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Integrated Cambrian biostratigraphy and carbon isotope chemostratigraphy of the Grönhögen-2015 drill core, Öland, Sweden

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Abstract – The Grönhögen-2015 core drilling on southern Öland, Sweden, penetrated 50.15 m of Cambrian Series 3, Furongian and Lower–Middle Ordovician strata. The Cambrian succession includes the Äleklinta Member (upper Stage 5) of the Borgholm Formation and the Alum Shale Formation (Guzhangian–Tremadocian). Agnostoids and trilobites allowed subdivision of the succession into eight biozones, in ascending order: the uppermost Cambrian Series 3 (Guzhangian) *Agnostus pisiformis* Zone and the Furongian *Olenus gibbosus*, *O. truncatus*, *Parabolina spinulosa*, *Sphaerophthalmus*? *flagellifer*, *Ctenopyge tumida*, *C. linnarssoni* and *Parabolina lobata* zones. Conspicuous lithologic unconformities and the biostratigraphy show that the succession is incomplete and that there are several substantial gaps of variable magnitudes. Carbon isotope analyses ($\delta^{13}C_{org}$) through the Alum Shale Formation revealed two globally significant excursions: the Steptoean Positive Carbon Isotope Excursion (SPICE) in the lower–middle Paibian Stage, and the negative Top of Cambrian Excursion (TOCE), previously referred to as the HERB Event, in Stage 10. The $\delta^{13}C_{org}$ chemostratigraphy is tied directly to the biostratigraphy and used for an improved integration of these excursions with the standard agnostoid and trilobite zonation of Scandinavia. Their relations to that of coeval successions in Baltoscandia and elsewhere are discussed. The maximum amplitudes of the SPICE and TOCE in the Grönhögen succession are comparable to those recorded in drill cores retrieved from Scania, southern Sweden. The results of this study will be useful for assessing biostratigraphic relations between shale successions and carbonate facies on a global scale.

Keywords: carbon isotope excursion, trilobites, agnostoids, Borgholm Formation, Alum Shale Formation, Scandinavia

1. Introduction

Throughout most of Cambrian and Ordovician times, Baltica was an isolated continent with distinctive and largely endemic faunas different from those of contemporary palaeoplates elsewhere. This substantial terrane encompasses much of northern Europe and is bounded by the Ural Mountains in the east, the Caledonides in the northwest and the Trans-European Suture Zone in the southwest (e.g. Cocks & Fortey, 1998; Torsvik & Cocks, 2005, 2013). Palaeomagnetic data indicate that Baltica was geographically inverted relative to its present configuration and lay at temperate to subtropical latitudes (35–65° south of the palaeoequator) during Cambrian times (Torsvik & Rehnström, 2001; Torsvik & Cocks, 2005, 2017; Cocks & Torsvik, 2005; Álvaro *et al.* 2013). Much of the craton was submerged under a shallow to moderately deep epeiric sea for long periods of Early Palaeozoic time (e.g. Cocks & Torsvik, 2005; Calner *et al.* 2013; Torsvik & Cocks, 2017). Extensive weathering and erosion during late Neoproterozoic time resulted in a low topography, and hence sediment starvation, for most of Cambrian and Early–Middle Ordovician times. The Cambrian through Middle Ordovician sedimentary cover of Baltoscandia (*sensu* Martinsson, 1974) is therefore condensed and relatively thin, commonly less than 300 m in total.

Outcrop areas with lower Palaeozoic sedimentary successions are widely distributed in Baltoscandia, from Finnmark in northernmost Norway to the island of Bornholm, Denmark, in the south (Fig. 1a; Nielsen & Schovsbo, 2007, fig. 1, 2011, fig. 1, 2015, fig. 1). Most outcrops occur within the East European (or Russian) Platform or in scattered outliers in Norway, on the mainland of Sweden, and on Bornholm. Numerous outcrops are also present in a relatively narrow belt with (par-)autochthonous and allochthonous rocks along the Caledonian thrust front. The preserved deposits are erosional remnants of what originally was a

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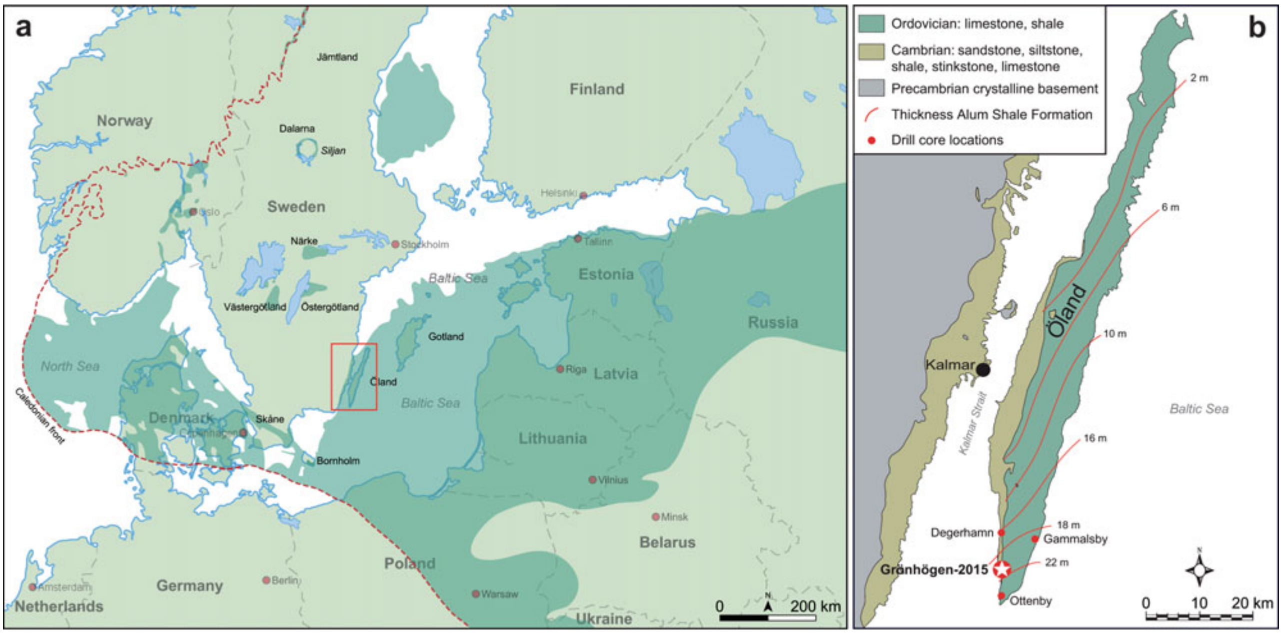

Figure 1. (a) Map of southern Sweden and the surrounding Baltoscandian region showing the distribution of lower Palaeozoic rocks (green shading). Modified from Lindskog & Eriksson (2017). (b) Simplified geological map of Öland, southern Sweden, showing the location of the Grönhögen-2015 drill site and the location of other core drillings referred to in the text. Unbroken lines represent isopachytes for the Cambrian Series 3 through Lower Ordovician (Tremadocian) Alum Shale Formation. Modified from Erlström (2016, fig. 1).

broad sedimentary blanket that covered most of Baltoscandia.

The Cambrian through lowermost Ordovician (Tremadocian) succession of Scandinavia can be broadly divided into two divisions: a lower division dominated by Terreneuvian and Cambrian Series 2 coarse-grained siliciclastic rocks, generally resting on Precambrian crystalline rocks, and an upper division consisting predominantly of Cambrian Series 3 through lower Tremadocian mudstones and shales with subordinate limestone beds and lenses. The boundary between these broad divisions is marked by a prominent unconformity ascribed to non-deposition and erosion during a eustatic sea-level fall that at least partially correlates with the regressive 'Hawke Bay Event' (Bergström & Ahlberg, 1981; Nielsen & Schovsbo, 2007, 2011, 2015). In western Baltica (Scandinavia) this sea-level fall coincided with epeirogenic uplift (Nielsen & Schovsbo, 2007, 2015). The upper division comprises the silt- and mudstone-dominated Borgholm Formation (Cambrian Series 3) followed by dark grey to black, organic-rich siliciclastic mudstones and shales of the Alum Shale Formation (Nielsen & Schovsbo, 2007). The latter formation ranges from the upper part of Cambrian Series 3 through the lower Tremadocian and contains subordinate limestone beds and concretionary lenses, referred to as *orsten* or stinkstone (for general reviews, see Martinsson, 1974; Bergström & Gee, 1985; Andersson *et al*. 1985; Thickpenny, 1987; Buchardt, Nielsen & Schovsbo, 1997).

The epeiric sea that covered the Baltoscandian (or Baltic) palaeobasin was characterized by significant spatial and temporal variations in the redox state of the seafloor and water column. The Terreneuvian and Cambrian Series 2 sandstone-dominated succession was deposited in shallow marine and well-oxygenated environments, whereas the kerogen-rich strata of the Alum Shale Formation suggest deposition under poorly oxygenated (dysoxic to anoxic) conditions in a shallow to moderately deep sea (e.g. Westergård, 1922; Henningsmoen, 1957; Thickpenny, 1984, 1987; Buchardt, Nielsen & Schovsbo, 1997; Schovsbo, 2001, 2002; Nielsen & Schovsbo, 2013; Egenhoff *et al*. 2015).

This paper focuses on the Cambrian succession in a new drill core, Grönhögen-2015, from the classical geological outcrop area of the island of Öland, southern Sweden. The purpose of the paper is to describe the general stratigraphy of the Grönhögen-2015 core, and to present a high-resolution biostratigraphy and a $\delta^{13}C_{org}$ isotope stratigraphy of its Cambrian portion. The biostratigraphy is based on agnostoids and polymerid trilobites. The $\delta^{13}C_{org}$ chemostratigraphy is tied directly to the biostratigraphy, and its relations to that of coeval successions in Baltoscandia and elsewhere are discussed. This is one of the very few $\delta^{13}C_{org}$ investigations in the Cambrian Series 3 through Lower Ordovician (Tremadocian) successions in Baltoscandia and also one of the few $\delta^{13}C_{org}$ studies dealing with this interval in the world.

2. Location and general remarks

In the spring of 2015, a core drilling, Grönhögen-2015, was performed adjacent to Mörbylånga municipality's groundwater wells at Grönhögen, southern Öland, Sweden (Erlström, 2016; Fig. 1b). The drilling penetrated a 50.15 m thick succession of Lower–Middle Ordovician (0–∼ 19.0 m), Furongian (∼ 19.0−25.73 m) and Cambrian Series 3 (25.73−50.15 m) strata. All depths are measured from the ground level. The core, which has a diameter of 83 mm down to 15.00 m and 61 mm between 15.00 and 50.15 m, is housed at the Geological Survey of Sweden, Lund, Sweden. The recovery of the tectonically undisturbed, essentially horizontal, core rock succession is close to 100 %.

The drilling was made by the Engineering Geology group of the Department of Measurement Technology and Industrial Electrical Engineering, Lund University, with an Atlas Copco CT20 drill rig (*Riksriggen*). The purpose of the drilling was to obtain information on the subsurface bedrock geology and to collect sample material for a chemical characterization of the bedrock. The core drilling included geophysical borehole logging, for example gamma ray logging, and a detailed XRF-scanning of the core (see Erlström 2016). The XRF (X-ray fluorescence) concentrations of more than 30 elements were determined. These elements include molybdenum and vanadium that are important proxies for redox conditions during deposition (for Mo and V logs, see Erlström 2016, fig. 11).

The major portion of the drill core is represented by the Cambrian Series 3 (Stage 5) Borgholm Formation and the Cambrian Series 3 (Guzhangian) through Lower Ordovician (Tremadocian) Alum Shale Formation (Erlström, 2016; Fig. 2). The succession shows no tectonic disturbances or major late diagenetic alteration, and has most likely not been buried below the oil window (cf. Buchardt, Nielsen & Schovsbo, 1997, fig. 19).

3. Materials and methods

The core was split up and examined at the centimetre scale in the laboratory. Fossils and macroscopic lithological characteristics were recorded and examined under a binocular light microscope. Subsequently, each fossil was meticulously studied and identified, generally to species level. Selected diagnostic fossils were painted with opaque matt black and then lightly coated with a sublimate of ammonium chloride prior to being photographed using a digital camera (Canon 550D) mounted on a table-set camera holder with four external light sources. Figured specimens are stored in the type collections of the Department of Geology, Lund University, Sweden (LO, which signifies Lund Original).

A total of 73 samples were collected from a 41.16 m thick rock interval (50.11–8.95 m) of the Grönhögen-2015 drill core. All samples were subjected to processing for $\delta^{13}C_{org}$ following the procedure described by Ahlberg *et al.* (2009) and Terfelt, Eriksson & Schmitz (2014). Carbon isotope analyses of organic carbon were performed with a Flash EA 2000 elemental analyser connected online to a ThermoFinnigan Delta V Plus mass spectrometer. All carbon isotope values are reported in the conventional δ-notation in per mil relative to the V-PDB (Vienna-Pee Dee Belemnite). Accuracy and reproducibility of the analyses were checked by replicate analyses of laboratory standards calibrated to international standards USGS 40 and 41. Reproducibility was ± 0.05 ‰ (1σ). The obtained $\delta^{13}C_{org}$ values are listed in Table 1 and used for the isotope curve described and discussed below.

4. Lithologic succession

The lowermost 18.45 m (50.15−31.70 m) of the Grönhögen-2015 drill core consists of a relatively uniform succession of alternating grey or reddish grey siltstones and siliciclastic mudstones with thin shale partings (Fig. 2). This succession represents the Äleklinta Member of the Borgholm Formation (see Nielsen & Schovsbo, 2007, 2015). Bioturbation and small-scale cross-bedding occur frequently throughout this interval, particularly in siltstone beds in the upper part (cf. Erlström, 2016).

The Äleklinta Member is disconformably overlain by the Cambrian Series 3 (Guzhangian) through Lower Ordovician (Tremadocian) Alum Shale Formation, which has a thickness of 22.30 m (31.70−9.40 m). The lowermost part of the Alum Shale Formation is represented by a *c.* 7 cm thick basal conglomerate with mudstone clasts, the Exporrecta Conglomerate Bed. This calcareous conglomerate rests with a distinct disconformity on the Äleklinta Member and is in turn disconformably overlain by dark grey silt-rich mudstones (31.63−30.42 m).

The remainder of the Alum Shale Formation (30.42−9.40 m) consists of dark grey to black shales and siliciclastic mudstones with several concretionary limestone lenses and prominent limestone beds, including the Kakeled Limestone Bed, which comprises several beds separated by black shale (cf. Nielsen & Schovsbo, 2007; Rasmussen, Rasmussen & Nielsen, 2017). Some of the limestone beds are conglomeratic or brecciated, the most conspicuous of them between 20.38 and 20.12 m.

The upper 9.40 m of the core succession includes the Lower Ordovician Bjørkåsholmen Formation (Tremadocian) and ‘Latorp Limestone’ (?Tremadocian−Floian, provisional topoformation), which in turn are overlain by the Middle Ordovician (Dapingian−Darriwilian) ‘Lanna’ and ‘Holen’ limestones (topoformations; see Lindskog & Eriksson, 2017).

5. Biostratigraphy

Cambrian Series 3 and Furongian strata of Scandinavia are generally richly fossiliferous. The faunas are commonly dominated by polymerid trilobites and agnostoid arthropods, which provide a firm basis for the biostratigraphic classification (e.g. Westergård, 1922, 1946, 1947*a*; Henningsmoen, 1957; Ahlberg, 2003; Axheimer & Ahlberg, 2003; Axheimer *et al.* 2006;

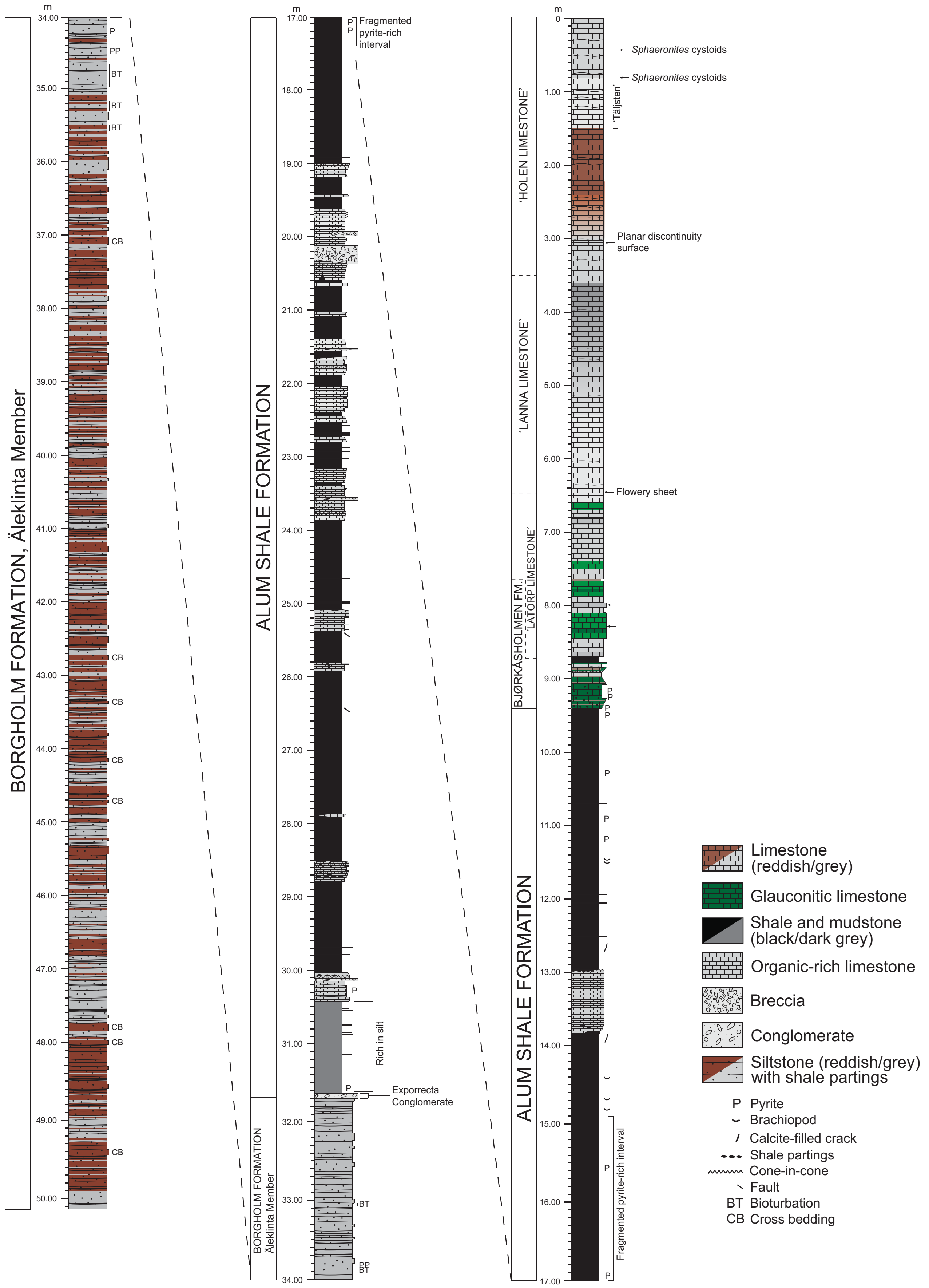

Figure 2. Lithological succession and formation classification of the Grönhögen-2015 drill core, Öland, Sweden. The m-figures to the left of the columns refer to drilling depth.

Table 1. Stable isotope data from organic matter ($\delta^{13}C_{org}$) from the Grönhögen-2015 drill core. All values are reported relative to Vienna-Pee Dee Belemnite (V-PDB)

Sample (core depth, m)	$\delta^{13}C_{org}$ (‰)	Biozone	Series
50.11	−28.93	*P. gibbus*?	Series 3
48.35	−28.46	*P. gibbus*?	Series 3
46.39	−28.65	*P. gibbus*?	Series 3
44.62	−28.83	*P. gibbus*?	Series 3
42.47	−28.59	*P. gibbus*?	Series 3
40.59	−28.60	*P. gibbus*?	Series 3
38.52	−28.80	*P. gibbus*?	Series 3
36.29	−28.73	*P. gibbus*?	Series 3
34.44	−28.82	*P. gibbus*?	Series 3
33.97	−28.45	*P. gibbus*?	Series 3
33.48	−28.61	*P. gibbus*?	Series 3
33.16	−28.78	*P. gibbus*?	Series 3
32.48	−28.97	*P. gibbus*?	Series 3
32.11	−28.72	*P. gibbus*?	Series 3
31.82	−28.36	*P. gibbus*?	Series 3
31.61	−31.37	*A. pisiformis*?	Series 3
31.50	−30.39	*A. pisiformis*?	Series 3
31.22 (I)	−30.74	*A. pisiformis*?	Series 3
31.22 (II)	−30.70	*A. pisiformis*?	Series 3
30.80 (I)	−30.19	*A. pisiformis*?	Series 3
30.80 (II)	−30.03	*A. pisiformis*?	Series 3
30.47	−29.62	*A. pisiformis*?	Series 3
29.82	−29.88	*A. pisiformis*	Series 3
29.53	−29.68	*A. pisiformis*	Series 3
29.24	−29.44	*A. pisiformis*	Series 3
28.85	−29.74	*A. pisiformis*	Series 3
28.81	−29.32	*A. pisiformis*	Series 3
28.48	−29.58	*A. pisiformis*	Series 3
28.10	−29.18	*A. pisiformis*	Series 3
27.70	−29.21	*A. pisiformis*	Series 3
27.45	−28.94	*A. pisiformis*	Series 3
27.10	−29.14	*A. pisiformis*	Series 3
26.80	−29.03	*A. pisiformis*	Series 3
26.62	−29.03	*A. pisiformis*	Series 3
26.55	−29.20	*A. pisiformis*	Series 3
26.43	−29.12	*A. pisiformis*	Series 3
26.30	−28.94	*A. pisiformis*	Series 3
26.00	−28.93	*A. pisiformis*	Series 3
25.69	−28.66	*O. gibbosus*	Furongian
25.50	−28.08	*O. gibbosus*	Furongian
25.03	−27.62	*Olenus*?	Furongian
24.70	−27.27	*Olenus*?	Furongian
24.51	−28.03	*Olenus*?	Furongian
24.41	−28.33	*Olenus*?	Furongian
24.28	−27.98	*Olenus*?	Furongian
24.08	−27.92	*Olenus*?	Furongian
23.91 (I)	−28.54	*Olenus*?	Furongian
23.91 (II)	−28.41	*Olenus*?	Furongian
23.38	−28.64	*P. spinulosa*	Furongian
23.08	−29.53	*P. spinulosa*	Furongian
22.85	−29.40	*P. spinulosa*	Furongian
22.57	−29.56	*P. spinulosa*	Furongian
22.42	−29.67	?	Furongian
21.90	−29.01	*S.? flagellifer*	Furongian
21.59	−28.81	*C. tumida*	Furongian
21.35	−28.88	*C. tumida*	Furongian
21.01	−28.74	*C. tumida*	Furongian
20.75	−29.20	*C. tumida*	Furongian
20.61	−29.30	*C. linnarssoni*	Furongian
20.12	−29.41	*C. linnarssoni*	Furongian
19.87	−29.48	*C. linnarssoni*	Furongian
19.55	−29.46	*P. lobata*	Furongian
19.20	−29.34	?	Furongian
18.95	−29.23	?	Furongian?
18.72	−29.54	?	Furongian?
18.70	−29.85	?	Lower Ordovician?
18.49	−29.85	?	Lower Ordovician?
17.65	−30.02	?	Lower Ordovician
16.60	−30.10	?	Lower Ordovician
15.60	−30.05	?	Lower Ordovician
14.45	−29.87	?	Lower Ordovician
14.40	−30.21	?	Lower Ordovician
12.60	−29.81	?	Lower Ordovician
10.80	−29.75	?	Lower Ordovician
9.90	−30.12	?	Lower Ordovician
8.95	−30.09	?	Lower Ordovician

Høyberget & Bruton, 2008). Recent efforts to produce a high-resolution trilobite zonation of the Series 3 and Furongian in Scandinavia, especially in southern Sweden and southern Norway, have resulted in new zonal nomenclature, and because of significant differences in ecologic and geographic distributions, separate zonal schemes are now being used for the polymerid trilobites and the agnostoids of Scandinavia (e.g. Terfelt *et al.* 2008; Terfelt, Ahlberg & Eriksson, 2011; Ahlberg & Terfelt, 2012; Nielsen *et al.* 2014; Rasmussen, Nielsen & Schovsbo, 2015; Babcock, Peng & Ahlberg, 2017).

The succession and ranges of agnostoids and trilobites in the Cambrian of Öland have been studied by, for example, Westergård (1922, 1936, 1944, 1947*b*), Wærn (1952), Weidner & Nielsen (2009) and Rasmussen, Rasmussen & Nielsen (2017). Their studies have shown that there are several unconformities and substantial gaps both in Series 3 and in the Furongian.

The preservation of fossils in the Grönhögen-2015 drill core is often excellent in the limestones, but less good in the shales and mudstones. In addition to agnostoids and polymerid trilobites, the Cambrian succession of the drill core also contains brachiopods, phosphatocopine arthropods and trace fossils.

5.a. Cambrian Series 3

Cambrian Series 3 is currently subdivided into three superzones (the *Acadoparadoxides oelandicus*, *Paradoxides paradoxissimus* and *Paradoxides forchhammeri* superzones) and seven agnostoid zones (Høyberget & Bruton, 2008; Nielsen *et al.* 2014; Babcock, Peng & Ahlberg, 2017). The *A. oelandicus* Superzone is well developed on Öland, whereas the *P. paradoxissimus* and *P. forchhammeri* superzones are incomplete (Westergård, 1946; Martinsson, 1974).

The Cambrian Series 3 succession is incomplete in the Grönhögen-2015 drill core and only represented by upper Stage 5 and Guzhangian strata (Fig. 3). Trace fossils occur in abundance in the thin-bedded mudstones and siltstones of the Äleklinta Member, but no body fossils were found. Elsewhere on Öland, the Äleklinta Member has locally yielded a fairly diverse fauna indicative of the *Ptychagnostus gibbus* Zone (upper Stage 5; Weidner & Nielsen, 2009). The Exporrecta Conglomerate is poorly constrained biostratigraphically, but generally considered equivalent to the

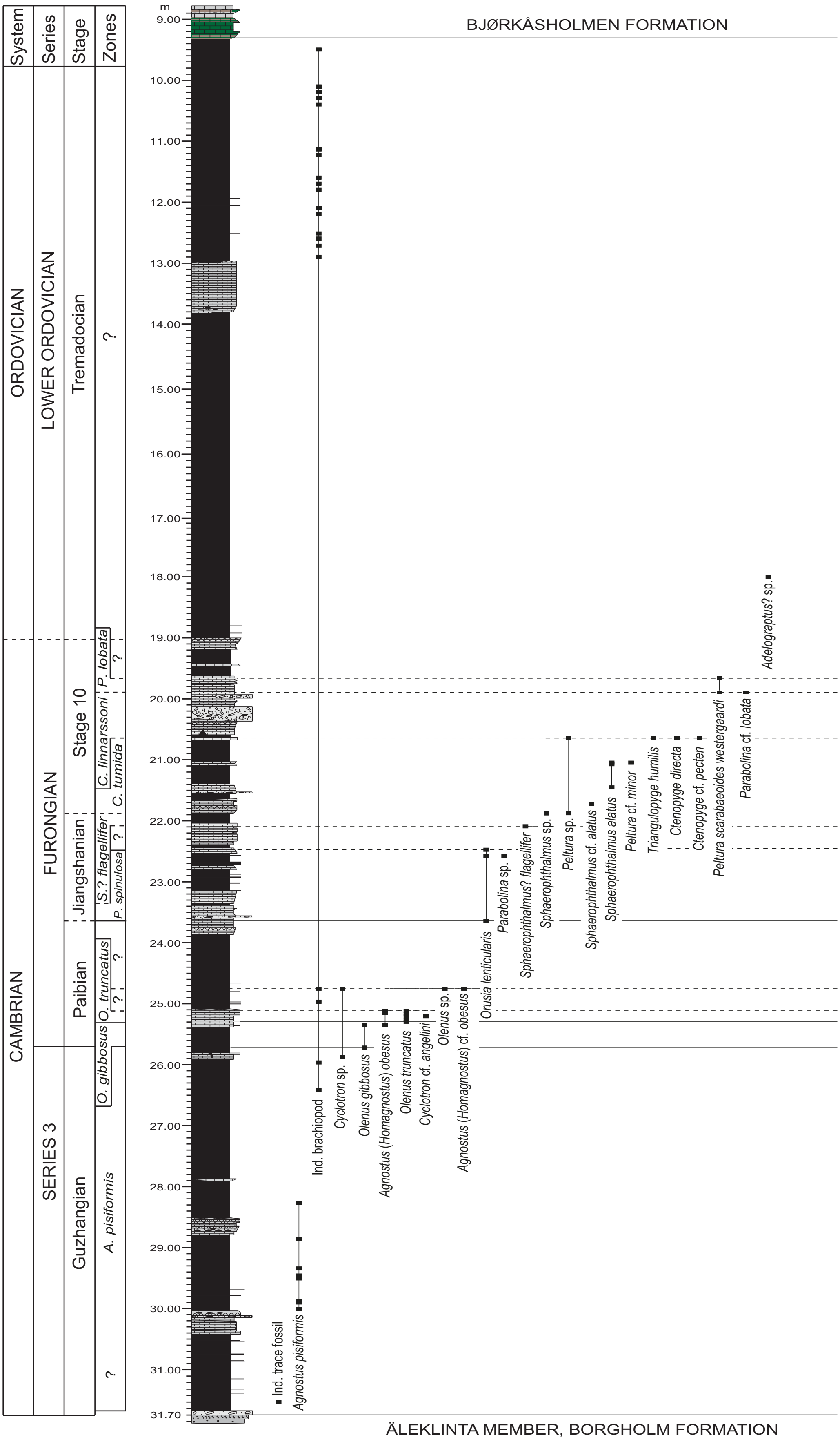

Figure 3. (Colour online) Biostratigraphy and ranges of fossils in the Alum Shale Formation of the Grönhögen-2015 drill core, Öland, Sweden.

Andrarum Limestone Bed (Guzhangian Stage; lower *Lejopyge laevigata* Zone) of Scania (Skåne), southern Sweden. The interval between 31.63 m and 25.73 m is assigned to the *Agnostus pisiformis* Zone (Fig. 3). The lower boundary of the zone is, however, difficult to firmly establish since the lowermost *c*. 1.6 m of this interval is largely unfossiliferous, except for a few trace fossils. The eponymous species (Fig. 4a) ranges from 30.00 m to 28.30 m and is abundant at some levels. The upper part of the *A. pisiformis* Zone is barren of body fossils, apart from a few phosphatocopine arthropods (*Cyclotron* sp.) and linguliformean brachiopods near the top of the zone.

5.b. Furongian

The Furongian biostratigraphy of Scandinavia is largely based on the succession of olenid trilobites. The rate of faunal turnover is very high, which enabled Westergård (1922, 1947*a*) and Henningsmoen (1957) to establish a high-resolution biostratigraphy. Their biostratigraphical scheme has subsequently been slightly modified (Terfelt *et al*. 2008; Terfelt, Ahlberg & Eriksson, 2011; Høyberget & Bruton, 2012; Weidner & Nielsen, 2013; Rasmussen, Nielsen & Schovsbo, 2015) and the Furongian of Scandinavia is now being subdivided into six superzones and 26 polymerid (olenid) trilobite zones that can be linked to four parallel agnostoid zones (Nielsen *et al*. 2014; Rasmussen, Rasmussen & Nielsen, 2017; Babcock, Peng & Ahlberg, 2017, fig. 3). In ascending order, the Furongian Series includes: the *Olenus*, *Parabolina*, *Leptoplastus*, *Protopeltura*, *Peltura* and *Acerocarina* superzones (Nielsen *et al*. 2014). All superzones have been recorded on Öland but they are partially or largely incomplete (Westergård, 1947*a*; Rasmussen, Rasmussen & Nielsen, 2017).

Agnostoids and trilobites allowed subdivision of the Furongian succession of the Grönhögen-2015 drill core into seven biozones, in ascending order: the *Olenus gibbosus*, *O. truncatus*, *Parabolina spinulosa*, *Sphaerophthalmus*? *flagellifer*, *Ctenopyge tumida*, *C. linnarssoni* and *Parabolina lobata* zones (Fig. 3). The biostratigraphy and conspicuously developed unconformities show that the Alum Shale Formation is incomplete and that there are several substantial gaps of variable magnitudes. The *Leptoplastus* (Jiangshanian) and *Acerocarina* (uppermost Stage 10) superzones appear to be missing, and the *Olenus* (Paibian) and *Protopeltura* (upper Jiangshanian) superzones are incomplete (Fig. 5).

The base of the Furongian Series and the Paibian Stage is placed at the lowest occurrence *Olenus gibbosus* (Fig. 4e). This species occurs at 25.73–25.35 m and is indicative of the *O. gibbosus* Zone, the base of which coincides with the first appearance datum (FAD) of *Glyptagnostus reticulatus* (see Peng *et al*. 2004; Ahlberg & Terfelt, 2012; Nielsen *et al*. 2014). The *O. gibbosus* Zone is succeeded by a 20 cm thick succession with *O. truncatus* (Fig. 4b–d), *Agnostus* (*Homagnostus*) *obesus* (Fig. 4g, h) and the phosphatocopine *Cyclotron* cf. *angelini* (Fig. 4f).

The base of the *Parabolina* Superzone, which roughly coincides with the base of the Jiangshanian Stage (Ahlberg & Terfelt, 2012), cannot be positively identified in the drill core, as there is a barren interval between the lower Paibian *O. truncatus* Zone and the Jiangshanian *Parabolina spinulosa* Zone. However, the orthid brachiopod *Orusia lenticularis* (Fig. 4i) is most commonly associated with *Parabolina spinulosa* (Westergård, 1922; Terfelt, 2003) and its presence in the 23.65–22.49 m interval is suggestive of the *P. spinulosa* Zone. Following the *Parabolina* Superzone there is a substantial hiatus and the *Leptoplastus* Superzone and most of the *Protopeltura* Superzone are missing; only the *Sphaerophthalmus*? *flagellifer* Zone has been positively identified in the middle and upper Jiangshanian, with the eponymous species occurring at 22.10 m.

Cambrian Stage 10 strata are represented by the *Ctenopyge tumida*, *C. linnarssoni* and *Parabolina lobata* zones. The base of the *C. tumida* Zone is placed at the first occurrence of a species of *Sphaerophthalmus* at 21.88 m (Fig. 4k; cf. Terfelt, Ahlberg & Eriksson, 2011). The lower and middle part of this zone has yielded *S. alatus* (Fig. 4l–n) and *Peltura* cf. *minor*. The *Ctenopyge bisulcata* Zone appears to be missing and the *C. tumida* Zone is followed by the *C. linnarssoni* Zone, the base of which is placed at 20.70 m and at the lowest occurrences of *Triangulopyge humilis* (Fig. 4o), *Ctenopyge directa* (Fig. 4j) and *C.* cf. *pecten*. The first occurrence of *Peltura scarabaeoides westergaardi* (Fig. 4r) and *Parabolina* cf. *lobata* (Fig. 4s) at 19.92–19.90 m is indicative of the base of the *P. lobata* Zone. The top of this zone is placed at the last occurrence of *P. scarabaeoides westergaardi* (Fig. 4q) at 19.65 m. The *Parabolina lobata* Zone is overlain by a thin (0.4 m) succession of unfossiliferous shales that may represent the *Peltura paradoxa* Zone. A prominent hiatus, probably comprising the uppermost four zones in the Furongian (the *Acerocarina granulata* Zone through the *Acerocare ecorne* Zone), is present between the top of the *Parabolina lobata*/*Peltura paradoxa* Zone and the lowermost Ordovician (Tremadocian) succession (Fig. 5). The base of the Ordovician is poorly constrained biostratigraphically but is tentatively placed at *c*. 19.0 m, below the first graptolite (*Adelograptus*? sp. at 17.95 m) and where there is a distinctive negative jump in the carbon isotopic curve.

6. $\delta^{13}C_{org}$ chemostratigraphy

During the last three decades, the potential of carbon isotopes for global stratigraphical correlation of Cambrian strata has attracted a great deal of international interest (e.g. Brasier 1993; Montañez *et al*. 2000; Saltzman *et al*. 2000, 2004; Zhu *et al*. 2004; Zhu, Babcock & Peng, 2006; Peng, Babcock & Cooper, 2012 and references therein). Although many studies on Cambrian chemostratigraphy have been carried

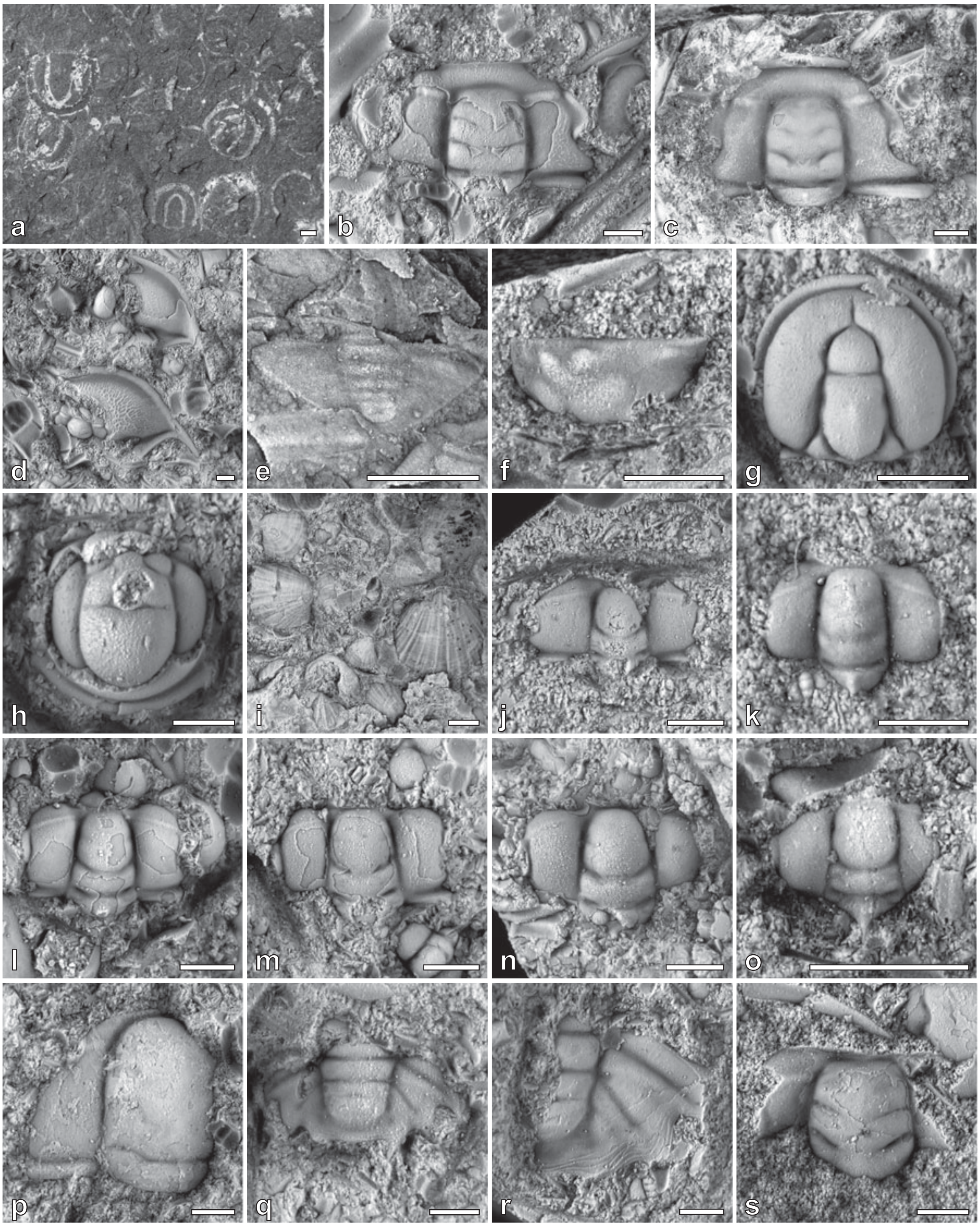

Figure 4. Fossils from Cambrian Series 3 and the Furongian in the Grönhögen-2015 drill core. Scale bars correspond to 1 mm. (a) *Agnostus pisiformis* (Wahlenberg, 1818), cephala and pygidia from the *A. pisiformis* Zone (29.90 m), LO 12418t. (b–d) *Olenus truncatus* (Brünnich, 1781) from the *O. truncatus* Zone: (b) cranidium (25.15–25.18 m), LO 12419t; (c) cranidium (25.25 m), LO 12420t; (d) cranidia and librigenae (25.15–25.18 m), LO 12421t. (e) *Olenus gibbosus* (Wahlenberg, 1818), pygidium from the *O. gibbosus* Zone (25.73 m), LO 12422t. (f) *Cyclotron* cf. *angelini* (Linnarsson, 1875) from the *O. truncatus* Zone (25.18–25.20 m), LO 12423t. (g, h) *Agnostus* (*Homagnostus*) *obesus* (Belt, 1867) from the *O. truncatus* Zone (25.15–25.18 m): (g) cephalon, LO 12424t; (h) pygidium, LO 12425t. (i) *Orusia lenticularis* (Wahlenberg, 1818), abundant specimens from the *P. spinulosa* Zone (23.65 m), LO 12426t. (j) *Ctenopyge directa* Lake, 1919, cranidium from the base of the *C. linnarssoni* Zone (20.65–20.70 m), LO 12427t. (k) *Sphaerophthalmus* sp., cranidium from the base of the *Ctenopyge tumida* Zone (21.88 m), LO 12428t. (l–n) *Sphaerophthalmus alatus* (Boeck, 1838) from the *Ctenopyge tumida* Zone (21.05–21.10 m): (l) cranidium, LO 12429t; (m) cranidium, LO 12430t; (n) cranidium, LO 12431t. (o) *Triangulopyge humilis* (Phillips, 1848), cranidium from the base of the *C. linnarssoni* Zone (20.65–20.70 m), LO 12432t. (p) *Peltura* sp., cranidium from the base of the *C. linnarssoni* Zone (20.65–20.70 m), LO 12433t. (q, r) *Peltura scarabaeoides westergaardi* Henningsmoen, 1957 from the *Parabolina lobata* Zone: (q) pygidium (19.65 m), 12434t; (r) pygidium (19.90–19.92 m), LO 12435t. (s) *Parabolina* cf. *lobata*, cranidium from the base of the *P. lobata* Zone (19.90–19.92 m), LO 12436t.

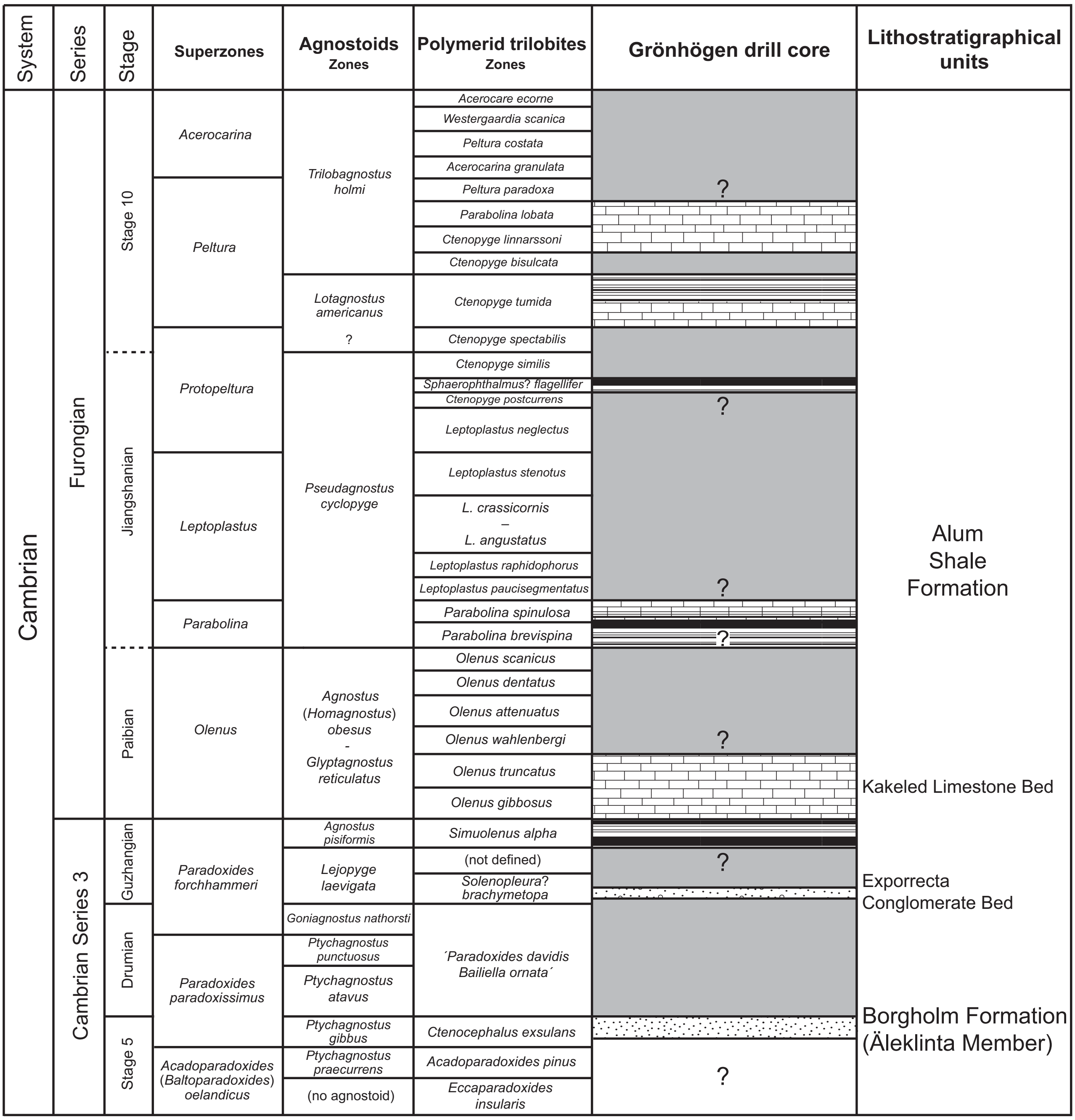

Figure 5. Stratigraphical subdivision of the Cambrian succession in the Grönhögen-2015 drill core, Öland, Sweden. Grey shading indicates unconformities. Biostratigraphy based on Axheimer *et al.* (2006), Høyberget & Bruton (2008), Terfelt *et al.* (2008), Terfelt, Ahlberg & Eriksson (2011), Nielsen *et al.* (2014), Rasmussen, Nielsen & Schovsbo (2015) and Babcock, Peng & Ahlberg (2017).

out, most investigations focused on $\delta^{13}C_{carb}$ using samples from carbonate-dominated or carbonate-rich successions. The Cambrian Series 3 through Furongian succession of Scandinavia is dominated by shales and siliciclastic mudstones. $\delta^{13}C_{org}$ has previously been used in the Cambrian of Scandinavia by Ahlberg *et al.* (2009), Lehnert *et al.* (2013), Terfelt, Eriksson & Schmitz (2014), Lundberg *et al.* (2016) and Hammer & Svensen (2017). These studies and the present one show that $\delta^{13}C_{org}$ chemostratigraphy is useful for correlations between the siliciclastic-dominated successions of Scandinavia and carbonate successions elsewhere in the world.

The 15 stratigraphically lowest samples from the Grönhögen-2015 drill are from the Äleklinta Member (upper Stage 5) and show $\delta^{13}C_{org}$ values between –29.1 and –28.4 ‰ (Fig. 6). At the base of the *Agnostus pisiformis* Zone (31.6 m), there is a significant negative shift in $\delta^{13}C_{org}$ of *c.* −2.5 ‰. This is followed by a positive trend with minor fluctuations in the *A. pisiformis* Zone (Fig. 6).

The carbon isotopic curve through the Furongian shows a distinctive positive excursion in the Paibian (core depth 25.7–23.6 m), which is tied closely to the biostratigraphy (Fig. 6). The amplitude and stratigraphic position of this excursion strongly suggests

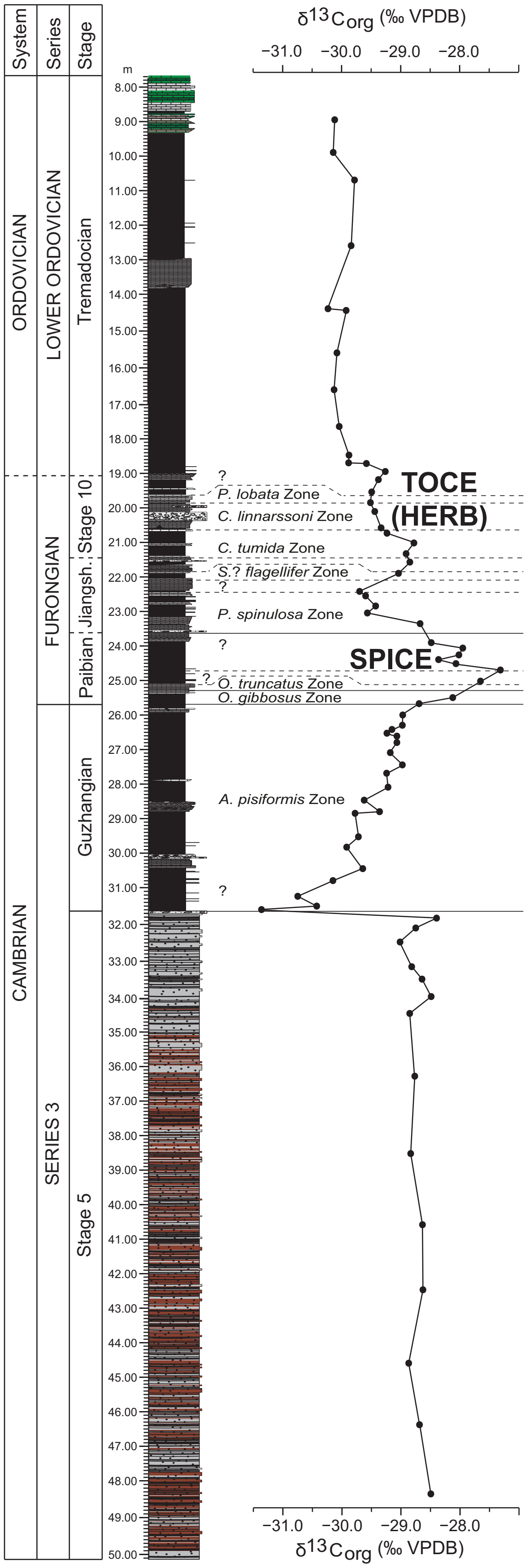

Figure 6. (Colour online) Lithologic log and plot of $\delta^{13}C_{org}$ values through the Cambrian and Lower Ordovician (Tremadocian) of the Grönhögen-2015 drill core. Note the positions of the SPICE and TOCE excursions recognized in the present study. Jiangsh. – Jiangshanian.

that it is the Steptoean Positive Carbon Isotopic Excursion (SPICE; e.g. Saltzman *et al.* 2000; Kouchinsky *et al.* 2008; Ahlberg *et al.* 2009; Gill *et al.* 2011; Wotte & Strauss, 2015; Schiffbauer *et al.* 2017). It has an amplitude of nearly +2 ‰, begins near the first appearance of *Olenus gibbosus* (base of the Paibian), and extends upward into the *O. truncatus* Zone and slightly younger beds (?upper *Olenus* Superzone). A relatively minor (*c.* −0.5 ‰) but consistent trend to more negative $\delta^{13}C_{org}$ values near the top of the Cambrian is seen near the base of the *Ctenopyge linnarssoni* Zone. It displays nadir values just below and above the *Parabolina lobata* Zone. Based on its stratigraphic position, we interpret this interval (21.0–∼ 19.0 m) as an equivalent to the Top of Cambrian Excursion (TOCE; Zhu, Babcock & Peng, 2006). The end of the putative TOCE cannot be precisely recognized because there is likely a gap between the *Parabolina lobata*/*Peltura paradoxa* Zone and the basal Ordovician. The transition between the Cambrian and the Ordovician is marked by a *c.* −0.6 ‰ shift in the carbon isotope values. In the lowermost Ordovician (lower Tremadocian) part of the drill core, $\delta^{13}C_{org}$ values are around –30 ‰ (Fig. 6).

7. Discussion

The Cambrian succession in the Grönhögen-2015 drill core is lithologically and stratigraphically similar to coeval intervals in other drill cores from southern Öland (see, e.g., Westergård, 1944, 1947*b*; Erlström, 2016). The Äleklinta Member is generally barren of body fossils and hence biostratigraphically poorly constrained. However, recent studies show that it should be assigned to the *Ptychagnostus gibbus* Zone (Weidner & Nielsen, 2009; Nielsen & Schovsbo, 2015). The Äleklinta Member is disconformably overlain by the Exporrecta Conglomerate (Guzhangian Stage, probably lower *Lejopyge laevigata* Zone; Axheimer *et al.* 2006), which in turn is overlain by the upper Guzhangian *Agnostus pisiformis* Zone. Thus, the entire Drumian Stage seems to be missing in the Grönhögen-2015 drill core (Fig. 5). The Alum Shale Formation has a thickness of 22.3 m. This figure is closely comparable to the thickness of this formation at Ottenby, 8 km south of Grönhögen (23.3 m; Westergård, 1944) and Gammalsby, 18 km northeast of Grönhögen (18.8 m; Westergård, 1944). The Alum Shale Formation gradually thins out towards the NNW of Öland (Westergård, 1944, 1947*b*; Erlström, 2016). On southernmost Öland, the top of the Cambrian is generally formed by a thin, less than 0.6 m thick, succession assigned to the *Acerocarina granulata* Zone of Weidner & Nielsen (2013) (Westergård 1944, 1947*a*,*b*). This zone and the underlying *Peltura paradoxa* Zone cannot be positively identified in the Grönhögen-2015 drill core owing to lack of fossils in the 19.6–19.0 m interval overlying the *Parabolina lobata* Zone. At the Degerhamn quarry, 15 km north of

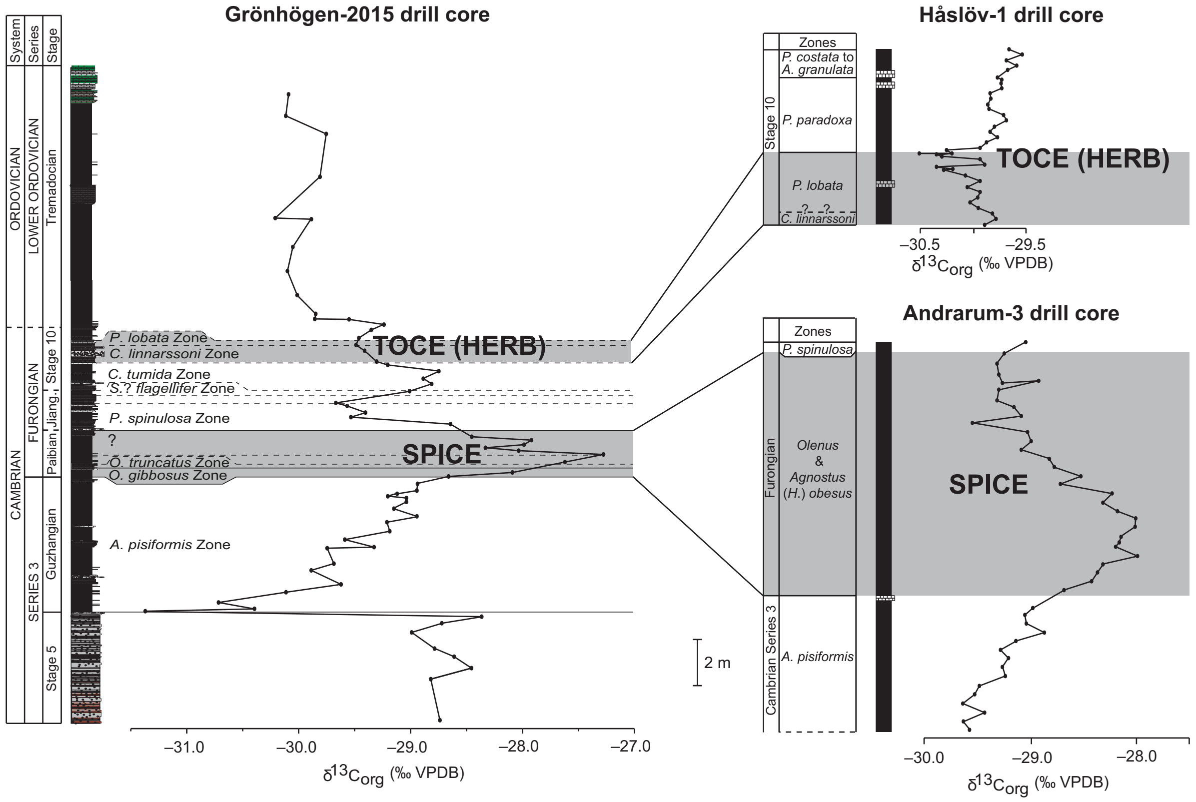

Figure 7. (Colour online) Comparison of the $\delta^{13}C_{org}$ curve from the Grönhögen-2015 drill core with $\delta^{13}C_{org}$ curves from the apparently continuous successions in the Andrarum-3 and Håslöv-1 drill cores from Skåne (Scania), southern Sweden. The Andrarum-3 curve is after Ahlberg *et al.* (2009) and the Håslöv-1 curve is after Terfelt, Eriksson & Schmitz (2014). Note the closely similar stratigraphic position of the SPICE and TOCE excursions in these successions. Jiang. – Jiangshanian.

Grönhögen, the top of the Cambrian consists of strata assigned to the *P. lobata* Zone (Rasmussen, Rasmussen & Nielsen, 2017).

Despite some scatter in the $\delta^{13}C_{org}$ values (Fig. 6) in parts of the drill core succession, two globally significant excursions can be identified, the SPICE and a subdued TOCE (previously referred to as the HERB Event; Ripperdan, 2002), both of which are generally considered as large and rapid excursions indicative of perturbations in the oceanic carbon cycle (e.g. Ripperdan *et al.* 1992; Saltzman *et al.* 2000, 2004; Miller *et al.* 2015). The onset of the SPICE is associated with the base of the Furongian Series (Peng *et al.* 2004), whereas the TOCE occurs in the lower *Eoconodontus* Conodont Zone near the top of the Cambrian (e.g. Miller *et al.* 2014, 2015). The SPICE and TOCE excursions have been recorded from most Cambrian palaeocontinents and have great potential for global correlation in the Paibian and Cambrian Stage 10, respectively (e.g. Saltzman *et al.* 2000; Sial *et al.* 2008, 2013; Landing, Westrop & Adrain, 2011; Woods *et al.* 2011; Gill *et al.* 2011; Miller *et al.* 2011, 2014, 2015; Ng, Yuan & Lin, 2014; Lim *et al.* 2016; Azmy, 2018). Although it has been argued (e.g. Landing, Westrop & Adrain, 2011) that the HERB Event is different from the TOCE excursion of Zhu, Babcock & Peng, (2006), we follow Peng, Babcock & Cooper (2012), Terfelt, Eriksson & Schmitz (2014), Miller *et al.* (2015) and Li *et al.* (2017) in considering them as the same carbon isotopic excursion.

The magnitude of the SPICE and TOCE in the Grönhögen-2015 succession is comparable to $\delta^{13}C_{org}$ curves from drill cores retrieved from Scania, southern Sweden (SPICE from the Andrarum-3 drill core and TOCE from the Håslöv-1 drill core; Ahlberg *et al.* 2009; Terfelt, Eriksson & Schmitz, 2014; Fig. 7) and at Krekling, southern Norway (SPICE; Hammer & Svensen, 2017). However, the amplitude and expression of the identified isotopic excursions, especially the TOCE, in Swedish successions are typically quite subdued compared to equivalents recorded in other areas (see below). In our drill core, the SPICE begins near the first appearance of *Olenus gibbosus*, which is considered to coincide with the first appearance of *Glyptagnostus reticulatus* and the base of the Furongian Series and the Paibian Stage (Terfelt *et al.* 2008; Terfelt, Ahlberg & Eriksson, 2011). It extends upward into the *O. truncatus* Zone and through unfossiliferous shales that may represent the middle and upper *Olenus* Superzone of Nielsen *et al.* (2014). Hence, the SPICE from the Grönhögen-2015 drill core spans a biostratigraphical interval approximately equivalent to that recorded in the Alum Shale of Scandinavia (Andrarum-3 drill core, southern Sweden, and at Krekling, southern Norway; Ahlberg *et al.* 2009; Hammer & Svensen, 2017) and the Outwoods Shale

Formation in Warwickshire, England (Woods *et al.* 2011). This biostratigraphical interval can be assigned to the lower–middle Paibian Stage. In the Grönhögen-2015 core, the putative TOCE begins near the base of the *Ctenopyge linnarssoni* Zone and has its nadir immediately below and above the *Parabolina lobata* Zone. In the Håslöv-1 drill core, the TOCE interval displays two peaks, a lower one in the upper *P. lobata* Zone and an upper one straddling the *Parabolina lobata–Peltura paradoxa* zonal boundary (Fig. 7; Terfelt, Eriksson & Schmitz, 2014). A double peak has also been recognized in, e.g., western Newfoundland (Stouge, Bagnoli & Azmi, 2016). The TOCE seemingly begins slightly earlier in our drill core and two peaks cannot be identified, probably because of condensation and/or too few data points. In terms of the Baltoscandian conodont biostratigraphy, the TOCE excursion spans the upper *Proconodontus muelleri* Zone and the *Cordylodus*? *andresi* Zone, i.e. an interval that can be correlated with the lower *Eoconodontus* Conodont Zone in Laurentia and elsewhere (Bagnoli & Stouge, 2014).

The negative −2.5 ‰ shift at the base of the Alum Shale Formation coincides with a substantial hiatus and a shift in lithology from mudstones and siltstones in the Äleklinta Member (upper Stage 5) to dark grey mudstone and shales in the lower Alum Shale Formation (upper Guzhangian). Throughout the overlying *Agnostus pisiformis* Zone (upper Guzhangian), $\delta^{13}C_{org}$ values increase until the base of the SPICE (Fig. 6). This positive trend has also been recorded from the pre-SPICE interval in the Andrarum-3 drill core from Scania, southern Sweden (Ahlberg *et al.* 2009), and elsewhere in the world, notably in South China, Kazakhstan and Australia (e.g. Saltzman *et al.* 2000; Wotte & Strauss, 2015). The post-SPICE and pre-TOCE $\delta^{13}C_{org}$ curve in the Grönhögen-2015 drill core displays variable values (between –28.8 and –29.7 ‰), with two 'cycles' in $\delta^{13}C$ being apparent. It is, however, worth noting that significant parts of the post-SPICE and pre-TOCE isotope curve are cut out by gaps in the Furongian succession, the most prominent one being in the middle–upper Jiangshanian Stage.

The overall trends in the presented isotope curve are similar to those present in some published $\delta^{13}C_{carb}$ curves through coeval stratigraphic intervals in other parts of the world. The shift of the $\delta^{13}C_{org}$ in the excursions recorded in the Grönhögen-2015 drill core is approximately half (SPICE) or less than one-fourth (TOCE) the magnitude of coeval $\delta^{13}C_{carb}$ excursions documented from other regions (see also Terfelt, Eriksson & Schmitz, 2014). This difference may be related to spatial and temporal variations in the origin, composition, alteration and diagenesis of the organic matter analysed (Ahlberg *et al.* 2009), with different geographic areas hosting unique geochemical conditions that influence and partly overprint the global $\delta^{13}C$ signal. Still, the present study shows that the SPICE and TOCE are useful for long-distance correlations in both shaly and carbonate successions.

8. Conclusions

The Grönhögen-2015 core drilling penetrated 50.15 m of Cambrian Series 3, Furongian and Lower–Middle Ordovician strata. The lower part of the drill core succession belongs to the upper Äleklinta Member (Borgholm Formation; Cambrian Series 3), which is disconformably overlain by the Cambrian Series 3 (Guzhangian) through Lower Ordovician (Tremadocian) Alum Shale Formation. The upper part of the drill core includes the Lower Ordovician Bjørkåsholmen Formation (Tremadocian) and 'Latorp Limestone' (?Tremadocian–Floian, topoformation), which in turn are overlain by the Middle Ordovician (Dapingian–Darriwilian) 'Lanna' and 'Holen' limestones (topoformations).

Agnostoids and trilobites allowed subdivision of the succession into eight biozones (in ascending order): the uppermost Cambrian Series 3 (Guzhangian) *Agnostus pisiformis* Zone and the Furongian *Olenus gibbosus*, *O. truncatus*, *Parabolina spinulosa*, *Sphaerophthalmus*? *flagellifer*, *Ctenopyge tumida*, *C. linnarssoni* and *Parabolina lobata* zones. The biostratigraphy and conspicuous unconformities show that the Alum Shale Formation is incomplete and that there are several substantial gaps of variable magnitudes. The Furongian *Leptoplastus* Superzone (Jiangshanian) and *Acerocarina* Superzone (Stage 10) appear to be missing, and the Paibian *Olenus* and upper Jiangshanian *Protopeltura* superzones are incomplete.

The Grönhögen-2015 drill core offers an excellent opportunity to calibrate the Furongian $\delta^{13}C_{org}$ curve with the Furongian standard trilobite and agnostoid zone succession of Baltoscandia. Carbon isotopic analyses ($\delta^{13}C_{org}$) through the Alum Shale Formation show two globally significant excursions, the Steptoean Positive Carbon Isotopic Excursion (SPICE) and the Top of Cambrian Carbon isotopic Excursion (TOCE), previously referred to as the HERB Event. The SPICE has an amplitude of *c.* +1.5–2 ‰, begins near the first appearance of *Olenus gibbosus* (base of the Furongian Series and the Paibian Stage), and extends upward into the *O. truncatus* Zone and slightly younger beds (middle and ?upper *Olenus* Superzone). The negative TOCE, which is poorly expressed in the studied succession (net shift *c.* −0.5 ‰), occurs in Stage 10, begins near the base of the *Ctenopyge linnarssoni* Zone and displays nadir values immediately below and above the *Parabolina lobata* Zone. The net shifts of the excursions are comparable to those recorded in drill cores retrieved from Scania, southern Sweden (SPICE from the Andrarum-3 drill core and TOCE from the Håslöv-1 drill core), but they are subdued compared to international counterparts. The occurrence of the TOCE $\delta^{13}C_{org}$ excursion in Stage 10 in southern Sweden has potential for global correlation of the uppermost Cambrian in Baltoscandia with coeval successions elsewhere in the world.

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