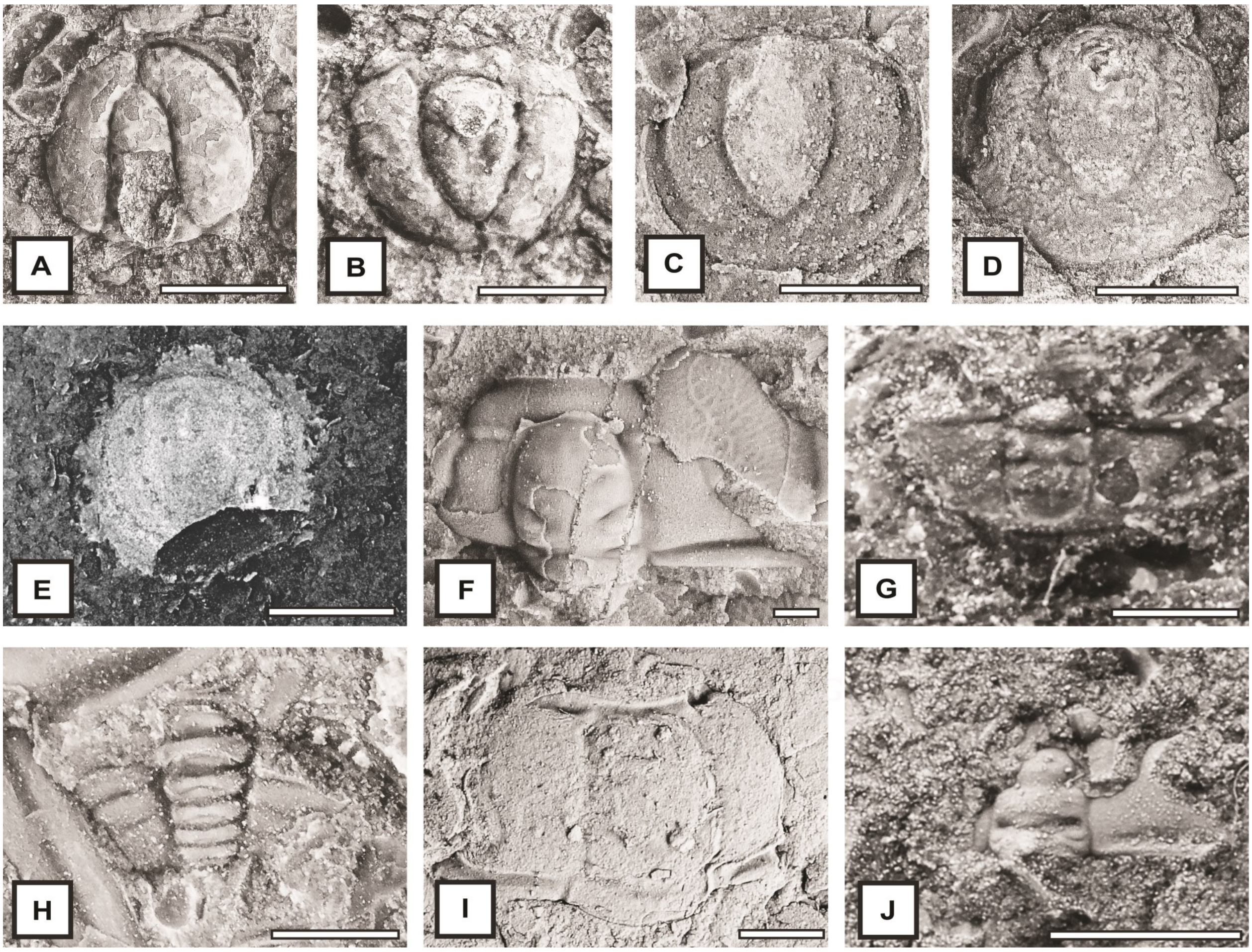


Fig. 11. Agnostoids and trilobites from the Tomten-1 drill core. Scale bars correspond to 2 mm. **A–B.** *Ptychagnostus gibbus* (Linnarsson, 1869) from the *P. gibbus* Zone. **A.** Cephalon (24.20 m). **B.** Pygidium (24.20 m). **C.** *Ptychagnostus* sp., pygidium from the *P. atavus* Zone (19.42 m). **D.** *Ptychagnostus*? sp., pygidium from the *P. atavus* Zone (21.42 m). **E.** Indeterminate agnostoid, pygidium from the *P. atavus* Zone (21.59 m). **F-G.** *Olenus gibbosus* (Wahlenberg, 1818), *O. gibbosus* Zone. **F.** pygidium (11.14 m). **G.** Juvenile pygidium (11.14 m). **H.** *Olenus* sp., pygidium. *O. gibbosus* Zone (11.14 m). **I.** *Ctenopyge linnarssoni* (Westergård, 1922), cephalon from the *C. linnarssoni* Zone (5.78 m). **J.** *Ctenopyge pecten* (Salter, 1864), cephalon from the *C. linnarssoni* Zone (2.42 m).

(Høyberget & Bruton (2008).

Peronopsis sp.

Fig. 10F

Material. – Two cephala and 33 pygidia.

Remarks. – The specimens are not well preserved, but resemble species of *Peronopsis* (e.g. Westergård 1946, pl. 3).

Occurrence. – *Peronopsis* sp. occurs in the upper part of the *L. laevigata* Zone in the Tomten-1 drill core. No associated species occur together with *Peronopsis* sp..

Family Ptychagnostidae Kobayashi, 1939
Genus *Lejopyge* Hawle & Corda, 1847

Lejopyge sp.

Fig. 10G

Material. – Ten cephala.

Remarks. – The specimens from the Tomten-1 drill core are poorly preserved and therefore left in open nomenclature. They have the characteristics of *Lejopyge,* as the cephala are effaced but have a well-developed posteroglabella (e.g. Westergård 1946, pl. 13; Robison 1984, p. 42).

Occurrence. – *Lejopyge* sp. occurs in the lower half of the *L. laevigata* Zone of the Tomten-1 drill core. Associated species are a brachiopod and an indeterminable polymerid trilobite.

Genus *Ptychagnostus* Jaekel, 1909

Ptychagnostus atavus (Tullberg, 1880)

Figs. 10H–I

Material. – Hundreds of specimens.

Remarks. – *P. atavus* has been described by Westergård (1946, pp. 76–77, pl. 11, figs. 8–23), Robison (1984, pp. 18–21, fig. 11) and Peng & Robison (2000, pp. 69–70, fig. 52). It was most recently described and discussed by Ahlberg et al. (2007) and Hong & Choi (2015). *P. atavus* is an important agnostoid for global correlations and its first appearance datum (FAD) defines the base of the Drumian Stage of Cambrian Series 3 (Babcock et al. 2005, 2007).

Occurrence. – *P. atavus* occurs throughout the lower half of the *P. atavus* Zone in the Tomten-1 drill core. It occurs sporadically as well as in abundance in the drill core. In the upper half of the zone it is absent, except at one level (19.45 m). The associated fauna in the Tomten-1 drill core consists of *Paradoxides*? sp., *Paradoxides* sp. and indeterminate brachiopods.
Ptychagnostus atavus can be recognized globally and has been reported from Australia, Vietnam, China, Korea, Russia, Kazakhstan, Sweden, Denmark, Norway, the United Kingdom, Greenland, Canada and the Unites States (Robison 1984; Geyer & Shergold 2000; Babcock et al. 2007).

Ptychagnostus cf. *atavus* (Tullberg, 1880)

Fig. 10J

Material. – One pygidium.

Remarks. – The specimen strongly resembles the pygidium of *P. atavus* (e.g. Westergård 1946, pl. 11), although the axial node is not well preserved. The anterior furrows of the axis are not as distinguishable as in *P. atavus*, and the specimen is left in open nomenclature.

Occurrence. – *P.* cf. *atavus* occurs in the lowest part of the *P. atavus* Zone. The *P. gibbus*/*P. atavus* boundary possibly occur 1 cm up in the succession with the appearance of *P. atavus*. It is associated with *Paradoxides*? sp. in the Tomten-1 drill core.

Ptychagnostus gibbus (Linnarsson, 1869)

Figs. 11A–B

Material. – 25 cephala and 16 pygidia.

Remarks. – The species is distinctive and characterized by several prominent spines (Westergård, 1946). In the Tomten-1 drill core only one cephalon exhibits a distinct cephalic spine, whereas the other specimens strongly resemble the appearance of *P. gibbus*. In several pygidia the axial spine appears to be broken off. It has been described by, e.g., Westergård (1946, pp. 70–71, pl. 9, figs. 17–24), Robison (1984, pp. 22–24, fig. 13) and Høyberget & Bruton (2008, pp. 51–53, pl. 8, figs N–S).

Occurrence. – *P. gibbus* occurs throughout its name bearing zone and it is the index fossil of the lowermost zone of the Alum Shale Formation in the Tomten-1 core. It is also the lowermost zone of the *P. paradoxissimus* Superzone. It is a common and geographically widespread species that has been reported from several palaeocontinents (e.g., Westergård 1946; Robison 1984; Høyberget & Bruton (2008).

Ptychagnostus sp.

Fig. 11C

Material. – Three pygidia.

Remarks. – The specimens are not well preserved but have the characteristics of *Ptychagnostus*, although species identification is difficult (e.g. Westergård 1946, pl. 9–12).

Occurrence. – Indeterminate species of *Ptychagnostus* occur in the lower–middle half of the *P. atavus* Zone in the Tomten-1 drill core. Associated fossil is a specimen of *Paradoxides*? sp.

Ptychagnostus? sp.

Fig. 11D

Material. – Five pygidia.

Remarks. – The specimens have the pygidial characteristics of *Ptychagnostus* (e.g. Westergård 1946, pl. 9–12), although they are not well preserved.

Occurrence. – It occurs in the middle of the *P. atavus* Zone in the Tomten-1 drill core. No associated fossils occur with *Ptychagnostus*? sp.

Indeterminate agnostoid

Fig. 11E

Material. – Seven pygidia.

Remarks. – The specimens are poorly preserved, although most likely representing agnostoids.

Occurrence. – Indeterminate agnostoids occur in the *P. atavus* and *L. laevigata* zones in the Tomten-1 drill core. Associated fossils are specimens of *Peronopsis* sp.

Class Trilobita Walch, 1771
Order Ptychopariida Swinnerton, 1945
Family Olenidae Burmeister, 1843
Genus *Olenus* Dalman, 1827

Olenus gibbosus (Wahlenberg, 1818)

Figs. 11F–G

Material. – Eight cranidia.

Remarks. – *O. gibbosus* was described in detail by Westergård (1922, pp. 124–125, pl. 5, figs. 1–10) and Henningsmoen (1957, pp. 105–106, pl. 9, fig. 7). Adult as well as juvenile specimens occur in the drill core.

Occurrence. – It occurs throughout the lower part of the *O. gibbosus* Zone in the Tomten-1 drill core. Associated species are *A.* (*Homagnostus*) *obesus* and *Olenus* sp. *O. gibbosus* occurs throughout Scandinavia and in the United Kingdom (Westergård 1922; Henningsmoen 1957; Terfelt et al. 2008).

Olenus sp.

Fig. 11H

Material. – Two cranidia and one pygidium.

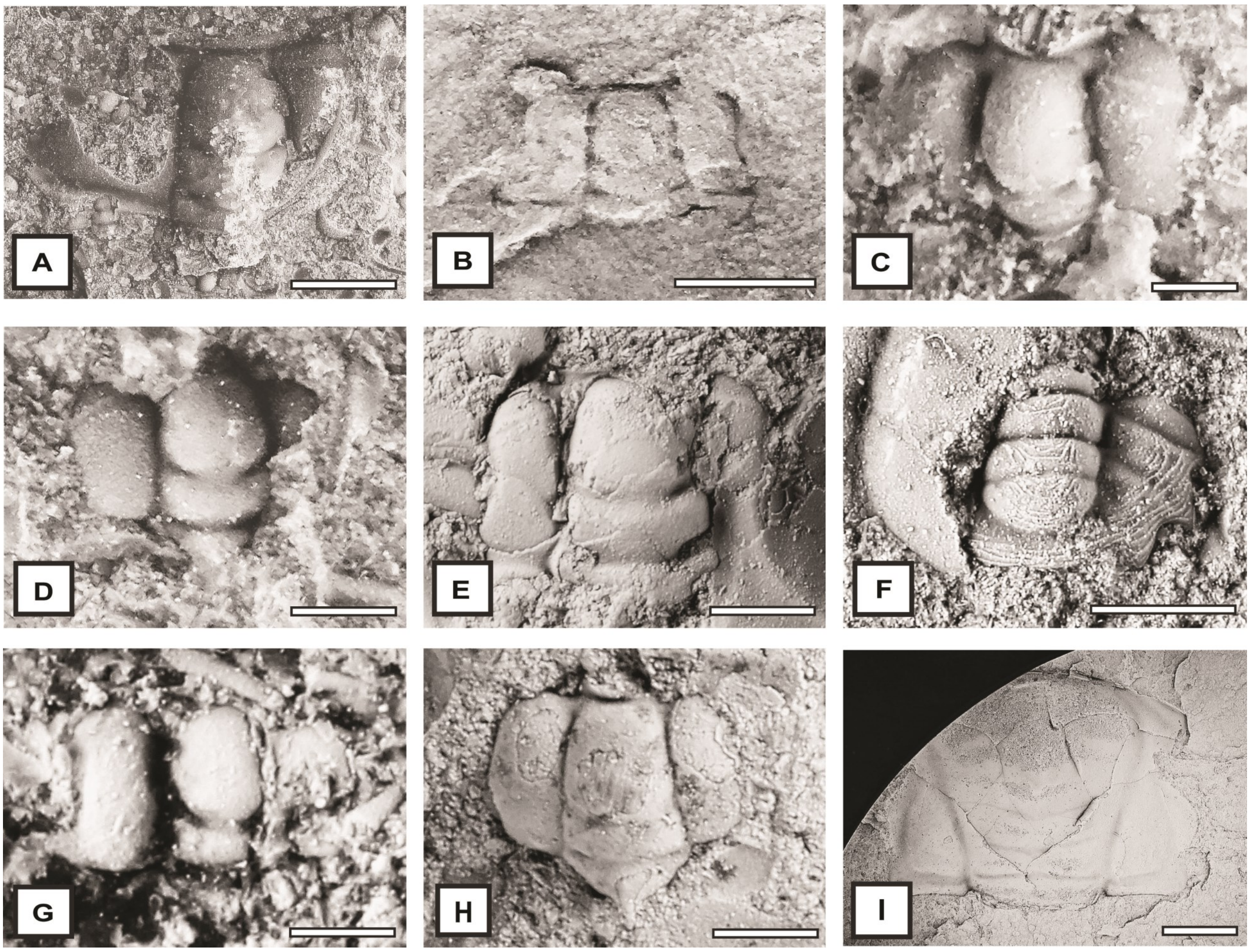


Fig. 12. Trilobites from the Tomten-1 drill core. Scale bars correspond to 2 mm. **A.** *Ctenopyge tumida* (Westergård, 1922), cephalon from the *C. tumida* Zone (8.54 m). **B.** *Ctenopyge* sp., cephalon from the *C. linnarssoni* Zone (5.35 m). **C.** *Sphaerophthalmus alatus* (Boeck, 1838), cranidia. *C. tumida* Zone (8.50 m). **D.** *Sphaerophthalmus* sp., cranidium from the *C. tumida* Zone (8.54 m). **E.** *Parabolinites* cf. *laticaudus* (Westergård, 1922), cranidium from the *C. tumida* Zone (8.94 m). **F.** *Peltura scarabaeoides scarabaeoides* (Wahlenberg, 1818), pygidium from the *C. linnarssoni* Zone (2.42 m). **G.** *Peltura*? sp., cranidium from the *C. tumida* Zone (8.80 m). **H.** *Triangulopyge humilis* (Philips, 1848), cephala from the *C. linnarssoni* Zone (2.42 m). **I.** *Paradoxides* sp., cephalon from the *P. atavus* Zone (19.32 m).

Remarks. – The specimens resemble an *Olenus* species (e.g. Westergård 1922, pl. 3–6), although they are difficult to identify to species level because of their poor state of preservation.

Occurrence. – The species is present in the *O. gibbosus* Zone in the Tomten-1 drill core. Associated species are *A.* (*Homagnostus*) *obesus* and *O. gibbosus*.

Genus *Ctenopyge* Linnarsson, 1880

Ctenopyge linnarssoni (Westergård, 1922)

Fig. 11I

Material. – Two cranidia.

Remarks. – *Ctenopyge linnarssoni* was described in detail by Westergård (1922, pp. 162–163, pl. 13, figs. 3–5) and Henningmoen (1957, p. 207, pl. 22, fig. 8).

Occurrence. – *C. linnarssoni* appears in the lowest part of the *C. linnarssoni* Zone in the Tomten-1 drill core. It co-occurs with *Peltura* sp.

Ctenopyge pecten (Salter, 1864)

Fig. 11J

Material. – One cephalon.

Remarks. – *Ctenopyge pecten* was described by Westergård (1922, pp. 160–161, pl. 12, figs 26–33, pl. 13, fig. 1).

Occurrence. – It occurs in the upper part of the *C. linnarssoni* Zone in the Tomten-1 drill core. Associated species are *P. s. scarabaeoides* and *T. humilis*. It is distributed throughout Sweden, the United Kingdom and Canada (Westergård 1922).

Ctenopyge tumida (Westergård, 1922)

Fig. 12A

Material. – 2 cephala.

Remarks. – *Ctenopyge tumida* was described by Westergård (1922, pp. 155–156, pl. 11, figs. 15–20) and Henningsmoen (1957, pp. 198–199, pl. 20, fig. 16). Høyberget & Bruton (2012) broadened the *C.*

tumida Zone concept, as *C. tumida* is also present in the formerly recognized *C. affinis* Zone.

Occurrence. – *C. tumida* occurs in the middle part of the *C. tumida* Zone in the Tomten-1 drill core. It is associated with *Sphaerophthalmus alatus*, *Sphaerophthalmus* sp. and *Peltura*? sp. The species has been reported from Norway, Sweden, Denmark, Great Britain and Poland (Høyberget & Bruton 2012).

Ctenopyge sp.

Fig. 12B

Material. – Six cephala.

Remarks. – The specimens are difficult to identify to species level (cf. Westergård 1922, pl. 10–12) since they are poorly preserved.

Occurrence. – It occurs throughout the *C. bisculata* and *C. linnarssoni* zones. Associated fossils are *P. s. scarabaeoides* and *Peltura* sp.

Genus *Sphaerophthalmus* Angelin, 1854

Sphaerophthalmus alatus (Boeck, 1838)

Fig. 12C

Material. – Three cranidia.

Remarks. – One variant was inaccurately described by Westergård (1922, pp. 163–165, pl. 13, figs. 9–18) as *S. alatus*. It was later revised and characterized by Henningsmoen (1957, pp. 212–215, pl. 22, fig. 8), and is presently identified as *T. humilis*. *S. alatus* was recently discussed also by Høyberget & Bruton (2012).

Occurrence. – *S. alatus* occur in the *C. tumida* Zone in the Tomten-1 drill core. It is associated with *Parabolinites* cf. *laticaudus*, *Peltura*? sp. and *C. tumida*.

Sphaerophthalmus sp.

Fig. 12D

Material. – One cranidium.

Remarks. – The cranidium resembles those of *Sphaerophthalmus* species (e.g. Westergård 1922, pl. 13), although it is difficult to identify to species level.

Occurrence. – It occurs in the *C. tumida* Zone in the Tomten-1 drill core, and is associated with *C. tumida*.

Genus *Parabolinites* Henningsmoen 1957

Parabolinites cf. *laticaudus* (Westergård, 1922)

Fig. 12E

Material. – One pygidium.

Remarks. – The specimen strongly resembles the pygidium of *Parabolinites* cf. *laticaudus* (e.g. Westergård 1922, pl. 8, figs. 1–7; Henningsmoen 1957, pl. 1, fig. 9, pl. 6). Westergård (1922) assigned the species to *Parabolinella*. Henningsmoen (1957) assigned it to the new genus *Parabolinites*. The preservation is not sufficient and the specimen is left in open nomenclature.

Occurrence. – *P* .cf. *laticaudus* occurs in the lower *C. tumida* Zone. It is associated with *S. alatus* in the Tomten-1 drill core.

Genus *Peltura* Milne Edwards, 1840

Peltura scarabaeoides scarabaeoides (Wahlenberg, 1818)

Fig. 12F

Material. – Numerous pygidia and fragments.

Remarks. – The species was described by Westergård (1922, pp. 173–174, pl. 15) and Henningsmoen (1957, pp. 237–239, pl. 26, figs. 1–2). A study of the ontogeny of the species was done by Whittington (1957).
The spines of the pygidium are indicative of the two subspecies of *P. scarabaeoides* (see Henningsmoen 1957 for further discussion). Additional indication of *P. s. scarabaeoides* affinity of the specimens in the Tomten-1 drill core is the co-occurring fossils. *P. s. westergaardi* occurs only in the upper *P. lobata* Zone (Terfelt et al. 2011), which is not present in the Tomten-1 drill core.

Occurrence. – *P. s. scarabaeoides* occurs in the *C. bisculata* and *C. linnarssoni* zones in the Tomten-1 drill core. It co-occurs with *Ctenopyge* sp., *C. linnarssoni*, *T. humilis* and *C. pecten*.

Peltura? sp.

Fig. 12G

Material. – Two pygidia.

Remarks. – Due to the state of preservation these pygidia could not be identified to species level (e.g. Westergård 1922, pl. 15). Also the generic affinity is uncertain.

Occurrence. – *Peltura*? sp. occurs in the *C. tumida* Zone in the Tomten-1 drill core. Associated species are *S. alatus* and *C. tumida*.

Genus *Triangulopyge* Høyberget & Bruton, 2012

Triangulopyge humilis (Phillips, 1848)

Fig. 12H

Material. – Two pygidia.

Remarks. – This species have been revised several times. Westergård (1922, pp. 215–217, pl. 22, figs. 7, 11–15) described it as *Sphaerophthalmus alatus*, and Henningsmoen (1957) separated the species into *S. alatus* and *S. humilis*. Høyberget & Bruton (2012) assigned the species within their new genus *Triangulopyge*. The specimens at hand lack a well preserved spine at the posterior margin.

Occurrence. – *T. humilis* occurs in the upper part of the *C. linnarssoni* Zone in the Tomten-1 drill core and

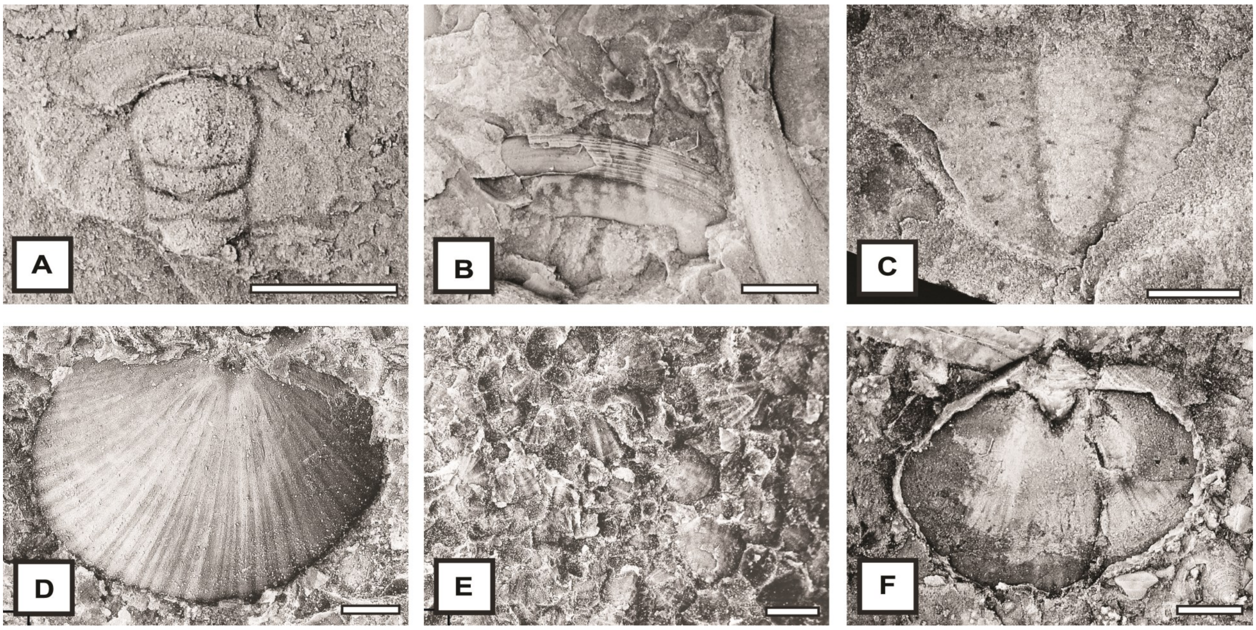


Fig. 13. Trilobites and brachiopods from the Tomten-1 drill core. Scale bars correspond to 2 mm. **A-B.** *Paradoxides*? sp. from the *P. atavus* Zone. **A.** Cranidium (23.07 m). **B.** Fragmented segments (23.86 m). **C.** Indeterminate polymerid trilobite, pygidium from the *L. laevigata* Zone (15.31 m). **D–E.** *Orusia lenticularis* (Wahlenberg, 1818), from the *P. spinulosa* Zone. **D.** large fine ornamented specimen (10.60 m). **E.** Abundant small specimens (10.53–10.58 m). **F.** Brachiopod from the *L. laevigata* Zone (16.64 m).

is associated with *P. s. scarabaeoides* and *C. pecten*.

Order Redlichiida Richter, 1932
Family Paradoxididae Hawle & Corda, 1847
Genus *Paradoxides* Brongniart, 1822

Paradoxides sp.

Fig. 12I

Material. – One cranidium.

Remarks. – The specimen at hand resembles cranidia of *Paradoxides*, but the poor preservation makes it difficult to assign to a certain species (see e.g. Westergård, 1953, pl. 8).

Occurrence. – In the Tomten-1 drill core, *Paradoxides* sp. occurs in the lowermost *P. atavus* Zone and co-occurs with *P. atavus*.

Paradoxides? sp.

Figs. 13A–B

Material. – Ten cranidia and abundant thoracic tergites.

Remarks. – The material is often highly fragmented, although the cranidia and especially the thoracic tergites appear to belong to *Paradoxides* (e.g. Westergård 1953, pl. 8).

Occurrence. – *Paradoxides*? sp. occurs throughout the lower half of the *P. atavus* Zone and is missing in the upper half of the Tomten-1 drill core. The associated fauna in the Tomten-1 drill core consists of *P. gibbus*, *P. atavus*, *P.* cf. *atavus*, *Paradoxides* sp., *Ptychagnostus* sp., *Paradoxides* sp., and indeterminate brachiopods.

Indeterminate polymerid trilobite

Fig. 13C

Material. – Three pygidia.

Remarks. – The material is poorly preserved and hence identification is difficult.

Occurrence. – Indeterminate polymerid trilobites occur in the *P. gibbus*, *L. laevigata* and *O. gibbus* zones of the Tomten-1 drill core.

Class Rhynchonellata Williams, Carlson, Brunton, Holmer & Popov, 1996
Order Orthida Schuchert & Cooper, 1932
Family Finkelnburgiidae Schuchert & Cooper, 1931
Genus *Orusia* Walcott, 1905

Orusia lenticularis (Wahlenberg, 1818)

Figs. 13D–E

Material. – Hundreds of specimens.

Remarks. – This orthid brachiopod is generally associated with the trilobite *P. spinulosa*. It also occurs in the lower *P. brevispina* Zone and in the lower part of the upper *Leptoplastus* Superzone (Terfelt et al. 2008; Nielsen et al. 2014). The species generally occurs in abundance in Västergötland (Terfelt 2000). Both the size and the ornamentation vary among the specimens recorded in the drill core.

Occurrence. – In the Tomten-1 drill core *O. lenticularis* is not associated with any other fossil. The *O.*

lenticularis is here assigned to the *P. spinulosa* Zone.

Indeterminate linguliformean brachiopods

Fig. 13F

Material. – Hundreds of specimens.

Remarks. – Except for *Orusia*, all brachiopods recorded from the Tomten-1 drill core are phosphatic-shelled linguliformeans, most likely representing lingulates.

Occurrence. – In the Tomten-1 drill core indeterminate brachiopods occur in the *P. gibbus*, *P. atavus*, *L. laevigata*, *A. pisiformis*, and *O. gibbosus* zones. In addition, brachiopods have been recorded from an unspecified interval between the *O. gibbosus* and *P. spinulosa* zones. In the lower *P. atavus* Zone, the brachiopods are associated with *Paradoxides*? sp..

7 Biostratigraphical remarks

The Alum Shale Formation of Västergötland, Sweden, is characterized by black shales and intercalated limestones. There are several stratigraphical breaks of various magnitudes within the succession and some biozones are missing. With the exception of the absence of most of the lowermost superzone (the *Acadoparadoxides oelandicus* Superzone), the Cambrian Series 3 succession is fairly complete as compared to the Furongian sequence which has more disturbed sediments and more hiatuses (Figs. 14–16). This is reflected also in the Tomten-1 drill core succession (Figs. 14–16).

The lowermost 1.5 m of the Cambrian Series 3 in the drill core is, except for brachiopods, unfossiliferous. The appearance of *Ptychagnostus gibbus* occurs at 24.20 m, and the FAD of *Ptychagnostus atavus* at 24.09. Westergård (1946) stated that the Exsulans Limestone Bed belongs to the *P. gibbus* Zone. The *P. gibbus* Zone probably continues downwards throughout the unfossiliferous strata in the drill core, ending with an unconformity at the boundary between the Alum Shale Formation and the Borgholm Formation in Västergötland (cf. Martinsson 1974; Nielsen & Schovsbo 2007). The lowest zone of the Cambrian Series 3, the *Eccaparadoxides insularis* Zone, is not present in Västergötland (Nielsen & Schovsbo 2007).

Ptychagnostus atavus is last recorded at 19.45 m in the drill core, closely coinciding with the LAD of *Paradoxides*? sp. and *Ptychagnostus* sp. The fossil content is sparse until 19.32 m with only one unidentified brachiopod recorded. The upper boundary of the *P. atavus* Zone is difficult to pinpoint as the index fossil is not present higher up in the biozone. However, the boundary can tentatively be placed on the top of the distinct unsampled 'Hypagnostus limestone bank' (located at 17.42–17.26 m). Weidner et al. (2004), who sampled a conglomeratic limestone between the 'Hypagnostus limestone bank' and the upper Exporrecta Conglomerate in Västergötland described the presence of fossils of the *P. punctuosus* and *G. nathorsti* zones.

The boundary of the *G. nathorsti/L. laevigata* zones is placed at a transition from limestone to Alum Shale (Weidner et al. 2004). The index fossil of the latter zone is not present although a specimen of *Lejopyge* was recorded at 15.31 m. The boundary of the *L. laevigata*/*A. pisiformis* zones is marked by the appearance of *Agnostus pisiformis* (see Ahlberg & Ahlgren 1996; Ahlberg & Terfelt 2012), which occurs in abundance. The Cambrian Series 3 and the *A. pisiformis* Zone extends upwards to 11.56 m.

The base of the Furongian Series coincides with the FAD of *Glyptagnostus reticulatus* (see Peng et al. 2004; Ahlberg & Terfelt 2012; Nielsen et al. 2014), which is not found in the drill core. However, *Olenus gibbosus* occurring at 11.55–11.14 m is indicative of the *O. gibbosus* Zone, which forms the basal polymerid zone in the Furongian of Scandinavia (Terfelt et al. 2008). Also *Agnostus (Homagnostus) obesus* appears at the same level as *O. gibbosus*, and ranges between 11.55 and 10.71 m in the drill core. The upper boundary of the *O. gibbosus* Zone is placed at 11.14 m. The LAD of *A. (Homagnostus) obesus* is generally indicative of the lower part of the *P. brevispina* Zone (Ahlberg & Ahlgren 1996). However establishing a lower boundary of the *P. brevispina* Zone is problematic since *A. (Homagnostus) obesus* might occur higher up in the drill core.

Westergård (1922) estimated the thickness of the *Olenus* Superzone to be 0.2 m in the Tomten quarry, whereas the upper *Parabolina* Superzone was estimated to be 0.6 m thick. The 0.95 m thickness of the *Olenus* Superzone in the Tomten-1 drill core is in clear contrast to the estimations of Westergård (1922). The discrepancy can be due to findings of fossils of the *Parabolina* Superzone in cave structures of the Kakeled Limestone Bed. Westergård (1922) only reported the *Olenus gibbosus* of the Tomten quarry, coherent with the findings of the Tomten-1 drill core.

The presence of *Orusia lenticularis* (10.60–10.29 m) is an indication for the *Parabolina* Superzone, although it can occur also in the lowest part of the overlying superzone (Terfelt et al. 2008; Nielsen et al. 2014). It is therefore difficult to establish the upper and lower boundary of the *Parabolina* Superzone (and obviously also the *P. brevispina*/*P. spinulosa?* zones of this superzone). *Orusia lenticularis* is most often associated with the trilobite *Parabolina spinulosa* (Westergård 1922; Terfelt 2000), and here the presence of *O. lenticularis* is taken as indicative of the *P. spinulosa* Zone.

The Furongian in the Tomten-1 drill core includes numerous biozones. However, biozones identified in the Furongian succession of the core may not be representative for the succession. Westergård (1922, pp. 70–71) identified several trilobites from the *Leptoplastus* Superzone in limestone concretions. As the drilling appears not to have penetrated some of these limestone concretions, a biased (i.e. incomplete) scheme of the biozones occurring in the successions of the Tomten quarry might occur.

Following the *Parabolina* Superzone there is a

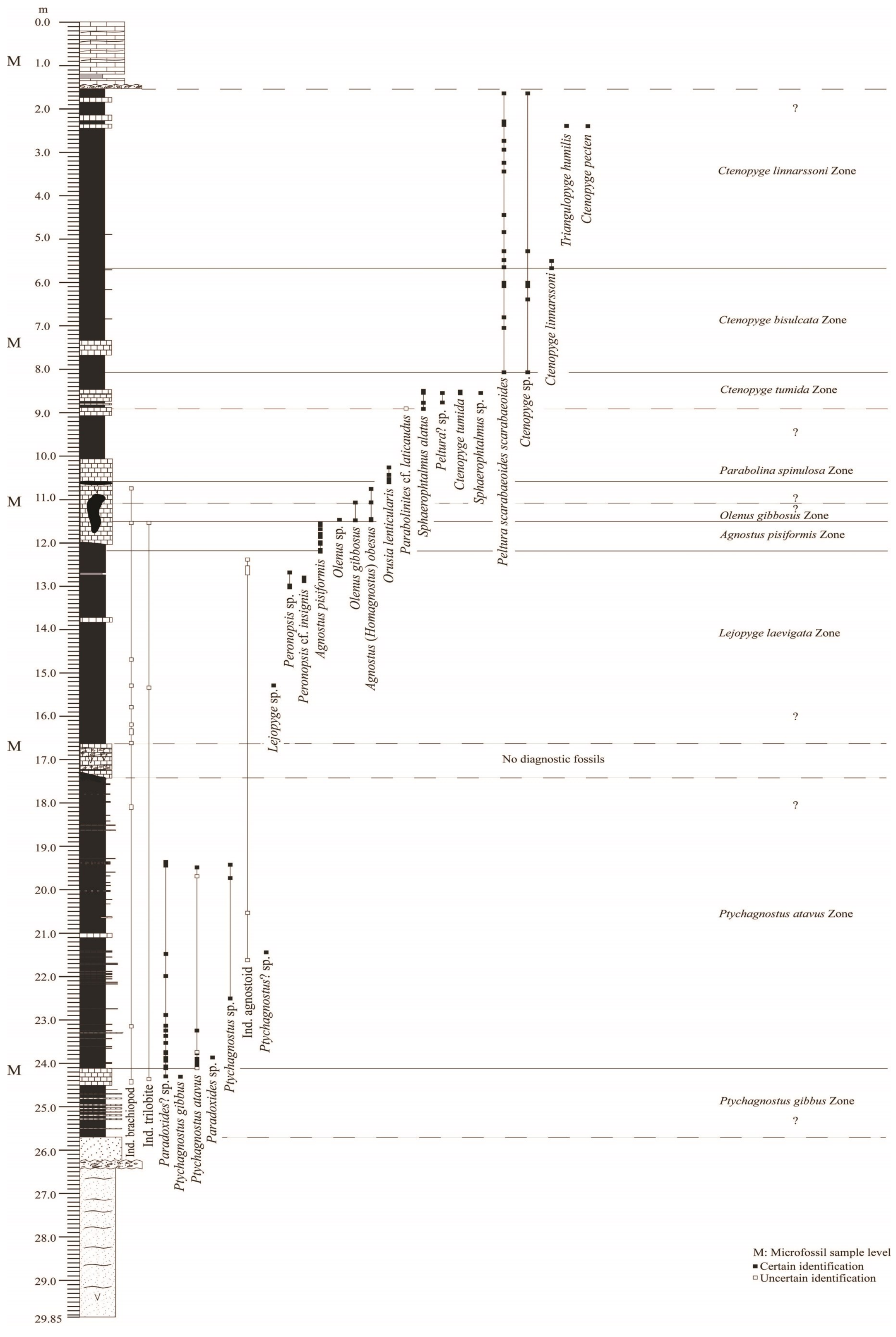


Fig. 14. Biostratigraphy, ranges of fossils and microfossil sample levels of the Alum Shale Formation of the Tomten-1 drill core, Torbjörntorp, Västergötland, Sweden.

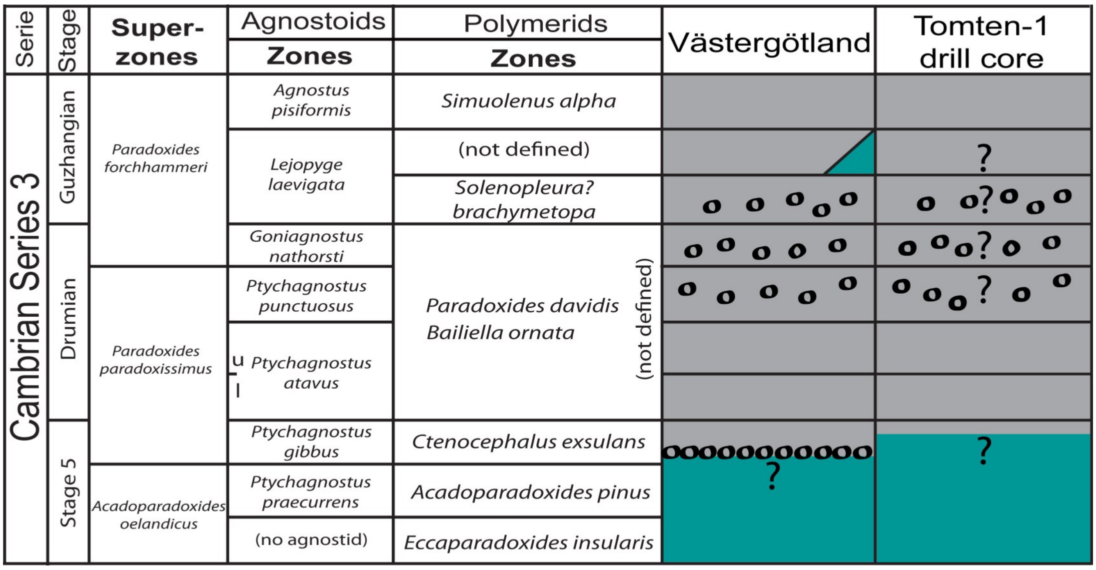


Fig. 15. Cambrian Series 3 succession (west-east) of Västergötland, Sweden with the Tomten-1 drill core as comparison. Note that the Tomten-1 drill core was retrieved from the Billingen-Falbygden area. Green colour marks hiatuses. Based on Westergård (1946), Martinsson (1974), Weidner et al. (2004) and Nielsen et al. (2014).

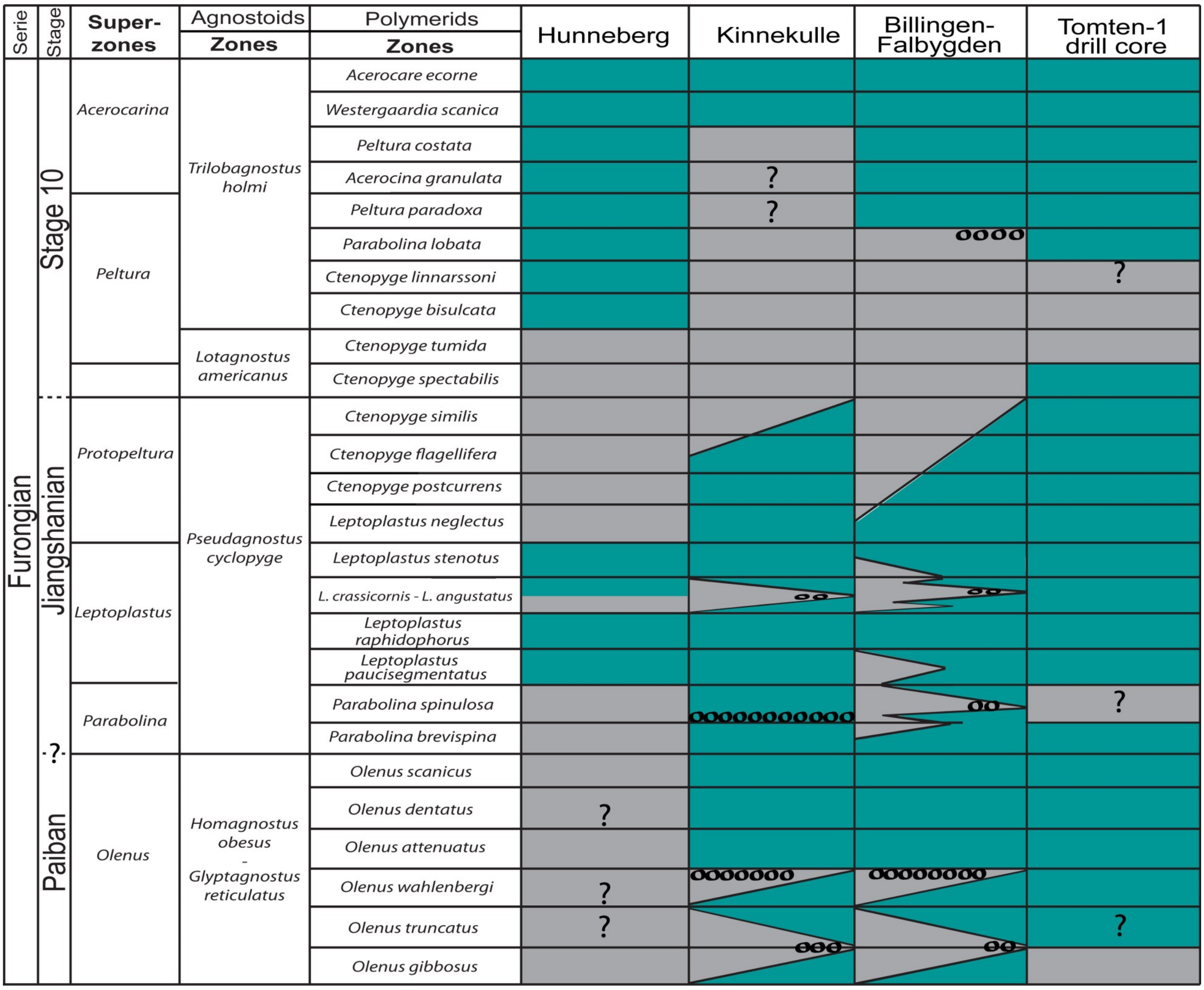


Fig. 16. Furongian succession (west-east) of Västergötland, Sweden with the Tomten-1 drill core as comparison. Note that the Tomten-1 drill core is retrieved from the Billingen-Falbygden area. Green colour marks hiatuses. Based on Westergård (1947), Martinsson (1974), Terfelt et al. (2008), Weidner & Nielsen (2011, 2013) and Nielsen et al. (2014).

considerable hiatus and the *Leptoplastus* and *Protopleura* superzones are missing. Correlating the δC^{13}-curve with corresponding curve from the Duibian section, China (Peng et al. 2012b), suggests that the *C. spectabilis* Zone could be present in the drill core. This would be in concert with findings in the Billingen-Falbygden area (see figure 15). However, the resolution of the δC^{13}-curve of the Tomten-1 drill core is insufficient to clearly say this is correct.

The first occurrence of *Sphaerophthalmus alatus* (at 8.80 m) is indicative of the base of the *Ctenopyge tumida* Zone (Terfelt et al. 2008), and the presence of *C. tumida* at 8.54 m, further establishes this biozone. The first appearance of *Peltura scarabaeoides scarabaeoides* at 8.11 m is indicative of the base of the *C. bisculata* Zone. Although the index fossil is not found in the Tomten-1 drill core, the upper boundary of the zone can be established with the occurrence of *Ctenopyge linnarssoni* at 5.78 m. *Ctenopyge linnarssoni* is indicative of the *C. linnarssoni* Zone and it is only present in the lowest part of the zone. However, *Peltura scarabaeoides scarabaeoides* ranges to the highest sampled level (1.70 m) of the Furongian in the Tomten -1 drill core, suggesting that the uppermost part of the Furongian belongs to the *C. linnarssoni* Zone. The LAD of *Peltura scarabaeoides scarabaeoides* provides additional evidence for the top of the *C. linnarssoni* Zone (Terfelt et al. 2008). A prominent hiatus is present between the top of the *C. linnarssoni* Zone and strata assigned to the Bjørkåsholmen Formation.

8 Remarks on preservation and the associated fauna

The preservation of the fossil fauna in Västergötland is often excellent in the limestone and less good in the shale (cf. Terfelt 2003; Eriksson & Terfelt 2007). In addition to the frequently occurring agnostoids and polymerid trilobites, the Tomten-1 drill core also contains brachiopods, conodont elements, fossils of uncertain affinity and trace fossils.

In the drill core, the faunal diversity increases from the Cambrian Series 3 to the Furongian. This coincides with a radiation among polymerid trilobites globally (e.g. Peng 2012). However, the abundance of fossils appears to be lower in the Furongian, with the exception of *O. lenticularis* that commonly occurs in great numbers. In the Cambrian Series 3 agnostoids, in particular *P. gibbus*, *P. atavus* and *A. pisiformis*, appear to occur in abundance at several levels in the drill core.

Apparent minor vertical borings are occasionally recorded in the drill core (Fig. 17A) which is in concert with the results of Newby (2012) who identified frequent borings in the upper part of the Furongian. In the Cambrian Series 3 horizontal borings are recorded (Fig. 17B). Irregular fabric in the alum shale (Fig. 4C) indicating abundant bioturbation is also present. This evidence of biotic activity suggests that the sea floor was at times oxygenated and housed infaunal taxa.

The remains of *Paradoxides*? sp. in the Cambrian Series 3 are often fragmental in the drill core. No complete specimens were found. The thorax is broken up and abundant thoracic segments can be seen. However, several cranidia are also present in the drill core. At one level (23.43 m) three cranidia of *Paradoxides*? sp. occur (Fig. 17C).

Several levels in the Furongian limestones of the drill core yields preserved olenid eyes. The lenses of the olenid eyes are composed of calcite, which make them rather resistant to decay (Clarkson et al. 2006). Brachiopods (Fig. 17D) and agnostoids are occasionally very poorly preserved, perhaps indicating (partial) dissolution (cf. Eriksson & Terfelt, 2007). The Kvarntorp Member contains abundant shell fragments of indeterminable brachiopods (Fig. 17E). Fossils of uncertain affinity (Figs. 17F–G) also occur in the drill core.

The lowest microfossil sample (24.26–24.20 m) from the upper *P. gibbus* Zone yielded acid resistant skeletal remains indicative of a diverse lingulate brachiopod fauna. The shells have frequent microborings (Fig. 17H). Alongside brachiopods, remains of hyoliths are also present. The sampled limestone at 16.70 –16.65 m, above the Exporrecta Conglomerate, yielded highly fragmented brachiopod shells (Fig. 17I). The sample from the *O. gibbosus* Zone and the lowest centimeter of an indeterminate biozone (11.07–11.15 m) yielded numerous conodont elements, e.g. the characteristic paraconodont genus *Westergaardodina* (Fig. 17J). The sample from the *C. bisculata* Zone (7.52–7.59 m) was barren of microfossils. The uppermost sample of the Lanna Limestone (1.09–1.00 m) yielded abundant faunal remains, e.g. *Westergaardina* sp. and a crinoid fragment (Fig. 17K).

At least four prominent levels lack macrofossils in the drill core (19.33–18.10; 15.32–14.73; 10.30–8.81; 8.12–7.14 m). The lack of macrofossil findings in the interval 8.12–7.14 m coupled with no findings of microfossils in the acid treated sample from the 7.52–7.59 m interval, suggests a so called ‘barren interval’. However, secondary diagenetic effects as a cause for these cannot be ruled out (Eriksson & Terfelt 2007).

9 Remarks on the depositional environment

9.1 Cambrian Series 2

During late Precambrian times, weathering of the Proterozoic crystalline basement resulted in a virtually flat Baltic peneplain. In the early Cambrian, the rising sea level resulted in rapid flooding and deposition of silt and sandstones (Nielsen & Schovsbo 2011).

The Lingulid Sandstone, forming the basal part of the drill core is initiated with fine-grained planar laminated sandstone that was deposited in an offshore environment. In the uppermost part of the Lingulid Sandstone the lithology becomes coarser grained and reworked, indicating a regression (Nielsen & Schovsbo 2011).

The global Hawke Bay regression resulted in a

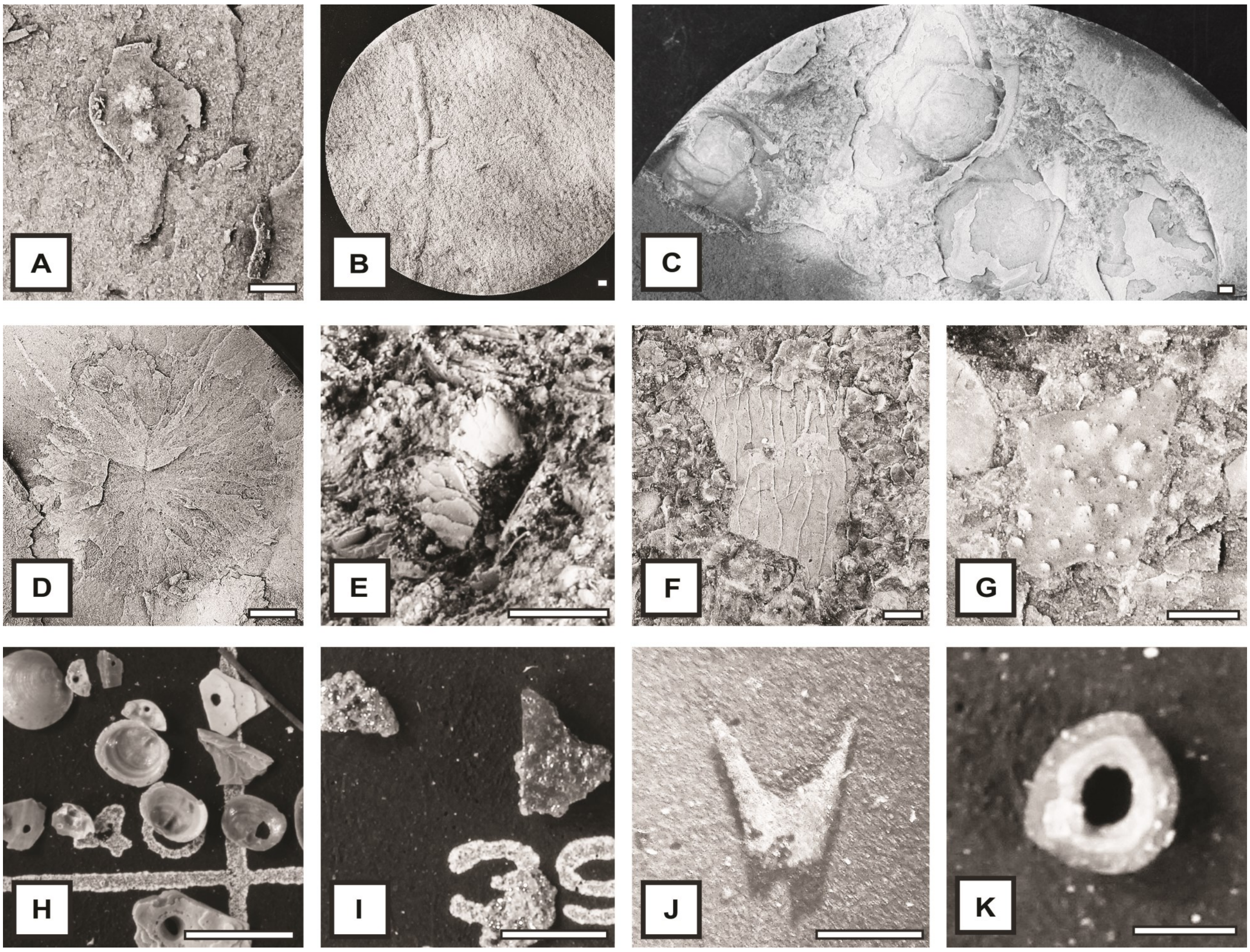


Fig. 17. Associated fauna of the Tomten-1 drill core. Scale bars correspond to 2 mm. **A.** Vertical boring (7.13 m). **B.** Horizontal boring (23.30 m) **C.** Cephala of *Paradoxides*? sp. (24.43 m). **D.** Poorly preserved indeterminate brachiopod (18.09 m). **E.** Indeterminate brachiopod of the Kvarntorp Member (26.30 m). **F.** Fossil of uncertain affinity (24.01 m). **G.** Fossil of uncertain affinity (16.64 m). **H.** Microboring of shells in the Exsulans Limestone Bed (24.26–24.20 m). **I.** Highly fragmented brachiopod shells (16.70–16.65 m). **J.** *Westergaardodina* (11.07–11.15 m). **K.** Crinoid fragment of the Lanna Limestone (1.09–1.00 m).

major sea level fall (Nielsen & Schovsbo 2007, 2015), which contributed to subaerial conditions, resulting in weathering and erosion of the Lingulid sandstone and the forming of the conglomerate marking the base of the Kvarntorp Member. The sedimentation rate of the overlying brachiopod-dominated glauconitic sandstone of the Kvarntorp Member was slow and occurred during a drowning event (Nielsen & Schovsbo 2015).

9.2 Cambrian Series 3

An unconformity in the basal part of the Alum Shale Formation marks a transgression with the deposition of shale and repeated regressions marked by deposition of glauconite. Thin section analyses indicate a steady increase of the fauna, suggesting a rising sea level trend. The basal part of the Exsulans Limestone Bed rests on an unconformity with subsequent cross bedding, and several sea level changes seem to have occurred as the limestone has fillings of alum shale. Throughout the limestone bed several facies shifts occur which indicate numerous sea level changes. In the top, weathering of a hanging wall and glauconite in a crack suggests a karst horizon, which indicates subaerial exposure. The fault occurring in the top suggests tectonic activity, perhaps due to rapid isostatic pressure. The Exsulans Limestone Bed was deposited in a deep subtidal environment during a global transgression (Babcock et al. 2004; Álvaro et al. 2010; Nielsen & Schovsbo 2105).

The succession is continuing with repeated regressions, with thin limestone seemingly replacing the glauconite beds. Thin sand packages occurring in the mid *P. atavus* Chron was probably deposited by bottom currents during storms (Nielsen & Schovsbo 2015). An orsten bed where the upper part shows erosional characteristics occur in the mid *P. atavus* Chron marks the acme of the Atavus highstand of Nielsen & Schovsbo (2015). The upper *P. atavus* Zone is marked by abundant grey mudstones and siliciclastic mudstones with cross lamination which indicates a very shallow sea level. The potential microbial mats further indicate nearshore deposition immediately below fair weather wave base (Prothero & Schwab 2013).

The transition to the *P. punctuosus* chron is associated with a major sea level fall (e.g. Babcock et al. 2015). The 'Hypagnostus Limestone Bed' in the upper

P. atavus Zone and overlying limestone and conglomerates are signs of repeated regression and the karst horizons and beach pebbles indicate subaerial exposure (cf. Westergård 1931; Flügel 2010). The tilted beds have formed a cave where the Exporrecta conglomerate has been deposited. The tilted beds seen in the Tomten-1 drill core are here suggested as a result of collapsing beds following dissolution of the limestone underneath. The shales of the lower *L. laevigata* Zone are evident of a transgression (Egenhoff et al. 2015), with subsequent minor limestone layers indicating repeated regressions.

9.3 Furongian

The Kakeled Limestone Bed marks a varying trend from shallow sea to subaerial conditions. However, there is a lowering sea level trend throughout this interval (Egenhoff et al. 2015). Several characteristics of subaerial conditions are present in the limestone bed, such as beach pebble, karst horizons and large calcite cracks. A cave structure also noted by Lehnert et al. (2012) from the Kakeled quarry, Kinnekulle, is conceivably seen in the Tomten-1 drill core. In the upper part of the Kakeled Limestone Bed a transgression occurs with beds of *O. lenticularis*.

The succession continues upwards with shale and inclusions of limestones marking episodes of transgression and regression. In the Furongian it appears that there is higher abundance of limestone concretions than in the Cambrian Series 3. The growth of limestone concretions occurred prior to compaction of the surrounding alum shale and was probably aided by activity of bacteria increasing the alkalinity in the pore waters (Buchardt et al. 1997).

9.4 Ordovician

The prominent disconformity between the Alum Shale and the Bjørkåsholmen conglomerate shows evidence of subaerial conditions. The well preserved trilobites originated from the underlying *C. linnarssoni* Zone suggest rapid burial and transgression (Lehnert et al. 2013a). The increase of shell fragments upwards further suggests a transgression.

The gap between the Latorp Limestone and the underlying Bjørkåsholmen conglomerate again marks a long time of non-deposition or removal of sediments with the absence of Lower Ordovician Limestone (see Calner et al. 2013, Fig. 36). The Latorp and Lanna Limestones indicates a colder environment (Cocks & Torsvik 2005) and the fauna seems to be more abundant higher up in the drill core which indicates a transgression (cf. Munnecke et al. 2010).

10 Chemostratigraphy

In the Cambrian rock record ten distinct carbon isotope excursions (CIE) have been recorded (Zhu et al. 2006). The CIE have become important tools for correlation on both a regional and a global scale over the last few decades. This is especially evident (and important) in successions where biologic markers are absent. The CIE can thus aid in solving the problem of correlation between shallow water settings and outer shelf seas (e.g. Peng 2004). Carbon isotope excursions are often associated with evolutionary radiations and/ or extinctions which generally reflect oceanographic events associated with tectonic activity or changes in climate (Zhu et. al 2004; Peng et al. 2012a).

The Cambrian Series 3 and the Furongian record three prominent global excursions, in stratigraphically ascending order: the Drumian Carbon Isotope Excursion (DICE), the Steptoean Positive Carbon Isotope Excursion (SPICE) and the Top of Cambrian Carbon Isotope Excursion (TOCE) (Zhu et. al 2006; Peng 2012). It is not possible to identify the TOCE in the Tomten-1 drill core, since its stratigraphic position is in the *P. lobata*/*P. paradoxa* biozones, which are not present (Fig. 14).

The $\delta^{13}C_{org}$ curve of the Tomten-1 drill core shows a steady increase in $\delta^{13}C_{org}$ values throughout the Cambrian Series 3 and Furongian (Fig. 18 and Table 1). The recorded values are in par with the trend of the global CIE record of the same stratigraphic interval (see Zhu et al. 2006, fig. 1).

There is a clear negative excursion from -31.57 ‰, at c. 19 cm above the Exsulans Limestone Bed in the drill core to a minimum value of -33.71 ‰ immediately below the bed. Following these two lower values there is again a positive shift downwards in the drill core. However, the values do not return to the values seen above the minimum peak excursion. Here this negative excursion is interpreted as the DICE. However, the net shift is c. 2.14 ‰ which can be compared to the global net shift of DICE, recorded as approximately 3 ‰ $\delta^{13}C$ (see; Zhu et al. 2006, fig.1).

The GSSP of the Drumian Stage in the Drumian Mountains, Utah, USA, is characterized by the first appearance (FAD) of *P. atavus* (Babcock et al. 2004; Zhu et al; 2006). The FAD of *P. atavus* is often associated with a transgression, that might have been intercontinental or even global (eustatic), and the negative isotopic shift of the DICE (Babcock et al. 2004; Zhu et al. 2006). However, the timing and relationship of the inferred transgression and DICE is difficult to assess in detail (Howley & Jiang 2010). The correlation is even more problematic as the timing of the first appearance of *P. atavus* may not be the same over the world, i.e., it likely is diachronous (Zhu et. al 2006).

Several occurrences of the DICE have been documented globally (Fig. 19). Zhu et al. (2004) placed it below and slightly above the FAD of *P. atavus* in two sections from China, respectively. A third occurrence of DICE was documented above the FAD of *P. atavus*, whereas the lower excursion was considerably lower stratigraphically than in the two other Chinese sections (Peng et al. 2012b). Babcock et al. (2007) described the DICE from the Drum Mountains, United States, occurring approximately 10 meters above the FAD of *P. atavus*, whereas Howley & Jiang (2010) established a correlation within platform and basin successions in

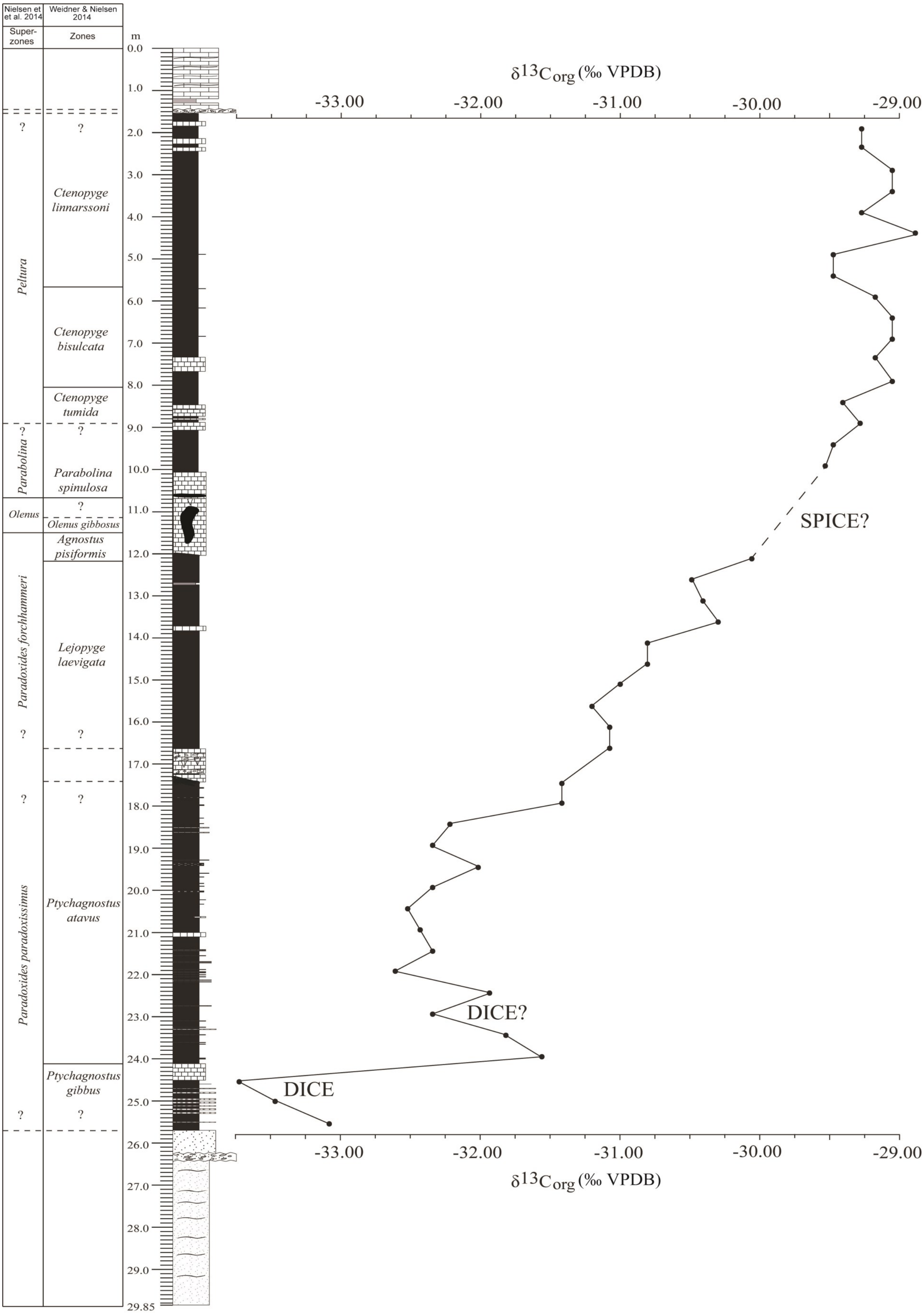


Fig. 18. $\delta^{13}C_{org}$ plot showing the Drumian Carbon Isotope Excursion (DICE) and the stratigraphic level of which the Steptoean Positive Carbon Isotope Excursion (SPICE) as it would be expected in the Tomten-1 core, Torbjörntorp, Västergötland, Sweden.

the western United States, using sequence- and chemostratigraphy. They indicated that the DICE occurs above the FAD of *P. atavus*.

Three previous studies from the DICE interval in Scandinavia have yielded three separate excursions from outer shelf deposits of Scania, southernmost Sweden. Analysis from the Almbacken drill core have yielded a net $\delta^{13}C_{org}$ shift of more than 1.5 ‰, thus resembling the Tomten-1 characteristics of net shift values as it also includes the corresponding limestone bed (Lehnert et al. 2013b). The DICE in the Almbacken drill core is situated between the top of the Gislöv Formation and the base of the Exsulans Limestone Bed, which correspond to the *P. praecurrens* or the lower *P. gibbus* Zone (Lehnert et al. 2013b). The records from Álvaro et al. (2010) give a clear net shift of 6.62 ‰ $\delta^{13}C_{carb}$ in the Exsulans Limestone Bed of the Brantevik section of Scania. A single marker point from the Andrarum-3 drill core shows a 0.7 ‰ $\delta^{13}C_{org}$ net shift, also coinciding with a limestone bed (Ahlberg et al. 2009).

SPICE signals can be seen globally in the uppermost Guzhangian, the Paiban and in the lower part of the Jiangshanian stages (Peng et al. 2012a). Thus, the stratigraphic interval should be embraced by the Tomten-1 drill core. In this study it is not possible to determine the occurrence of the SPICE because of lack of $\delta^{13}C_{carb}$-sampling in the lithologically highly variable Kakeled Limestone Bed (Figs. 2, 14). Since the agnostoid *Glypagnostus reticulatus* (cf. Terfelt et al. 2008; Ahlberg & Terfelt 2012) has not been identified in the Tomten-1 drill core, it makes it further problematic to establish a marker where the base of SPICE could occur (Ahlberg et al. 2009).

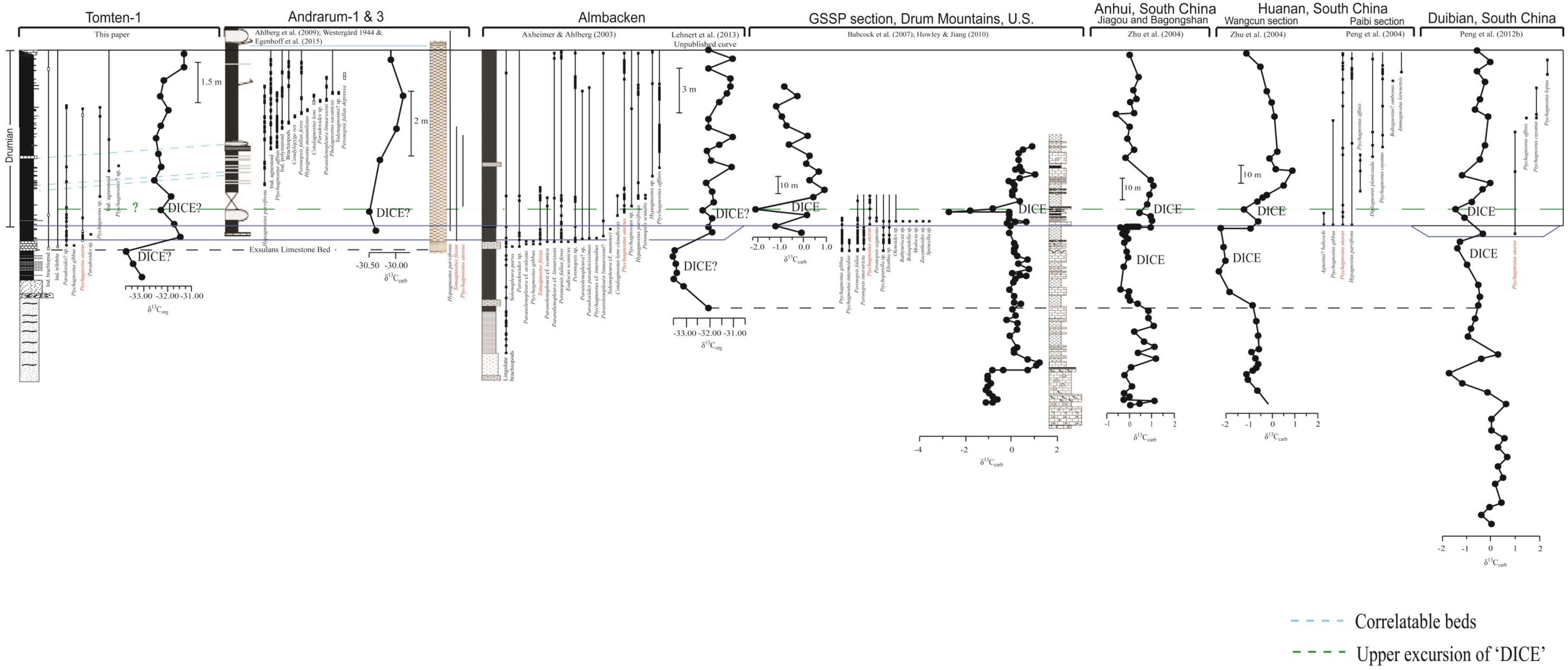
11 Correlation

In order to identify hiatuses in the Tomten-1 drill core an integrated bio- litho- and chemostratigraphic correlation can be adopted. The negative DICE excursion in the lower *P. atavus* Zone can tentatively be correlated globally (Fig. 19). This renders the FAD of the *P. atavus* in the Tomten-1 drill core occurring below the Drumian Stage (defined by the global FAD of the *P. atavus*). Thin but distinctive sandstone beds (Fig 3F) of the Tomten-1 drill core can be correlated with the Andrarum-3 drill core throughout the lower *P. atavus* Zone (Fig. 19; Appendix B). In the middle *P. atavus* Zone of Swedish drill cores there are abundant thick limestones, which coincide with a global $\delta^{13}C$ negative excursion. In the upper *P. atavus* Zone in the Swedish drill cores brachiopods and limestone are abundant, whereas the fauna of the Paiban section, China, appears to display a change of appearances of fossil

Table 1. Stable isotope data ($\delta^{13}C$) and carbon percentage from alum shale of the Tomten-1 drill core.

Metres	$\delta^{13}C_{VPDB}$ (‰)	% C	Zone	Series
1.90 m	-29.3	10.8	*C. linnarssoni*	Furongian
2.35 m	-29.3	12.5	*C. linnarssoni*	Furongian
2.90 m	-29.1	14.0	*C. linnarssoni*	Furongian
3.40 m	-29.1	15.5	*C. linnarssoni*	Furongian
3.90 m	-29.3	14.8	*C. linnarssoni*	Furongian
4.40 m	-28.9	17.9	*C. linnarssoni*	Furongian
4.88 m	-29.5	13.5	*C. linnarssoni*	Furongian
5.40 m	-29.5	17.5	*C. linnarssoni*	Furongian
5.90 m	-29.2	17.4	*C. bisulcata*	Furongian
6.40 m	-29.1	14.9	*C. bisulcata*	Furongian
6.90 m	-29.1	15.0	*C. bisulcata*	Furongian
7.35 m	-29.2	13.6	*C. bisulcata*	Furongian
7.90 m	-29.1	12.6	*C. bisulcata*	Furongian
8.40 m	-29.4	11.4	*C. bisulcata*	Furongian
8.90 m	-29.3	9.3	?	Furongian
9.40 m	-29.5	12.9	?	Furongian
9.90 m	-29.6	11.2	?	Furongian
12.10 m	-30.1	8.8	*A. pisiformis*	Cambrian Series 3
12.62 m	-30.5	8.4	*L. laevigata*	Cambrian Series 3
13.10 m	-30.4	9.4	*L. laevigata*	Cambrian Series 3
13.60 m	-30.3	8.1	*L. laevigata*	Cambrian Series 3
14.10 m	-30.8	8.3	*L. laevigata*	Cambrian Series 3
14.60 m	-30.8	8.3	*L. laevigata*	Cambrian Series 3
15.09 m	-31.0	8.3	*L. laevigata*	Cambrian Series 3
15.60 m	-31.2	8.5	*L. laevigata*	Cambrian Series 3
16.10 m	-31.1	6.6	*L. laevigata*	Cambrian Series 3
16.60 m	-31.1	6.5	*L. laevigata*	Cambrian Series 3
17.42 m	-31.4	2.7	*P. atavus*	Cambrian Series 3
17.90 m	-31.4	1.2	*P. atavus*	Cambrian Series 3
18.41 m	-32.2	4.9	*P. atavus*	Cambrian Series 3
18.90 m	-32.3	4.3	*P. atavus*	Cambrian Series 3
19.41 m	-32.0	4.3	*P. atavus*	Cambrian Series 3
19.90 m	-32.3	2.6	*P. atavus*	Cambrian Series 3
20.40 m	-32.5	7.5	*P. atavus*	Cambrian Series 3
20.90 m	-32.4	7.2	*P. atavus*	Cambrian Series 3
21.40 m	-32.3	6.8	*P. atavus*	Cambrian Series 3
21.89 m	-32.6	9.8	*P. atavus*	Cambrian Series 3
22.40 m	-31.9	3.3	*P. atavus*	Cambrian Series 3
22.90 m	-32.3	6.3	*P. atavus*	Cambrian Series 3
23.40 m	-31.8	3.8	*P. atavus*	Cambrian Series 3
23.91 m	-31.6	3.7	*P. atavus*	Cambrian Series 3
24.50 m	-33.7	6.1	*P. gibbus*	Cambrian Series 3
24.98 m	-33.4	8.2	*P. gibbus*	Cambrian Series 3
25.54 m	-33.1	6.3	*P. gibbus*	Cambrian Series 3

Fig. 19. Global litho-, bio- and chemostratigraphy of the *P. atavus* Zone. Three Swedish drill cores are included alongside the $\delta^{13}C$-curves of the GSSP and Chinese sections for comparison. The upper negative excursion of DICE can be correlated globally, whereas the lower excursion occurring in the upper *P. gibbus* Zone cannot be correlated (modified from Axheimer & Ahlberg 2003; Peng et al. 2004; Zhu et al. 2004; Babcock et al. 2007; Ahlberg et al. 2009; Howley and Jiang 2010; Peng et al. 2012b; Lehnert et al. 2013 (unpublished data) and Egenhoff et al. 2015).


Tomten-1
This paper
Andrarum-1 & 3
Ahlberg et al. (2009); Westergård 1944 & Egenhoff et al. (2015)
Almbacken
Axheimer & Ahlberg (2003)
Lehnert et al. (2013) Unpublished curve
GSSP section, Drum Mountains, U.S.
Babcock et al. (2007); Howley & Jiang (2010)
Anhui, South China
Jiagou and Bagongshan
Zhu et al. (2004)
Huanan, South China
Wangcun section
Zhu et al. (2004)
Paibi section
Peng et al. (2004)
Duibian, South China
Peng et al. (2012b)
Drumian
1.5 m
2 m
3 m
10 m
DICE?
DICE
Exsulans Limestone Bed
?
$\delta^{13}C_{org}$
$\delta^{13}C_{carb}$
Correlatable beds
Upper excursion of 'DICE'

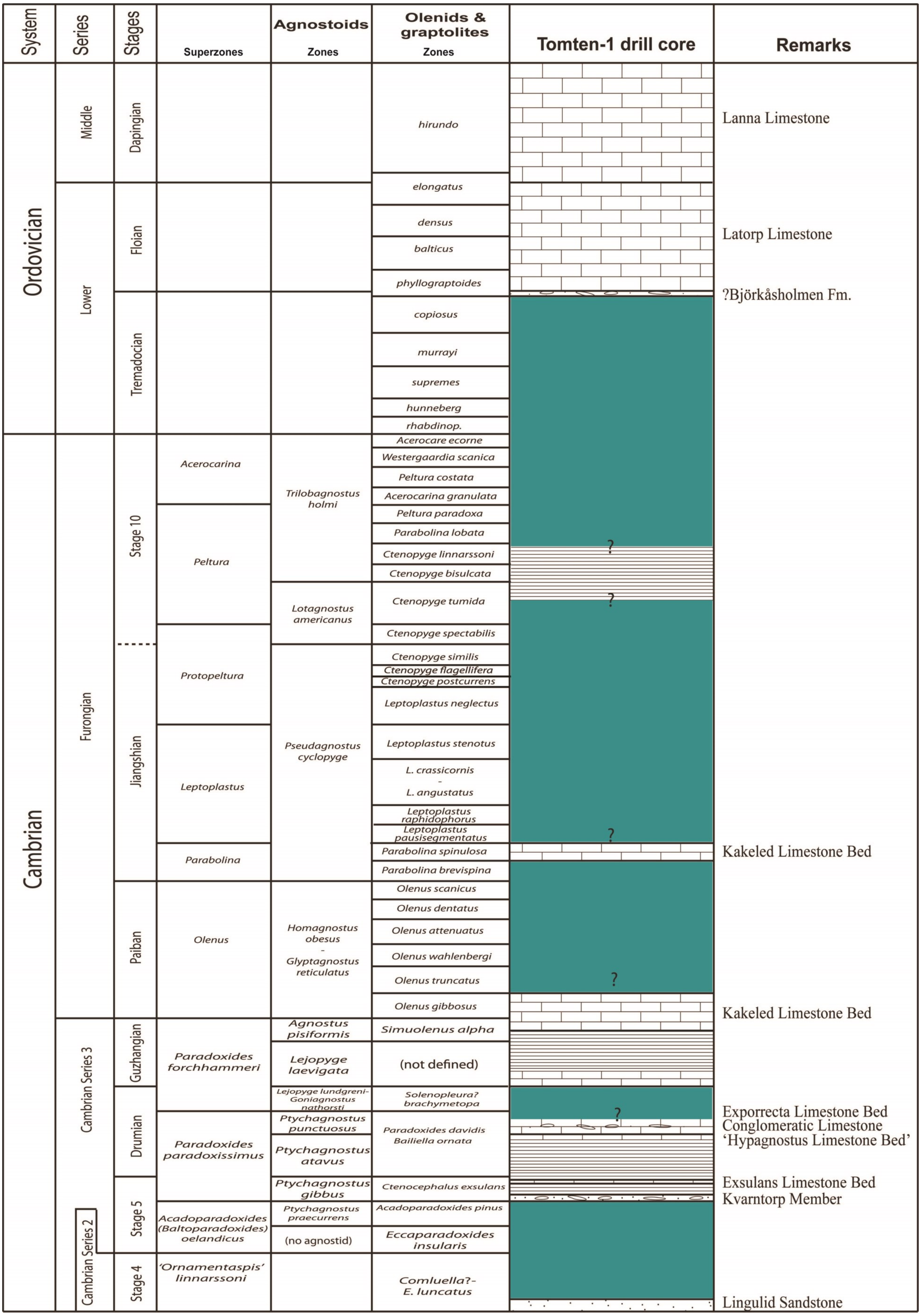


Fig. 20. Succession of the Tomten-1 drill core, Västergötland, Sweden. Green colour marks hiatuses.

specimens (Fig. 19).

Based on defined boundaries of the biozones and identification of lithologies in the Tomten-1 drill core, correlation can be rendered within Scandinavia (Appendix B) showing that the Tomten-1 drill core displays often more substantial hiatuses than other corresponding drill cores. The data presented in this paper show that the succession in the Tomten-1 drill core is incomplete and there are several substantial gaps of various magnitudes (Fig. 20).

12 Discussion

12.1 Depositional environment

The environment during deposition of the Alum Shale Formation has often been regarded as formed under poorly oxidized (dysoxic to anoxic) conditions (e.g. Thickpenny 1987; Buchardt et al. 1997). However, Newby (2012) studied the lithological characteristics of the uppermost Furongian in the Tomten-1 drill core and recorded several different facies, indicating distal to proximal settings on the shelf. Based on borings it appears that dysoxic conditions prevailed during deposition (Newby 2012; Egenhoff et al. 2015). The findings of borings in the Tomten-1 drill core show that dysoxic conditions, at least occasionally, were present during deposition of the Alum Shale Formation.

It has been assumed by several authors (e.g. Andersson et al. 1985; Bergström & Gee 1985; Buchardt et al. 1997; Nielsen and Schovsbo 2011) that the Scandinavian shelf was tectonically stable during the Cambrian Epoch 3 and the Furongian. However, recent studies (Newby 2012; Egenhoff et al. 2015) have provided evidence for tectonic activity in the Scandinavian basin. The collapsed sediments at 16.95−16.72 m in the Tomten-1 drill core overlay a synchronic fault of the Andrarum-3 drill core. This could imply that tectonic activity rendered the collapse of the sediments, however, dissolution of the basal limestone appear to have main cause of formation. The fault occurring in the top of the Exsulans Limestone Bed in the Tomten-1 drill core suggests that some tectonic activity occurred occasionally during deposition of the Alum Shale Formation. However, Nielsen and Schovsbo (2015) discuss the reasons for the major regressions occurring in the Scandinavian basin. Both glacial and tectonic factors are discussed. The evidence of tectonic activity seen in the drill core always appears to be associated with extreme sea-level fluctuations. However, glacial influence cannot be ruled out as the paleocontinent was situated at low paleolatitudes during the Cambrian.

If the evidence of tectonic activity seen in the upper Exsulans Limestone Bed has occurred over a large

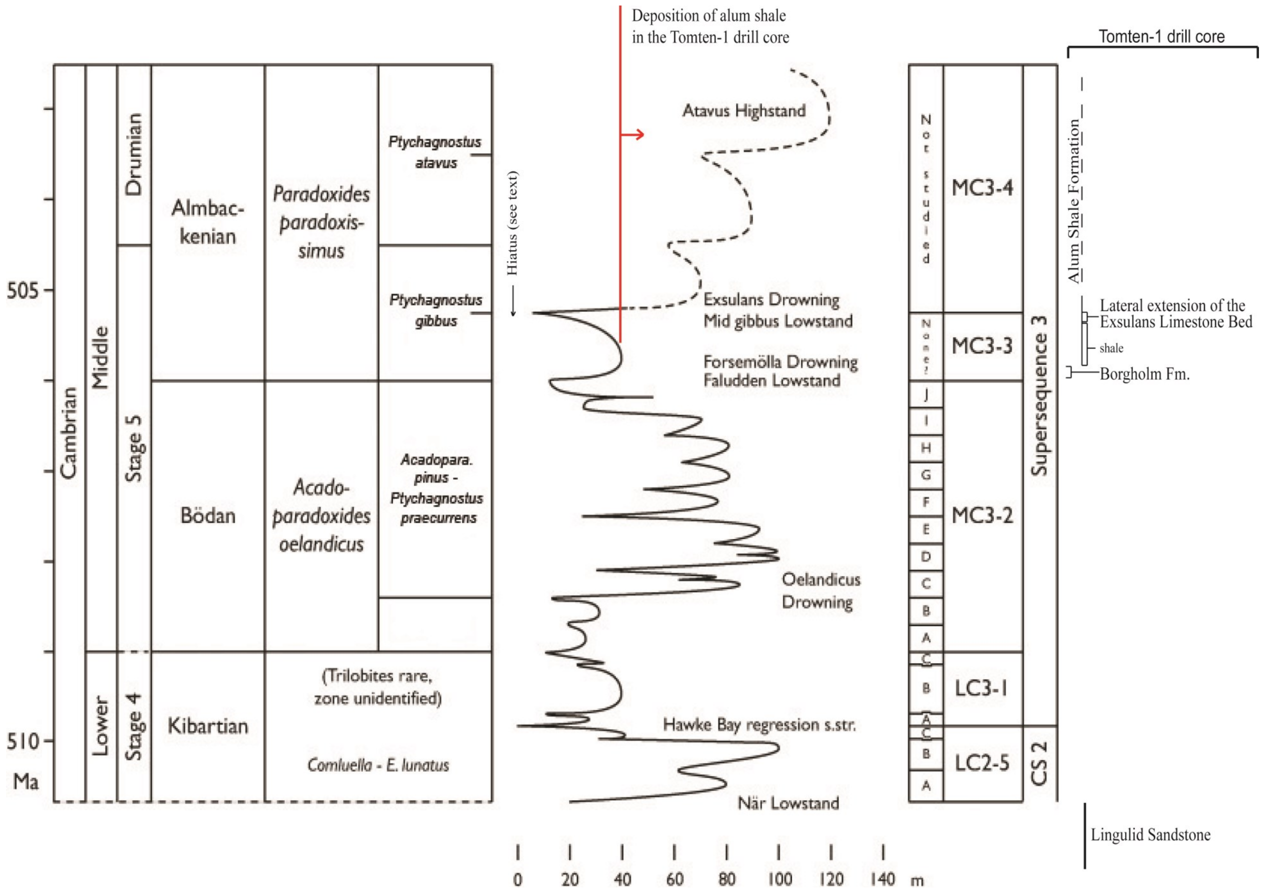


Fig. 21. Inferred Early and mid-Cambrian sea-level changes of Scandinavia. The succession occurring in the Tomten-1 drill core is marked. A hiatus is indicated before the Exsulans Drowning. The red line marks deposition of shale in the Tomten-1 drill core, as seen in the lower *P. gibbus* Zone (Modified from Nielsen & Schovsbo 2015).

area this event could be correlated. Several other events appear to be correlatable within the Scandinavian basin. The calcite crack in the Kakeled Limestone Bed of the Tomten-1 drill core (see figure 2) can tentatively be correlated with the top of the cave structure seen in the Kakeled area (see Calner et al. 2013, p. 45), suggesting a major regression.

The thin glauconite layers, mud and limestone beds of the Tomten-1 drill core could be a sign of rhythmicity. In the Furongian, both a large-scale and a minor cyclicity can be seen (Newby 2012; Babcock et al. 2015), however, it is beyond the scope of this report to study this in detail. However, karst horizons seem to reflect large scale cyclicty, whereas glauconite and limestone layers in the Cambrian Series 3 appear to reflect small scale rhythmicity.

As noted by Peng (2012 and citations therein) there seems to be a strong relationship between the sea-level and the δ^{13}C-curve in the Cambrian Series 3. In the Swedish drill cores this can also be observed. Brachiopods in particular appear at negative excursions in the δ^{13}C-curve.

12.2 Chemostratigraphy

The peak $\delta^{13}C_{org}$ DICE value of 2.14 ‰ measured in the Tomten-1 drill core is not of exceptional magnitude, but it is still close to the global shift of 3 ‰ (Zhu et al. 2006, fig. 1). As it is only recorded from one data point it is possible that the true value is closer to the global 3 ‰ (Zhu et al. 2006, fig. 1). The signature of the SPICE observed by Ahlberg et al. (2009), also gave relatively low magnitudes compared to global measurements, which perhaps is due to use of $\delta^{13}C_{org}$ instead of $\delta^{13}C_{carb}$. Diagenetic processes could, however, possibly alter absolute δ^{13}C values (Kump & Arthur 1999; Howley & Jiang 2010).

As the curve does not return to pre-DICE values (cf. Zhu et al. 2006, fig. 1) there could be a hiatus in the lower part of the Alum Shale Formation in the drill core, as is indicated with the truncation of conglomerate of the Borgholm Formation.

The net shift from the Almbacken drill core is less prominent than the net shift of the Tomten-1 drill core. The prominent net shift of Álvaro et al. (2010) indicates that the minimum peak value of the DICE is within the Exsulans Limestone Bed, although the study only measured two sample levels. The DICE signature from Ahlberg et al. (2009) is tentatively DICE, however the sample levels are not dense. Although, the correlation with the Andrarum-1 drill core suggests that the limestone sample actually is the upper DICE excursion.

Higher-density sampling of the Exsulans Limestone Bed and surrounding shales of the DICE interval in the Tomten-1 drill core could give further information of the signatures of the excursion.

In order to record the SPICE excursion, sampling of whole rock carbon ($\delta^{13}C_{carb}$) from the Kakeled Limestone Bed at a high resolution is necessary. Detecting *G. reticularis* would further help in pinpointing the position of the SPICE. It must be emphasized, however, that the Tomten-1 drill core has many hiatuses in the interval covering the SPICE excursion (Figs. 2, 14).

12.3 Base of the *P. atavus* Zone and sea -level changes

The Exsulans Limestone of the Tomten-1 drill core is lithologically comparable to the Exsulans Limestone in the Almbacken drill core as described by Álvaro et al. (2010). However, compared to Almbacken there are abundant facies shifts in the Tomten-1 drill core. Hyoliths, calcite-walled brachiopods and echinoderm ossicles are also present, at least in some intervals, in the Tomten-1 drill core. Similarities in the upper part of the limestone bed in the Tomten-1 drill core are the microfossil sample yielding autigenic minerals and microbored shells which are in concert with the Scanian findings. The Tomten-1 drill core also displays dolomitization in the top of the Exsulans Limestone Bed. Thus, the top of the Exsulans Limestone in Scania (Almbacken) and Västergötland (Tomten) seems to correlate, as suggested in figure 19.

The Exsulans Limestone Bed of the Tomten-1 drill core apparently contains hiatuses (Fig. 4). The basal part of the Exsulans Limestone Bed shows at least three erosional surfaces, and the shifting lithologies higher up in the bed could also indicate hiatuses. The hiatus in the upper part are in contrast to the present view (e.g. Nielsen & Schovsbo 2007, 2015), that Västergötland was not exposed to subaerial conditions during the upper half of the *P. gibbus* Chron.

The upper part of the Exsulans Limestone Bed is associated with a rapid transgression, the Exsulans drowning event of Nielsen & Schovsbo (2015). It is not clearly understood how high the sea level was in the Västergötland during the Exsulans drowning event and the beginning of the Drumian Age. The appearance of *P. atavus* is associated with a new transgression during the earliest Drumian (Babcock et al. 2015). In the Tomten-1 drill core, *P. atavus* appears just above the top of the Exsulans Limestone Bed.

Tomagnostus fissus is a geographically widespread species that has been recorded from the *O. gibbus* and *P. atavus* zones in many parts of the world (Robison 1994). Westergård (1946) used it as an index fossil for his *T. fissus–P. atavus* Zone, but did not define the base of the zone. In Scania, *T. fissus* appears in the Exsulans Limestone and it cannot be used for defining the base of the *P. atavus* Zone. *T. fissus* has not been recorded in the Tomten-1 drill core.

If there is a hiatus above the Exulans Limestone Bed in the Tomten-1 drill core it probably means that the sea level has been much lower than suggested in figure 21. As there is shale deposited in the lower *P. gibbus* Zone in the Tomten-1 drill core it appears that not more than 40 m sea level is required for deposition of alum shale.

Although the sea-level changes are often in concert with the sea-level changes of Egenhoff et al. (2015), the Tomten-1 drill core displays additional changes. The extremely low sea level seen in the *G. nathorsti/L. laevigata* zones of the Tomten-1 drill may at least partially correspond to the lowstand represented by the Andrarum Limestone in the Andrarum-3 drill core. A more precise correlation of, e.g. the Tomten-1 and the Andrarum-3 drill cores, will likely help to construct more detailed curve of the sea-level changes in the Scandinavian basin.

13 Conclusions

The Tomten-1 drill core from Västergötland, southern Sweden was studied with respect to bio- litho- and chemostratigraphy. The succession consists of strata from the uppermost part of Cambrian Series 2, Cambrian Series 3, Furongian and the Lower and Middle Ordovician. The lowermost part of the succession belongs to the Lingulid Sandstone Member (File Haidar Formation), consisting of light sandstones that become coarse-grained and massive near the top. The Lingulid Sandstone is truncated by the basal conglomerate of the Kvarntorp Member (Borgholm Formation), which grades into a glauconitic sandstone forming most of the member. The Kvarntorp member is overlain by the Alum Shale Formation that consists mostly of dark grey to black, fine-grained mudstones with minor carbonate intercalations and lenses. The lower part of the formation has abundant thin limestone and glauconite beds. Four prominent limestone beds can be identified in the Alum Shale Formation (in ascending order): the Exsulans Limestone Bed, the 'Hypagnostus Limestone Bed', the Exporrecta Limestone Bed and the Kakeled Limestone Bed. The Alum Shale Formation is disconformably overlain by a thin conglomerate of the Tremadocian Bjørkåsholmen Formation. The uppermost part of the Tomten-1 succession belongs to the Middle Ordovician Lanna Limestone, which rests on the Bjørkåsholmen Formation with a prominent disconformity.

The Alum Shale Formation of Cambrian Series 2 and the Furongian can be subdivided into the following agnostoid and polymerid biozones (in ascending order): the *P. gibbus*, *P. atavus*, *L. lejopyge*, *A. pisiformis*, *O. gibbosus*, *P. parabolina*, *C. tumida*, *C. bisculata* and *C. linnarssoni* zones.

The varying lithologies within the Cambrian succession reflect different depositional environments. Sand and conglomerates were deposited in proximal, near-shore environments under the influence of waves and currents, whereas the shales and mudstones of the Alum Shale Formation represent more distal facies. At different stratigraphic levels throughout the drill core, beach pebbles and karst horizons have been identified, indicating very shallow water environments and even subaerial exposure.

The Steptoean Positive Carbon Isotope Excursion (SPICE) has not been recorded, largely because of lack of $\delta^{13}C_{carb}$-sampling in the lithologically highly variable Kakeled Limestone Bed and the incompleteness of the lower Furongian. The Drumian Carbon Isotope Excursion (DICE) can be tentatively identified as one of two negative excursions recognized in the *P. gibbus* Zone and lower *P. atavus* Zone, respectively. The negative excursion in the lower *P. atavus* Zone is based on a few samples only. Detailed and dense sampling is required in order to delimit the range and amplitude of this excursion. The lower negative excursion is prominent and has a recorded shift of 2.14 ‰. It is largely restricted to the *P. gibbus* Zone with a peak value just below the Exsulans Limstone Bed. Hence, this negative excursion seems to be older than the DICE as recognized in the GSSP in the Drum Mountains, USA. A corresponding negative excursion was recently described from the *P. gibbus* Zone of the Almbacken drill core, Scania (Lehnert et al. 2013).

Tentative attempts to correlate the Tomten-1 drill core with regionally (Andrarum-3 drill core) and globally, show that there are similarities in lithologies and facies changes, suggesting that deposition was influenced by eustatic sea level changes.

Biostratigraphical data and lithological characteristics show that the succession in the Tomten-1 drill core is incomplete and that there are several substantial gaps of various magnitudes. The most significant gaps have been recorded in the Furongian and Lower Ordovician.

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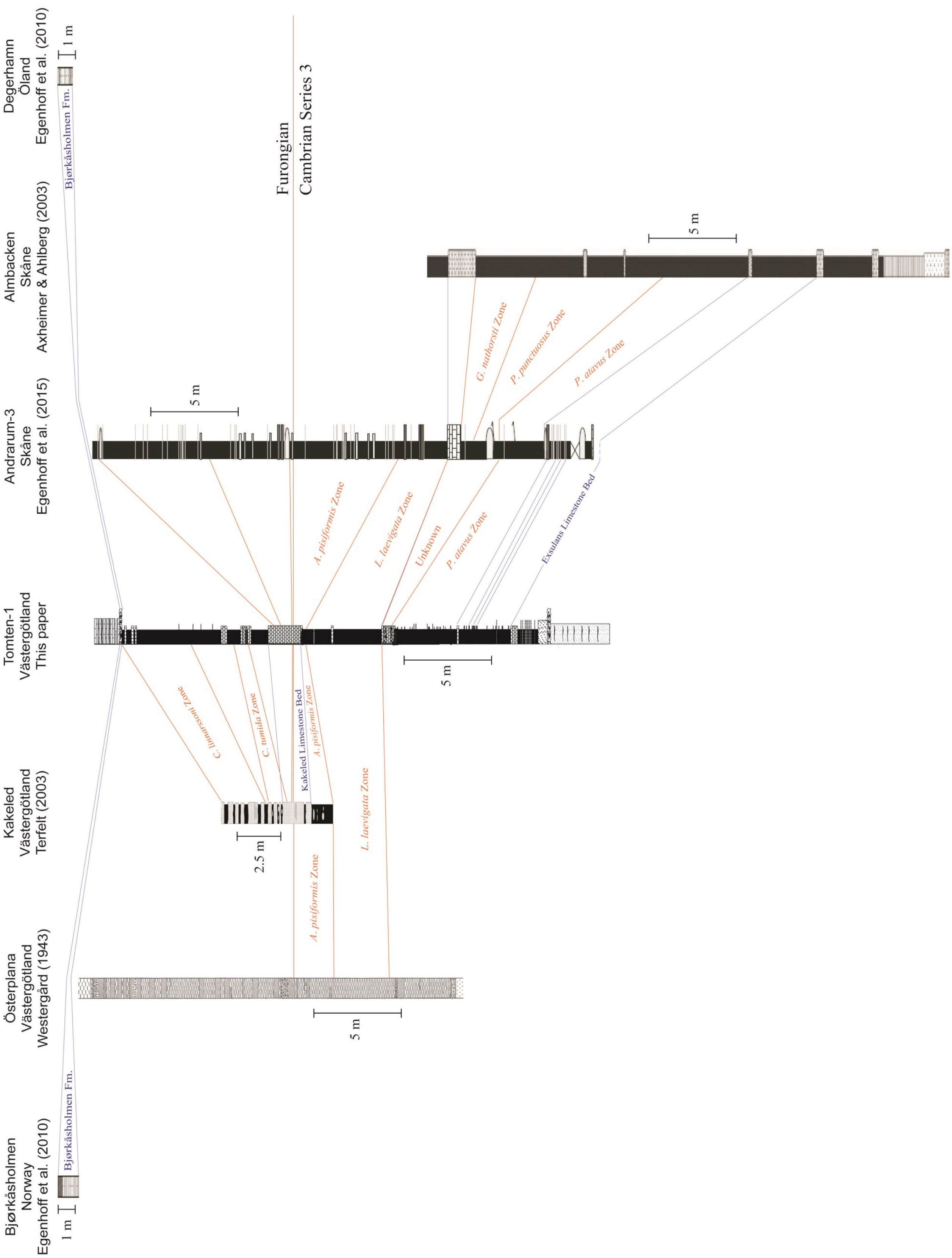
Appendix A

Appendix B



Degerhamn
Öland
Egenhoff et al. (2010)
1 m
Bjørkåsholmen Fm.
Almbacken
Skåne
Axheimer & Ahlberg (2003)
5 m
Andrarum-3
Skåne
Egenhoff et al. (2015)
5 m
Tomten-1
Västergötland
This paper
5 m
Kakeled
Västergötland
Terfelt (2003)
2.5 m
Österplana
Västergötland
Westergård (1943)
5 m
Bjørkåsholmen
Norway
Egenhoff et al. (2010)
1 m
Bjørkåsholmen Fm.
Furongian
Cambrian Series 3
G. nathorsti Zone
P. punctuosus Zone
P. atavus Zone
A. pisiformis Zone
L. laevigata Zone
Unknown
P. atavus Zone
Exsulans Limestone Bed
C. linnarssoni Zone
C. tumida Zone
Kakeled Limestone Bed
A. pisiformis Zone
L. laevigata Zone
A. pisiformis Zone

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Geologiska institutionen
Lunds universitet
Sölvegatan 12, 223 62 Lund