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Cambrian stratigraphy of the Tomten-1 drill core, Västergötland, Sweden

PER AHLBERG[1], MATS E. ERIKSSON[1], FRANS LUNDBERG[1] and ANDERS LINDSKOG[1]

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Abstract: The Tomten-1 drilling at Torbjörntorp in Västergötland, southern Sweden, penetrated 29.85 m of Cambrian Series 2, Cambrian Series 3, Furongian, and Lower–Middle Ordovician strata. Lithostratigraphically the succession includes the File Haidar, Borgholm and Alum Shale formations, and the Latorp and Lanna limestones. The drill core succession is described herein for the first time, with special focus on the biostratigraphy of the Cambrian Alum Shale Formation. 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. The succession is interrupted by numerous stratigraphic gaps of variable magnitudes, as is evident from the biostratigraphy and conspicuous unconformities.

Key words: Cambrian, biostratigraphy, trilobites, agnostoids, Tomten, Västergötland, Sweden.

[1] *Department of Geology, GeoBiosphere Science Centre, Lund University, Sölvegatan 12, SE-223 62 Lund, Sweden; per.ahlberg@geol.lu.se, mats.eriksson@geol.lu.se, frans.a.lundberg@gmail.com, anders.lindskog@geol.lu.se*

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Introduction

During Cambrian times, Baltica was situated 30–60° south of the palaeoequator. It was inverted relative to its present configuration and largely characterized by shallow to moderately deep shelf environments (Torsvik & Rehnström 2001; Cocks & Torsvik 2005; Álvaro et al. 2013). The Cambrian and Early Ordovician witnessed a global sea-level rise (Haq & Schutter 2008), albeit with a pronounced cyclicity characterized by second- and third-order eustatic changes (Peng et al. 2012; Babcock et al. 2015). Several regionally developed unconformities, including subaerially formed karstic surfaces that reflect pronounced lowstands, have been recognized in the Cambrian of Baltica (Nielsen & Schovsbo 2011, 2015; Lehnert et al. 2012, 2013; Calner et al. 2013).

The basal Cambrian (Terreneuvian and Cambrian Series 2) succession of Scandinavia is dominated by coarse-grained siliciclastics deposited on a well-developed Precambrian peneplain that was formed following extensive weathering and erosion during the late Neoproterozoic (Martinsson 1974; Lidmar-Bergström 1995, 1996; Gabrielsen et al. 2015). This succession is disconformably overlain by more fine-grained siliciclastics, followed by darker and more kerogen-rich shales that form the Cambrian Series 3 through lower Tremadocian Alum Shale Formation (Bergström & Gee 1985). The remainder of the Early and Middle Ordovician of Baltica was characterized by deposition of grey shale and cool-water carbonates.

The Alum Shale Formation, which is the main focus of this study, consists of black to dark grey shales and siliciclastic mudstones with subordinate limestone beds and lenses, colloquially referred to as 'Orsten' or stinkstone (e.g. Andersson et al. 1985). It is widely distributed across Scandinavia and has a maximum thickness of approximately 160 m in southern Scandinavia (Bergström & Gee 1985; Buchardt et al. 1997; Nielsen & Schovsbo 2007). The Alum Shale has total organic carbon (TOC) values between 2 and 22 wt% and was predominantly deposited under dysoxic conditions, with sedimentation rates as low as 1–10 mm/1000 years (e.g. Thickpenny 1987; Buchardt et al. 1997; Egenhoff et al. 2015). The wide areal extension and relative thinness of the Alum Shale suggest deposition on a stable platform, with only minor vertical movements (Bergström & Gee 1985).

In this paper, a new drill core, Tomten-1, from the classical area of Västergötland, south-central Sweden, is described. In addition to a general description of the lithologic succession, we present a high-resolution biostratigraphy of the Alum Shale Formation of the drill core. The biostratigraphy is based on agnostoids and polymerid trilobites, which enable subdivision of the drill core succession into biostratigraphic superzones and zones. In the province of Västergötland several of these are lacking or are incomplete, forming hiatuses in the succession.

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, 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 Cambrian succession 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 Middle Ordovician (0−1.10 m), Lower Ordovician (1.10−1.55 m), Furongian (1.55−11.55 m), Cambrian Series 3 (11.55−26.45 m) and Cambrian Series 2 (26.45−29.85 m). The major portion of the drill core is represented by the Alum Shale Formation, which mainly consists of dark shale and subordinate black bituminous limestone (Fig. 2). The diameter of the core is 71 mm.

Materials and methods

In order to evaluate the fossil content and biostratigraphy of the drill core, the shale intervals were split up approximately every centimetre, 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 surfaces of each core slab were examined under a stereo microscope and all fossils were marked for more detailed observation and their occurrence was noted in a spread sheet. Subsequently each fossil was thoroughly studied and identified. 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. All figured specimens are deposited in the type collection at the Department of Geology, Lund University, Sweden (LO for Lund Original).

Lithologic succession

The entire drill core succession is subdivided into the File Haidar, Borgholm and Alum Shale formations, and the Latorp and Lanna limestones (Fig. 3). The lowermost part (29.85−26.43 m) of the drill core consists of the upper Lingulid Sandstone Member of the File Haidar Formation. This light-grey fine-grained quartz arenite is succeeded by the Kvarntorp Member of the Borgholm Formation (26.43−25.70 m), which is represented by a basal conglomerate and sandstone rich in glauconite. The conglomerate rests with a distinct disconformity on the underlying Lingulid Sandstone and is disconformably overlain by the greenish glauconitic sandstone.

The Alum Shale Formation (25.70−1.55 m) forms the major part of the drill core and consists of dark grey to black shales and siliciclastic mudstones with several prominent limestone beds, including distinctive marker beds such as the Exporrecta Conglomerate and the Kakeled and 'Hypagnostus limestone' beds (for precise drill core depths, see Fig. 3). In addition, a lateral equivalent to the Exsulans Limestone Bed occurs in the lowermost part of the formation (Fig. 3).

A thin glauconitic packstone bed (1.55−1.53 m), bounded by prominent disconformities, caps the Alum Shale Formation. It is referred to the Latorp Limestone (1.55−1.10 m), which mainly comprises a dark grey, glauconitic limestone. The uppermost part of the Tomten-1 drill core is represented by the Lanna Limestone (1.10−0 m), which is characterized by extensively bioturbated light grey beds belonging to the Mid-Ordovician 'orthoceratite limestone'.

Biostratigraphy of the Alum Shale Formation

The Alum Shale Formation of Scandinavia is generally richly fossiliferous, and the faunas are dominated by polymerid trilobites and agnostoids that form the basis of a detailed biostratigraphical framework (e.g., Westergård 1946, 1947; Henningsmoen 1957; Ahlberg 2003; Axheimer & Ahlberg 2003; Terfelt et al. 2008; Ahlberg & Terfelt 2012; Nielsen et al. 2014).

The faunal succession and ranges of trilobites and agnostoids in the Cambrian of Västergötland have been studied by, e.g., Westergård (1922), Ahlberg & Ahlgren (1996) and Terfelt (2003). These studies have shown that there are several gaps of various magnitudes within the succession. Cambrian Series 3 is currently subdivided into three superzones (in ascending order): the *Acadoparadoxides oelandicus*, *Paradoxides paradoxissimus* and *Paradoxides forchhammeri* superzones (Nielsen et al. 2014). The *A. oelandicus* Superzone is largely absent in Västergötland, and the latter two are incomplete. The Furongian Series includes six superzones (in ascending order): the *Olenus, Parabolina, Leptoplastus, Protopeltura, Peltura* and *Acerocarina* superzones (Nielsen et al. 2014). Except for Kinnekulle, the upper *Acerocarina* Superzone is absent in Västergötland, whereas the other five are partially incomplete (Westergård 1947; Weidner & Nielsen 2013).

Cambrian Series 3

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) and it is used herein (Fig. 4) with minor modifications introduced by Axheimer et al. (2006), Høyberget & Bruton (2008), Weidner & Nielsen (2014) and Weidner & Ebbestad (2014). Peng & Robison (2000) divided the traditional 'middle' Cambrian (roughly corresponding to Cambrian Series 3) 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). Note that the *P. bulbus* Zone is represented by the upper *L. laevigata* Zone in Scandinavia, and that the *Agnostus pisiformis* Zone now forms the uppermost zone in the Cambrian Series 3 of Scandinavia (Axheimer et al. 2006).

With the exception of the absence of most, or all, of the lowermost superzone (the *Acadoparadoxides oelandicus* Superzone), the Cambrian Series 3 succession is fairly complete in the Tomten-1 drill core (Fig. 4). The lowermost 1.5 m in the drill core is largely unfossiliferous, except for lingulate brachiopods. The lowest occurrence of *Ptychagnostus gibbus* is at 24.20 m, and that of *P. atavus* is at 24.13 m (Figs 4, 5). *Ptychagnostus atavus* (Fig. 5G–J, O) ranges up to 19.45 m. The interval between 19.32 and 13.10 m is poorly fossiliferous, and the upper boundary of the *P. atavus* Zone is difficult to firmly establish. That boundary probably is located in or close to the unfossiliferous 'Hypagnostus limestone bank' (located at 17.42–17.26 m; cf. Weidner et al. 2004). The *P. punctuosus* and *G. nathorsti* zones have not been identified in the Tomten-1 succession. The base of the *L. laevigata* Zone probably is located somewhere within the limestone interval between 17.42 and 16.5 m. Ten poorly preserved specimens of *Lejopyge* sp. were recorded at 15.31 m (Fig. 5P). The base of the overlying *A. pisiformis* Zone is marked by the appearance at 12.18 m of the eponymous species (Fig. 5N, Q; see also 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.

Furongian

Based on the significant works of Westergård (1922, 1947) and Henningsmoen (1957), Terfelt et al. (2008, 2011) divided the Furongian (roughly corresponding to the traditional 'Upper Cambrian', excluding the *A. pisiformis* Zone) of Scandinavia into two parallel zonations based on agnostoids and polymerids, respectively. This biostratigraphical scheme is used herein (Fig. 4) with minor amendments suggested by Høyberget & Bruton (2012), Weidner & Nielsen (2013), Nielsen et al. (2014) and Rasmussen et al. (2015).

The base of the Furongian Series is defined by the first appearance datum (FAD) of *Glypagnostus reticulatus* (see Peng et al. 2004; Ahlberg & Terfelt 2012; Nielsen et al. 2014), which is not found in the drill core. However, *Olenus gibbosus* (Fig. 6E–G, M, N) occurs at 11.56–11.14 m and is indicative of the *O. gibbosus* Zone, the base of which coincides with the FAD of *G. reticulatus* (Terfelt et al. 2008, 2011). Moreover, *Agnostus* (*Homagnostus*) *obesus* (Fig. 6I, J), which also is indicative of the base of the *G. reticulatus* Zone (Ahlberg & Terfelt 2012), appears at the same level as *O. gibbosus*, and ranges between 11.56 and 10.71 m in the drill core. The upper boundary of the *O. gibbosus* Zone is tentatively placed at 11.14 m. The last occurrence of *A.* (*Homagnostus*) *obesus* is generally indicative of the lower part of the *P. brevispina* Zone (Ahlberg & Ahlgren 1996; Ahlberg & Terfelt 2012), which, however, has not been positively identified in the drill core.

The presence of the orthid brachiopod *Orusia lenticularis* (Fig. 6P, Q; 10.60–10.29 m) is an indication of the *Parabolina* Superzone, although it can occur also in the lowest part of the succeeding *Leptoplastus* 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 commonly associated with *Parabolina spinulosa* (Westergård 1922; Terfelt 2003), and the presence of *O. lenticularis* is here taken as indicative of the *P. spinulosa* Zone.

Following the *Parabolina* Superzone there is a considerable hiatus and the *Leptoplastus* and *Protopletura* superzones are missing. The first occurrence of *Sphaerophthalmus alatus* (at 8.80 m; Fig. 6A, B) is indicative of the base of the *Ctenopyge tumida* Zone (Terfelt et al. 2008), and *C. tumida* occurs at 8.54 m (Fig. 6O). The first occurrence of *Peltura scarabaeoides scarabaeoides* at 8.11 m is indicative of the base of the *C. bisculata* Zone. Although the eponymous fossil is not found in the Tomten-1 drill core, the upper boundary of the zone is conterminous with the first occurrence of *Ctenopyge linnarssoni* at 5.78 m. *Ctenopyge linnarssoni* is only present in the lowest part of the zone (Fig. 6C). However, *Peltura scarabaeoides scarabaeoides* (Fig. 6H) ranges to the top of the Furongian (at 1.70 m) in the Tomten-1 drill core, suggesting that the uppermost part of the Furongian belongs to the *C. linnarssoni* Zone. A prominent hiatus is present between the top of the *C. linnarssoni* Zone and the Lower Ordovician strata.

Remarks on preservation and associated fauna

The preservation of Cambrian fossils in Västergötland is often excellent in the limestones and less good in the shales (Westergård 1922; Terfelt 2003). In addition to the frequently occurring agnostoids and polymerid trilobites, as outlined above, the Tomten-1 drill core also contains brachiopods, conodont elements, fossils of uncertain affinity and trace fossils.

Brachiopods and agnostoids are occasionally very poorly preserved, perhaps indicating (partial) dissolution (cf. Eriksson & Terfelt 2007). The Kvarntorp Member contains abundant shell fragments of indeterminate lingulate brachiopods. The lack or scarcity of macrofossils, trilobites and agnostoids in particular, in some levels of the drill core (19.33–15.32 m; 10.28–8.95 m) could be regarded as so-called 'barren intervals' (see Eriksson & Terfelt 2007).

Discussion

Westergård (1946) assigned the Exsulans Limestone Bed to the *P. gibbus* Zone. The eponymous species has only been recorded from that limestone unit in the drill core, and therefore the lower boundary of the zone cannot be precisely located. It is uncertain whether the lowermost and poorly fossiliferous 1.5 m of the Alum Shale Formation belongs to the *P. gibbus* or *Ptychagnostus praecurrens*/*Acadoparadoxides pinus* Zone (see also Nielsen & Schovsbo 2007). Recent data suggest, however, that it should be assigned to the *P. gibbus* Zone (Nielsen & Schovsbo 2015).

Westergård (1922, pp. 70–71, fig. 35) described the Cambrian stratigraphy in the Tomten quarry. He estimated the '*Olenus* Superzone' to be 0.2 m thick and the *Parabolina spinulosa* Zone as 0.6 m thick. Due to lack of diagnostic fossils, the precise thicknesses of these biostratigraphic units cannot be unambiguously determined in the Tomten-1 drill core.

Westergård (1922) identified the '*Leptoplastus* Superzone' in the top part of Kakeled Limestone Bed (previously known as the 'Great Orsten Bank'). Fossils indicative of this superzone were not recorded from the drill core.

The thin glauconitic packstone that forms the basal bed of the Lower Ordovician Latorp Limestone in the drill core belongs to the *Paroistodus proteus* conodont Zone, and thus the uppermost Tremadocian or lowermost Floian (Hunneberg Baltoscandian Stage). The glauconitic packstone is in turn truncated by another hiatus spanning the overlying *Prioniodus elegans* Zone, and the remainder of the Latorp Limestone records the uppermost Floian (Billingen Baltoscandian Stage) *Oepikodus evae* Zone (Olgun 1987; cf. Lehnert et al. 2012, 2013; Calner et al. 2013). The presence of the trilobite species *Varvia breviceps* and *Megistaspis estonica* in the Latorp Limestone in the Tomten quarry (Thorslund 1937; Tjernvik 1956) is consistent with the above interpretation (see Pärnaste et al. 2013), but the local Ordovician trilobite zonation remains to be documented in detail.

The Lanna Limestone beds that form the uppermost part of the Tomten-1 drill core belong to the *Baltoniodus triangularis*–*Baltoniodus navis* interval (Olgun 1987), and are thus early Dapingian (Middle Ordovician) in age. Lehnert et al. (2012, 2013) and Calner et al. (2013) assigned the Ordovician succession in the Tomten quarry to the Tremadocian Bjørkåsholmen Formation and the Darriwilian Holen Limestone. While the facies within the lowermost bed(s) of the Ordovician succession in Tomten resemble that of the Bjørkåsholmen Formation (see Egenhoff et al. 2010), this distinction is not supported by palaeontological data (Thorslund 1937; Tjernvik 1956; Olgun 1987). The Holen Limestone is, however, present in the uppermost part of the quarry.

Conclusions

The Tomten-1 drill core succession consists of strata spanning the uppermost part of Cambrian Series 2, Cambrian Series 3, Furongian and the Lower–Middle Ordovician. The lowermost part of the succession belongs to the Lingulid Sandstone Member (File Haidar Formation), which is disconformably overlain by the Kvarntorp Member (Borgholm Formation). The succeeding Alum Shale Formation forms the bulk of the succession. It is truncated by the Lower Ordovician (?Tremadocian–Floian) Latorp Limestone, which in turn is overlain by the Middle Ordovician (Dapingian) Lanna Limestone. Biostratigraphically, the Alum Shale Formation is subdivided into the following agnostoid and polymerid 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. Biostratigraphy and conspicuous unconformities show that the drill core succession is incomplete and that there are several substantial gaps of various magnitudes (Fig. 7). The most significant gaps have been recorded in the Furongian and Lower Ordovician.

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Figures

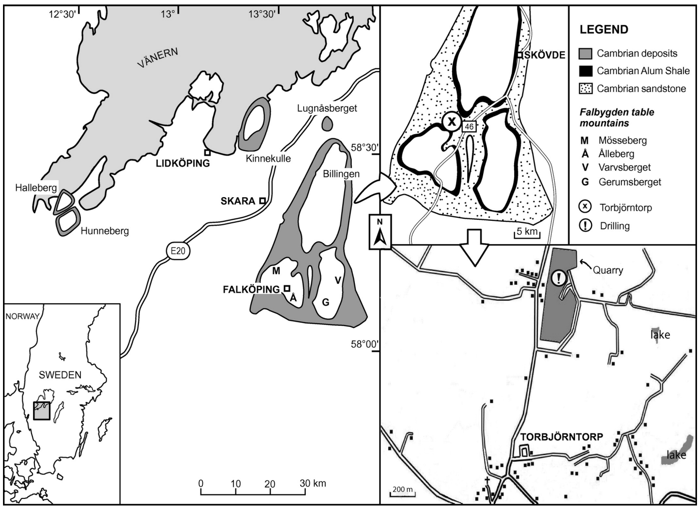

Fig. 1. Map of Västergötland, Sweden, showing Cambrian outcrop areas and the location of the Tomten-1 drill site close to the municipality of Torbjörntorp. Modified from Axheimer et al. (2006, fig. 3).

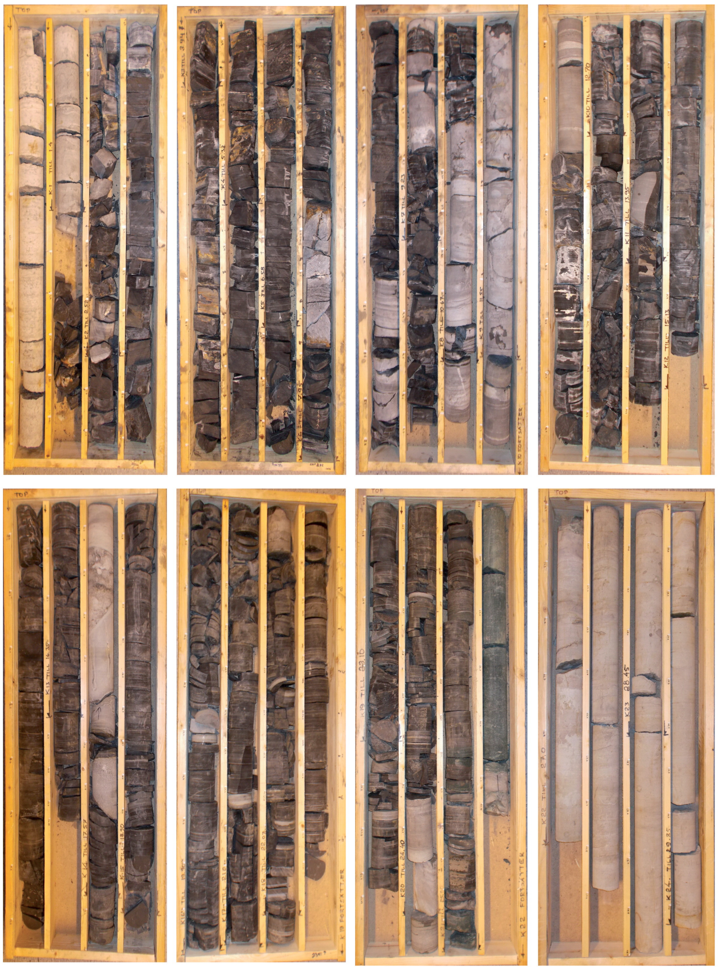

Fig. 2. Overview of the complete Tomten-1 drill core. Topmost part at the upper left corner and basal part at lower right corner. Each drill core box is c. 1 m long.

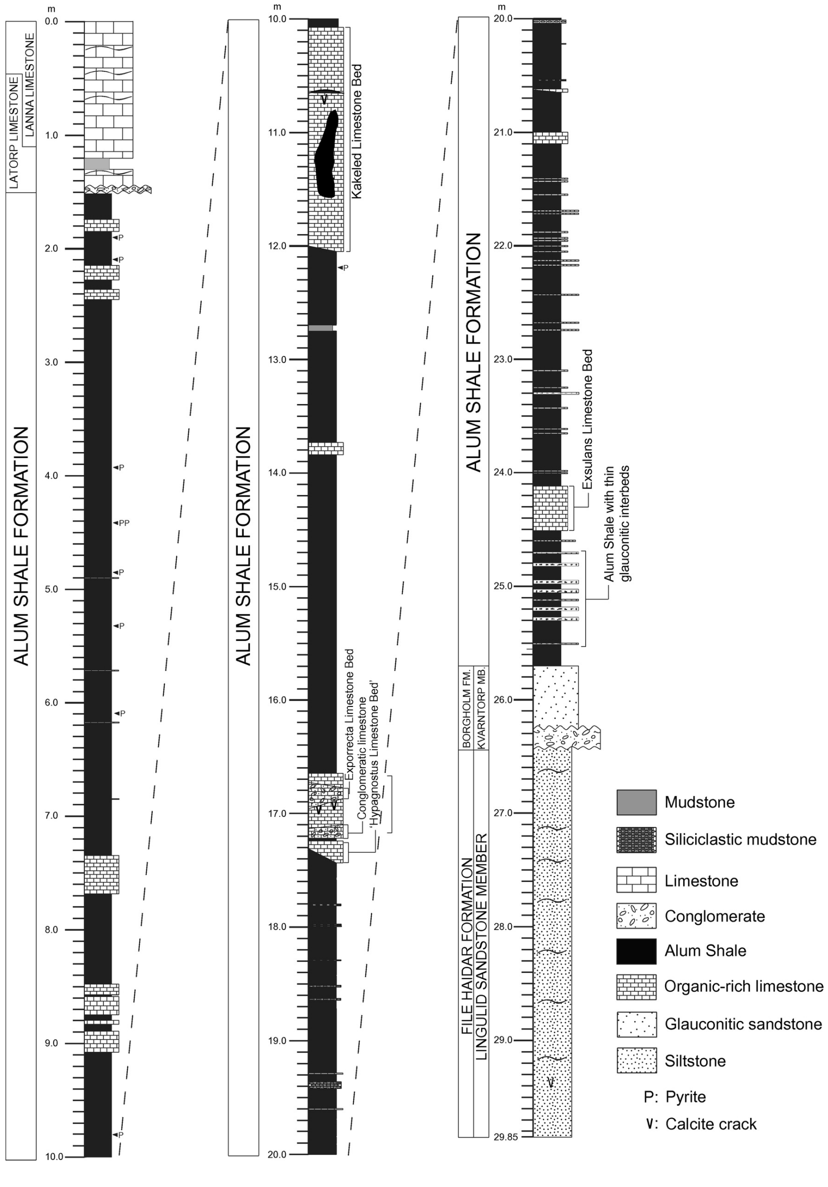

Fig. 3. Lithological succession of the Tomten-1 drill core, Torbjörntorp, Västergötland, Sweden.

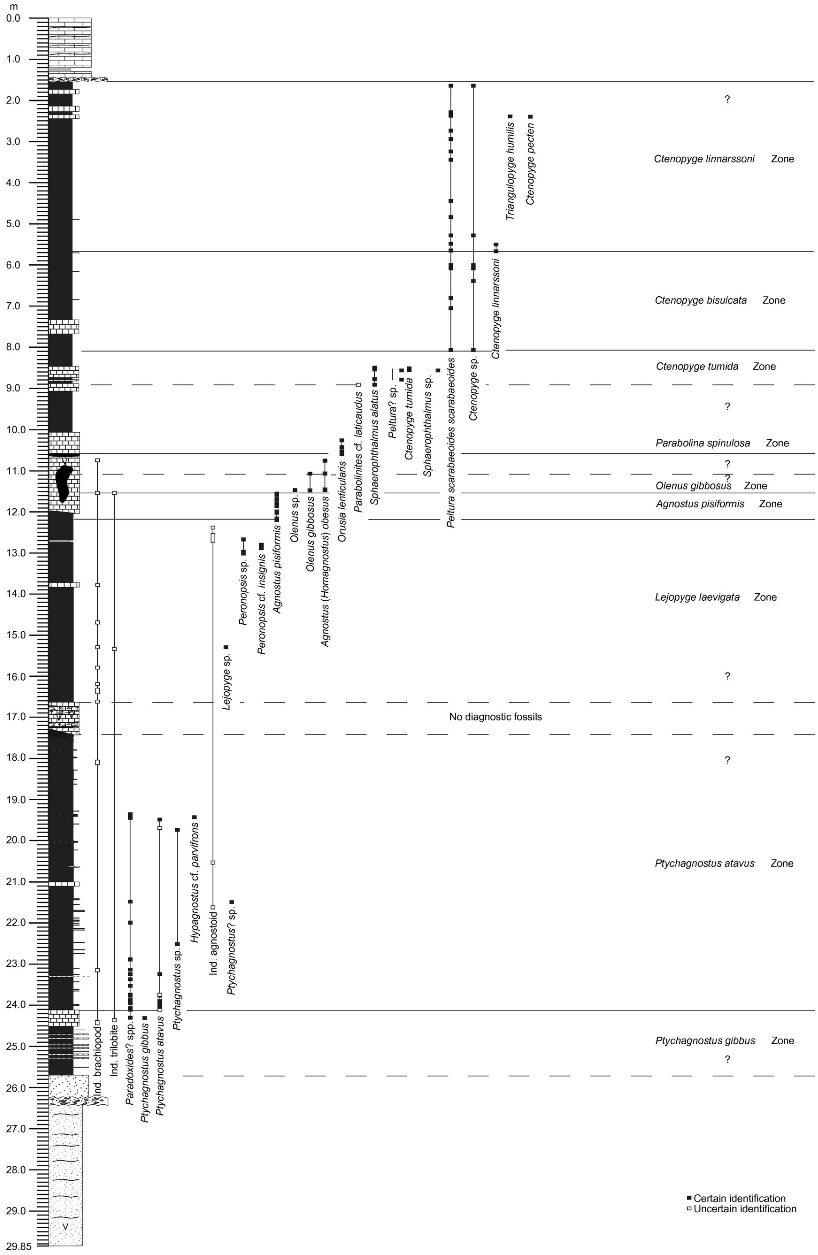

Fig. 4. Biostratigraphy and ranges of fossils in the Alum Shale Formation of the Tomten-1 drill core, Torbjörntorp, Västergötland, Sweden.

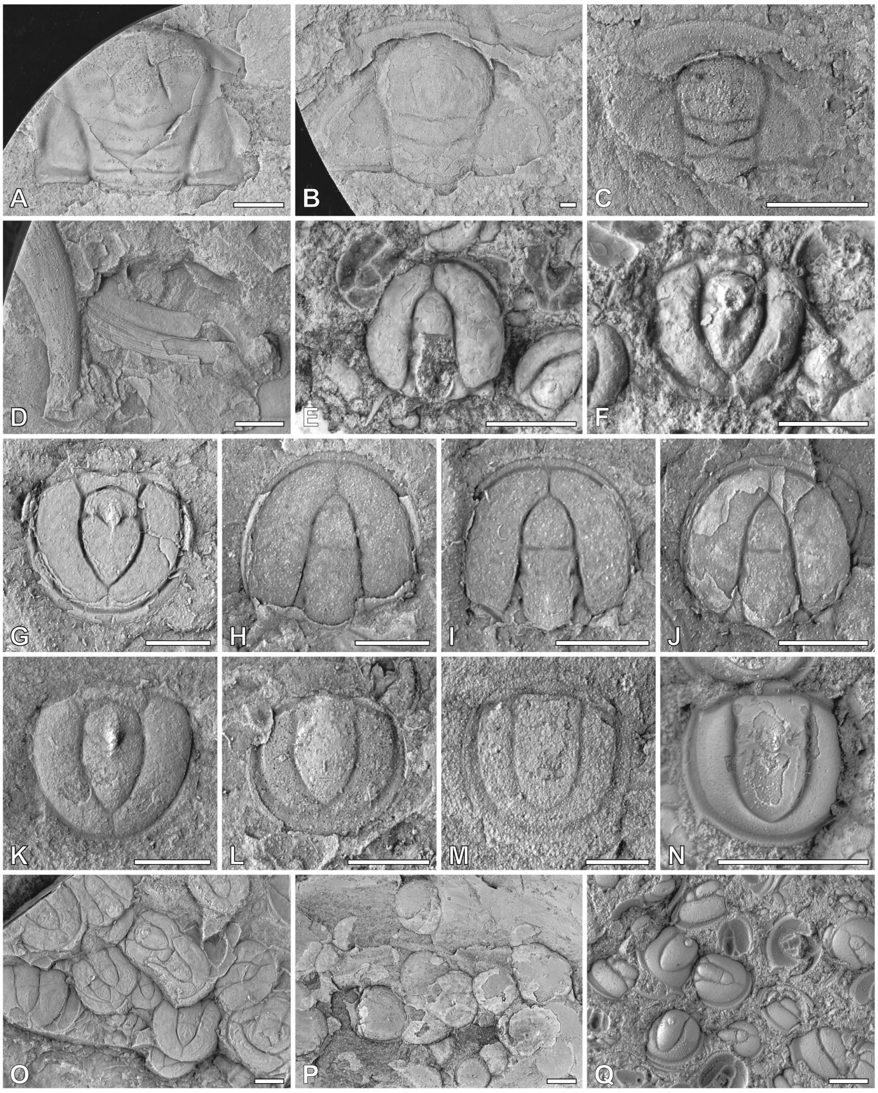

Fig. 5. Agnostoids and trilobites from Cambrian Series 3 in the Tomten-1 drill core. Scale bars correspond to 2 mm. **A–D.** *Paradoxides*? spp. from the *P. atavus* Zone. **A.** Cranidium (19.32 m), LO 12349t. **B.** Cranidium (23.43 m), LO 12350t. **C.** Juvenile cranidium (23.71 m), LO 12351t. **D.** Cephalic border and librigenal spine (23.86 m), LO 12352t. **E–F.** *Ptychagnostus gibbus* (Linnarsson, 1869) from the *P. gibbus* Zone (24.20 m). **E.** Cephalon, LO 12353t. **F.** Pygidium, LO 12354t. **G–J.** *Ptychagnostus atavus* (Tullberg, 1880) from the *P. atavus* Zone (23.67 m). **G.** Pygidium, LO 12355t. **H.** Cephalon, LO 12356t. **I.** Cephalon, LO 12357t. **J.** Cephalon, LO 12358t. **K.** *Ptychagnostus* cf. *atavus*, pygidium from the *P. atavus* Zone (24.09 m), LO 12359t. **L.** *Hypagnostus* cf. *parvifrons* (Linnarsson, 1869), pygidium from the *P. atavus* Zone (19.42 m), LO 12360t. **M.** *Peronopsis* sp., cephalon from the *L. laevigata* Zone (13.02 m), LO 12361t. **N.** *Agnostus pisiformis* (Wahlenberg, 1818), pygidium from the *A. pisiformis* Zone (11.92 m), LO 12362t. **O.** Mass occurrence of *Ptychagnostus atavus* (Tullberg, 1880) from the *P. atavus* Zone (24.02 m), LO 12363t. **P.** Mass occurrence of *Lejopyge* sp. from the *L. laevigata* Zone (15.31 m), LO 12364t. **Q.** Mass occurrence of *Agnostus pisiformis* from the *A. pisiformis* Zone (11.92 m), LO 12365t.

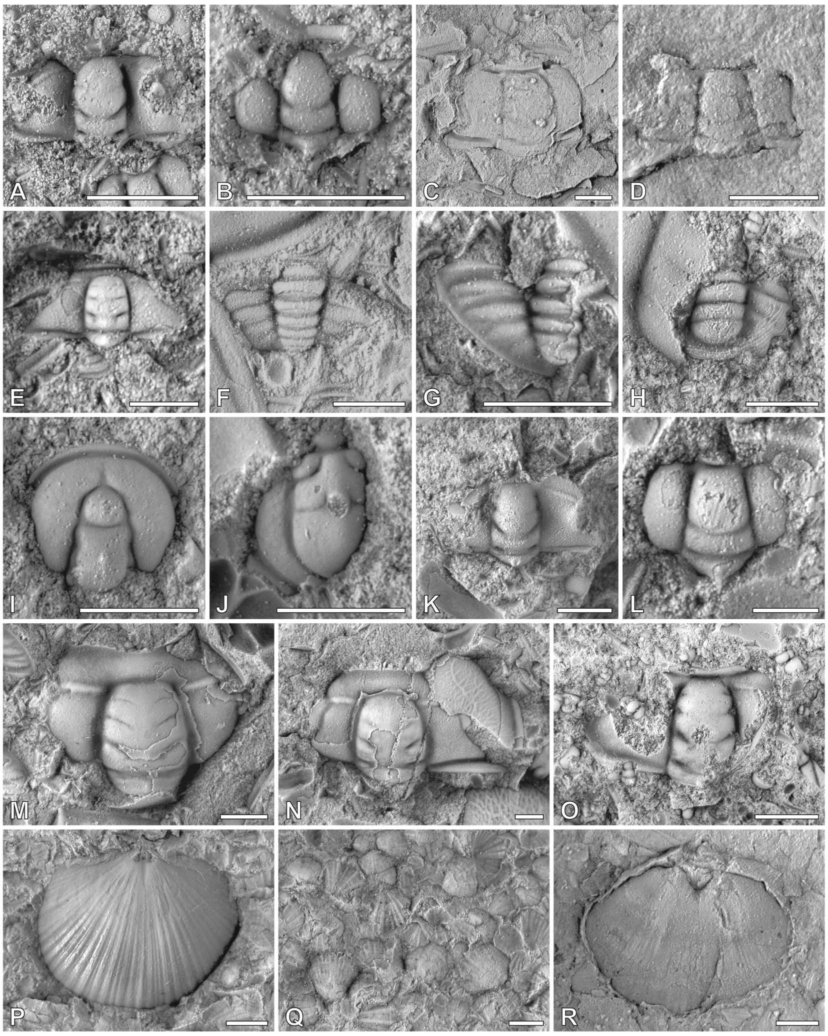

Fig. 6. Agnostoids, trilobites and brachiopods from the Furongian in the Tomten-1 drill core. Scale bars correspond to 2 mm. **A–B.** *Sphaerophthalmus alatus* (Boeck, 1838) from the *Ctenopyge tumida* Zone (8.50 m). **A.** Cranidium, LO 12366t. **B.** Cranidium, LO 12367t. **C.** *Ctenopyge linnarssoni* Westergård, 1922, cranidium from the *C. linnarssoni* Zone (5.78 m), LO 12368t. **D.** *Ctenopyge* sp., cranidium from the *C. linnarssoni* Zone (5.35 m), LO 12369t. **E–G.** *Olenus gibbosus* (Wahlenberg, 1818) from the *O. gibbosus* Zone (11.14 m). **E.** Juvenile cranidium, LO 12370t. **F.** Pygidium, LO 12371t. **G.** Pygidium, LO 12372t. **H.** *Peltura scarabaeoides scarabaeoides* (Wahlenberg, 1818), pygidium from the *C. linnarssoni* Zone (2.42 m), LO 12373t. **I–J.** *Agnostus* (*Homagnostus*) *obesus* (Belt, 1867) from the *O. gibbosus* Zone (11.14 m). **I.** Cephalon, LO 12374t. **J.** Pygidium, LO 12375t. **K.** *Ctenopyge pecten* (Salter, 1864), cranidium from the *C. linnarssoni* Zone (2.42 m), LO 12376t . **L.** *Triangulopyge humilis* (Phillips, 1848), cranidium from the *C. linnarssoni* Zone (2.42 m), LO 12377t. **M–N.** *Olenus gibbosus* from the *O. gibbosus* Zone (11.14 m). **M.** Cranidium, LO 12378t. **N.** Cranidium and librigena, LO 12379t. **O.** *Ctenopyge tumida* Westergård, 1922, cranidium from the *C. tumida* Zone (8.54 m), LO 12380t. **P–Q.** *Orusia lenticularis* (Wahlenberg, 1818) from the *P. spinulosa* Zone. **P.** Partially exfoliated dorsal valve showing adductor muscle scars and the cardinal process (10.60 m), LO 12381t. **Q.** Abundant small specimens (10.55 m), LO 12382t. **R.** Indeterminate brachiopod from the *L. laevigata* Zone (16.64 m), LO 12383t.

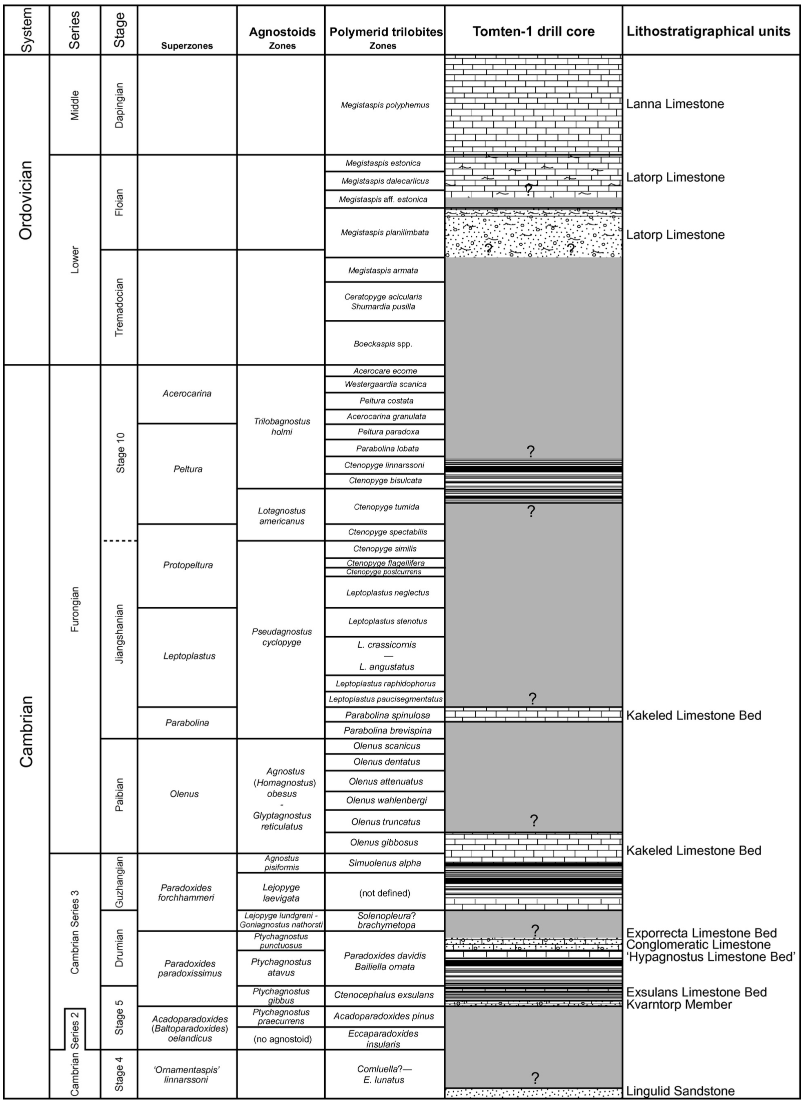

Fig. 7. Stratigraphical subdivision of the succession in the Tomten-1 drill core, Västergötland, Sweden. Grey shading marks hiatuses. Cambrian biostratigraphy based on Axheimer et al. (2006), Høyberget & Bruton (2008), Terfelt et al. (2008, 2011), Nielsen et al. (2014), and Rasmussen et al. (2015). Ordovician trilobite zonation after Pärnaste et al. (2013).