Glacial erratic boulders from Jutland, Denmark, feature an uppermost lower Cambrian fauna of the Lingulid Sandstone Member of Västergötland, Sweden

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Weidner, T., Geyer, G., Ebbestad, J. O. R. & von Seckendorff, V. 2015. Glacial erratic boulders from Jutland, Denmark, feature an uppermost lower Cambrian fauna of the Lingulid Sandstone Member of Västergötland, Sweden. © 2015 by Bulletin of the Geological Society of Denmark, Vol. 63, p. 59-86. ISSN 2245-7070. (www.2dgf.dk/publikationer/bulletin).

Reinvestigation of glacial erratic boulders from Jutland, Denmark, and from northern Germany, has revealed a moderately diverse fauna with the trilobites Holmiella? sp., Epichalinipsus anartanus, Epichalinipsus sp. A, Epichalinipsus sp. B, and Berabichia erratica, three species of lingulid brachiopods, one hyolith species, and trace fossils comparable to Halopoa imbricata. Comparison with faunas from the Cambrian of Scandinavia strongly suggested a biostratigraphic position equivalent to the uppermost part of the (revised) Holmia kjerulfi--Ornamentaspis' linnarssoni to lowermost Comluella?–Ellipsocephalus lunatus zones sensu Nielsen & Schovsbo (2011), or the lower to middle part of the traditional 'Ornamentaspis' linnarssoni Zone, but probably a particular horizon and biofacies not yet discovered in Scandinavia. Considerations of glacial transport regimes and the distribution of comparable rock units, as well as a petrographical analysis of the material from the studied erratic boulders and rocks from outcrops in Sweden, indicate that the boulders were derived from the Lingulid Sandstone Member of the File Haidar Formation and the source area is situated in the vicinity of the present-day outcrops in the Halleberg–Hunneberg area, Västergötland, Sweden.

Keywords: Trilobites, Lingulid Sandstone Member, lower Cambrian, Cambrian Series 2, Västergötland, Sweden, Denmark, biostratigraphy, glacial boulders.

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Received 21 April 2015
Accepted in revised form 2 November 2015
Published online 4 December 2015

Trilobite-bearing lower Cambrian strata (provisional Cambrian Series 2) in Sweden have been studied mainly at scattered localities in the south (Scania) and in numerous outcrops along the Caledonian mountain range (Jämtland, Ångermanland and Lapland), in both the autochthonous and allochthonous sequences (Fig. 1A). Rocks of early Cambrian age predominantly consist of siltstone and sandstone. Trilobites recorded from these strata of Baltica are fairly restricted by comparison to those from other Cambrian continents and belong to the olenelloid family Holmiidae (Holmia, Holmiella, Kjerulfia and Schmidtiellus), to the ptychoparioid family Ellipsocephalidae (with species assigned, or provisionally attributed to the genera Comluella, Ellipsocephalus, Ornamentaspis and Strenuaeva), and to the eodiscid genera Runcinodiscus, Calodiscus, Chelodiscus and Neocobbodia. The early Cambrian faunas and biostratigraphy of the Swedish regions are portrayed by Bergström (1973), Ahlberg & Bergström (1978, 1983, 1991), Ahlberg (1979, 1980, 1984a, 1984b, 1984c, 1985), Bergström & Ahlberg (1981), Ahlberg et al. (1986), Nielsen & Schovsbo (2006, 2011) and Høyberget et al. (2015). Studies during the last 15 years have increased our knowledge about these faunas, particularly of those from localities in the northern Caledonides (Moczydłowska et al. 2001; Axheimer et al. 2007; Cederström et al. 2009, 2011, 2012). Due to both outcrop conditions and depositional environments, polymerid trilobites are mostly fragmentary and often
Fig. 1. A, map of Scandinavia showing outcrops of the Cambrian with inserts of the areas in Denmark and Sweden treated in the text; B and B1, maps of Jutland, Denmark, with localities (red) yielding boulders of the fossil-bearing Lingulid Sandstone; C, map of Västergötland showing Lower Palaeozoic outcrops at Halleberg, Hunneberg, Kinnekulle, and Falbygd to the east with localities (red) yielding the fossil-bearing Lingulid Sandstone; C1, detailed map of Halleberg with the localities Ovandalen and Kvillen (base map from Andersson et al. 1985).
do not permit a precise determination; they belong to genera or species endemic to Baltica and are of limited use for intercontinental or even global correlation, whereas correlation into other Cambrian continents is facilitated by the species of *Calodiscus* and *Chelediscus*. The lower Cambrian biostratigraphy of Scandinavia and Baltica in general has thus been in a state of preliminary subdivision and was recently revised by Nielsen & Schovsbo (2011) as shown in Fig. 2.

Of particular interest is the upper lower Cambrian part of the succession, which provides distinct problems for correlation into other regions as emphasized in the discussions on the Cambrian Series 2–Series 3 and Stage 4–Stage 5 boundary (e.g., Geyer & Palmer 1995; Fletcher 2003; Geyer 2005; Sundberg et al. in press). The traditional subdivision and subsequent zonal schemes that recognize a *Holmia kjerulfi* group Zone, a *Proamphyx* (or ‘*Ornamentaspis*’) *linnarssoni* Zone, and a ‘*Protolenus*’ Zone (Fig. 2) are equally unable to characterize the trilobite faunas, lack a recognizable evolutionary development of the trilobites, and are not even readily correlatable with the neighbouring regions of Baltica in northern Poland or the Holy Cross Mountains in southern Poland.

Geyer et al. (2004) described trilobites of the ellipsocephaloid genera *Epichalnipsus* and *Berabichia* from glacial erratic boulders collected at As Hoved and other localities in Denmark and northern Germany. These boulders of trilobite-bearing quartzitic sandstones were interpreted as being derived from the Lingulid Sandstone Member of Västergötland and to represent an unidentified stratigraphical interval. Based on close morphological affinities with ellipsocephaloid trilobites from the Moroccan Atlas ranges, Geyer et al. (2004) proposed a stratigraphic correlation with the *Sectigena* Zone of Morocco, West Gondwana. However, differences in lithology suggested that this type of Lingulid Sandstone was unknown in Sweden.

**Lingulid Sandstone: distribution, lithology, and biostratigraphy**

A key unit for the upper lower Cambrian is the Lingulid Sandstone which is generally treated as a member of the File Haidar Formation (Thorslund &
Westergård 1938; Thorslund 1960; Bergström & Gee 1985; Nielsen & Schovsbo 2006. The Lingulid Sandstone was first adequately recognized by Holm (in Holm & Munthe 1901) who separated Linnarsson’s Fucoid Sandstone (see Wallin 1868) into a lower and an upper unit termed Mickwitzia and Lingulid Sandstone, respectively, based on differences in lithological characters and bedding thicknesses. It is generally regarded as a depositional tongue of the File Haidar Formation extending from the stratotype on Gotland (Thorslund & Westergård 1938; Bergström & Gee 1985) into Öland, Västergötland, Östergötland and Närke. The two units of the File Haidar Formation form the uppermost part of the traditional lower Cambrian succession, but their vertical extent shows an opposite trend. The Mickwitzia Sandstone Member increases in thickness eastward, whereas the Lingulid Sandstone Member has its maximum thickness in the west. In addition, the boundary between the two is locally (Lugnäs, Billingen) marked by a conglomeratic or coarse-grained layer (Linnarsson 1871; Hadding 1927; Westergård 1931; Bergström & Gee 1985; Jensen 1997; Nielsen & Schovsbo 2006) which appears to indicate a hiatus of unknown extent between the units. The Lingulid Sandstone Member appears to testify a change in depositional regime and has been interpreted as a result of deposition in deeper water than the Mickwitzia Sandstone Member, and the sparse amount of fine-grained material has been understood as indication of increased wave action (Hadding 1927; Westergård 1931). Nevertheless, Martinsson (1974) advocated the differences to be a result of deposition at a later stage in the basin. Nielsen & Schovsbo (2011) interpreted both units as two sequences of a continuous depositional history.

Nielsen & Schovsbo (2006) selected the stratotype of the Lingulid Sandstone Member in the Bårstad-2 drill core in Östergötland, which has been described in detail by Eklund (1990).

The Lingulid Sandstone Member is widely distributed in Västergötland in narrow outcrops at the flanks of the renowned table mountains, where it is composed of light grey, moderately to poorly cemented fine-grained quartz sandstone. Its maximum thickness in Västergötland is 28.6 m in the DBH 15/73 core of southern Billingen (Nielsen & Schovsbo 2006).

Only three reports of trilobite findings exist for the Lingulid Sandstone Member of Västergötland (Ahlberg et al. 1986). The upper part of the member in the quarry at Stora Stolan, northern Billingen, yielded a large fragment of a cheek with a genal spine that was tentatively assigned to Holmia grandis Kiær 1917, a species otherwise known only from the lower part of the Holmia kjærefi Zone of the Mjøsa area, Norway (Kiær 1917; Ebbesø et al. 2003). The other report is a fragmentary pygidium identified as Holmiella sp. from the lower part of the Lingulid Sandstone Member in a quarry at Hälleks at Lake Vänern, Kinnekulle (Ahlberg et al. 1986). However, this specimen had originally been attributed to the Mickwitzia Sandstone (Bergström 1981; Ahlberg 1984c). This incomplete pygidium and numerous cranidial fragments from this locality were assigned to Holmiella sp. Both olenelloid taxa were assumed to indicate the Holmia kjærefi Zone and are of little biostratigraphic significance, although Jensen (1997) emphasized the lithological equivalence of the host rocks with the Mickwitzia Sandstone. Furthermore, Jensen (1997) cited the discovery of a relatively complete trilobite by collector Holger Buentke in 1992, which has remained unpublished since and also is uncertain with respect to its precise stratigraphic position. Additional specimens of olenelloids were discovered at the eastern tip of Halleberg by Jan Johansson (personal communication to TW), and ellipsocephalid trilobites were collected by Frank Rudolph in erratic boulders in northern Germany (unpublished, examined by TW).

Eponymous linguliform brachiopods are also known from several localities but have rarely found their way into collections. In summary, the fossil content of the Lingulid Sandstone appears to be far less sparse than commonly assumed, and the poor record is primarily an artefact of collecting and sampling.

This macrofossil record permits an unequivocal assignment to one of the established zones. Nielsen & Schovsbo’s (2011) sequence stratigraphical approach placed the Lingulid Sandstone Member into the LC2–4 sequence of the newly established Comituella–Ellipsocephalus lunatus Zone. This issue is discussed below (under ‘Stratigraphy’) in some detail.

Acritarchs from the File Haidar Formation were studied in some detail from drill cores obtained on Gotland, the Gotska Sandön and the southern Bothnian Sea (Hagenfeldt 1989a, 1989b; Hagenfeldt & Bjerkeus 1991), and from Östergötland (Eklund 1990). The recovered assemblages include the Heliosphaeridium dissimilare–Skiagia ciliosa, Volkovia dentifera–Liepaina plana and part of the Eliasum–Cristallinimum assemblage zones, but are of little significance for a precise determination of the boundary between the members (see discussion in Landing et al. 2013 and Sundberg et al. in press).

The lithology of the Gröttingbo-1 core from Gotland was used by Hagenfeldt & Bjerkeus (1991) to introduce a subdivision of the File Haidar Formation into four units termed the Viklau Sandstone, När Shale, När Sandstone and Gröttingbo Siltstone, of which the Viklau Sandstone and the Gröttingbo Siltstone were ranked as formal members (Hagenfeldt 1994). The När Shale and När Sandstone, in contrast, have been regarded as subunits of a När Member but were subsequently classified as members in the Öland-
Gotland region by Nielsen & Schovsbo (2006), who subdivided the formation into the Viklau, När Shale, När Sandstone and Grötlingbo Members. Of these, the När Sandstone Member is regarded as more or less equivalent to the Lingulid Sandstone Member.

Localities

As Hoved locality

As Hoved is a c. 6 km long cliff-framed headland near Palsgård manor, situated 8 km north of Juelsminde (around 55°45′N, 10°04′E; Fig. 1B) at the east coast of Denmark, facing the Kattegat sea. This locality has an exceptional accumulation of glacial erratic boulders of Cambrian age. Along the shore thousands of boulders of lower Cambrian sandstones occur together with hundreds of boulders of middle Cambrian bituminous limestone (Swedish: orsten), limestone, conglomerate and alum shale, and thousands of boulders of Furongian bituminous limestone and shale (Fig. 3). Glacial erratic blocks of the middle Cambrian Paradoxides paradoxissimus Superzone act as index blocks which allow tracking their origin to Sweden, because the rocks of this superzone show particular characteristics for each province in southern and central Sweden (Scania, Öland, Västergötland, Östergötland and Närke). The foremost rock types at As Hoved that unmistakably point to Västergötland (Fig. 1C) as the source area of all the boulders are:

a. a phosphoritic sandstone conglomerate (Swedish: basalkonglomerat) with constituents of the Lingulid Sandstone. This unit marks the boundary between the lower Cambrian and the middle Cambrian sequence in Västergötland;

b. a greenish limestone of the Triplagnostus gibbus Zone with Jincella munsteri as found at Oltorp, Billingen (Westergård 1953, p. 12);

c. a greenish glauconitic limestone of the Acidusus atavus Zone occurring in situ at Oltorp and as loose boulders from other localities in southern and northern Billingen and on Mount Kinnekulle;

d. a highly fossiliferous, metamorphosed (‘baked’) bituminous limestone of the Acidusus atavus, Ptychagnostus punctuosus and Goniagnostus nathorsti zones found in situ at Munkesten, Hunneberg;

e. the existence of a thin conglomeratic layer spanning the Ptychagnostus punctuosus and Goniagnostus nathorsti zones, discovered for the first time at As Hoved; eventually proven in Falbygden and on Mount Kinnekulle (Weidner et al. 2004);

f. countless blocks of dolerite that now cap the Lower Palaeozoic strata in Västergötland.

g. Houmark-Nielsen (1987, 1994, locality 92) demonstrated that the four Pleistocene glacial tills exposed at As Hoved cliff were derived from the north (Norway) and the north-east (Västergötland). The glacial erratic boulders transported from the north are dominated by rhomb porphyry and sedimentary rocks from the Danish subsurface, mostly of Palaeogene and Cretaceous age.

h. No index blocks from Scania (Exsulans Limestone) or Öland (“Oelandicus shales”, “Paradoxissimus Sandstone”) have been found at As Hoved.

Fig. 3. The cliff section at As Hoved near Palsgård, Jutland, with glacial erratic boulders along the beach.
Additional erratic boulders with Lingulid Sandstone lithology and equivalent fossils of *Epichalnipsus* faunal aspect have already been described from Ulbjerg and Melbjerg, Jutland, Denmark, and Sandesneben (Herzogtum Lauenburg county, Schleswig-Holstein), northern Germany, by Geyer et al. (2004). Other material has subsequently been collected from Damsdorf and Stocksee (both Segeberg county, Schleswig-Holstein), and Köhlen (Cuxhaven county, Niedersachsen), Germany.

Halleberg localities

Fossiliferous quartzitic sandstones have a wide geographical distribution in glacial deposits. In Denmark they are found, in addition to As Hoved, at other localities with Pleistocene moraines containing rocks characteristic of Västergötland (Bøgehoved, Trelde, Melbjerg, and Ulbjerg cliffs, Fig. 1). These sandstones are also scattered over the whole of northern Germany. However, they are unknown in Sweden, which prompted one of the authors (TW) to search for their source primarily in the Falbygden and Kinnekulle areas of Västergötland (Fig. 1), from where most of the middle Cambrian material from As Hoved has originated. Ten years of investigation in natural and man-made outcrops, as well as loose boulders in Västergötland, subsequently also in Östergötland and Närke, was unsuccessful. Only the regular Lingulid Sandstone was met in the field, with all boulders devoid of trilobite remains. In 2011, the search was extended to the Halleberg–Hunneberg outliers, two tablemountains in the far west of Västergötland. Andersson et al. (1985, fig. 11) has shown that at certain parts of Halleberg and Hunneberg (Fig. 1C), a dolerite sill rests directly upon the Lingulid Sandstone or on a thin stratum of middle Cambrian alum shale and that the “diabase intrusion had baked the alum shale” Andersson et al. (1985, p. 19).

Four exposures, a few metres long, and known since a long time in the literature (Hansen 1933), can be studied in the Ovandalen valley in the north-western corner of Halleberg where the public trail starts to descend from the dolerite platform down to Lake Vänern. Between 50 and 150 m north of the trail, three outcrops expose the dolerite sill where it is underlain (in descending order) by metamorphosed alum shale (c. 40 cm), metamorphosed bituminous limestone of the *Triplagnostus gibbus* Zone (*Paradoxides paradoxissimus* Superzone; c. 25 cm) and again by metamorphosed alum shale (c. 35 cm). The lower boundary of this alum shale bed is covered by debris of dolerite, soil and vegetation (Fig. 4). The foot of the approximately 10 m high slope is strewn with smaller blocks of quartzitic sandstone of a lithology quite similar to the erratic boulders known from As Hoved, but trilobite remains were not discovered in the material. Another section c. 100 m to the south of the trail indicates that the alum shale pinches out, and the boundary between the dolerite sill and the
underlying Lingulid Sandstone is visible (Fig. 5). This section lies 150 m from the nearest outcrop north of the trail. The same quartz-arenitic sandstones are also found as loose pebbles along the prehistoric shore-line at Kvillen close to the south-eastern corner of Halleberg. Trilobite remains from this locality were reported by Jan Johansson (personal communication 2002) but the material has not been published.

Karlsson (2001) demonstrated that the 90 m thick Permo–Carboniferous dolerite cap on Halleberg and Hunneberg, either resting directly on or only separated from the underlying sandstone by a thin cover of alum shales, has influenced the diagenetic development by hydrothermal overprint. This resulted in the regionally restricted occurrence of the quartzitic variety of the Lingulid Sandstone. In the east, at Billing, in contrast, the dolerite cap attains only 45 m, and the dolerite is further separated by a thick Palaeozoic cover from the sandstone beneath. Therefore, the Lingulid Sandstone remained largely unaffected in the eastern areas of Västergötland.

Thus, we conclude that the quartzitic sandstones found in great quantity at As Hoved were derived from the Halleberg–Hinneberg area or another area where the dolerite was in close contact with the underlying sandstone, but in which the whole succession has been subject to denudation. Ovandalen is the only available outcrop on Halleberg–Hinneberg that reveals the boundary between the Cambrian rocks and the dolerite sill. Only the uppermost metre of the sandstone is exposed (the lower parts being concealed by large dolerite blocks), and therefore the exact position of this level within the Lingulid Sandstone Member of Västergötland remains uncertain.

Lithology and petrology of samples from the As Hoved cliff and the Lingulid Sandstone of Västergötland

The sandstone of the glacial erratic boulders from As Hoved and bedrock samples from Västergötland were studied to allow a reliable comparison of lithological characters. The As Hoved samples and two samples from the Kvillen section, Halleberg, and the Djupadalen locality were examined petrographically in thin sections. See Appendix 1 for systematic comparisons.

The studied sandstone of the As Hoved cliff displays a variety of lithological characteristics. The sandstones are either platy (most frequently separating into slabs with thicknesses of 1–2 cm) or massive blocks with bed thicknesses of up to 30 cm. The general colour is light grey, occasionally with a yellowish, greenish or reddish stain. The sand grains are generally fine-grained, with nearly even sizes, and relatively pure, indicating a high maturity.

Thin sections (Fig. 6A–D) indicate a pore volume of c. 1–5 vol.%. Quartz grains constitute c. 94 vol.% of the rock and range from 0.03 to 0.3 mm in diameter, with the prevalence of a slight longitudinal shape. They show high compaction and cementation as suggested by inconspicuous concave–convex and saturated grain contacts, and syntaxial overgrowths. Ferritic/limonitic coats are rarely present. Feldspar accounts for c. 1 vol.%, mica for c. 2 vol.%, glauconite for c. 2 vol.%, and zircon and tourmaline together for c. 0.5 vol.%. Alkali feldspar as well as plagioclase grains are fairly fresh and present as slightly rounded cleavage fragments (up to 0.3 mm in size, but generally around 0.1 mm and less). Mica consists nearly exclusively of white mica; only a few flakes of dark mica are present. Glauconite grains are generally around 0.1 mm in size and slightly rounded, mostly compacted and partly show a pale brown crust. The argillaceous-chloritic and illitic porous cement is restricted to minute interporous spaces. A secondary diffuse film of rust is occasionally visible between the quartz grains.

Sedimentary structures are usually inconspicuous. Most samples show a fine, nearly parallel bedding or a very low angle cross-stratification, which becomes obvious after splitting.

A sample of typical thick-bedded sandstone of the Lingulid Sandstone Member from the Kvillen section, Halleberg (sample 09/05), shows remarkable similarity to the As Hoved sample. Thin sections (Fig. 6E, F) indicate the same amount of pore space of c. 1–5 vol.%, which is in accordance with the results of Karlsson (2001), who determined a porosity of 3–6 vol.% for samples collected at Hunneberg (with a resulting permeability of 0 mD). The quartz grains constitute c. 90 vol.% of the rock and are from 0.04 to 0.15 mm in size, with the prevalence of slightly longitudinal grains. Ferritic coats are rarely observed. Feldspar accounts for c. 1 vol.%, mica for c. 3 vol.%, glauconite for c. 5 vol.%, and zircon and tourmaline together for c. 0.5 vol.%. Alkali feldspar and plagioclase grains are fairly fresh and present as cleavage fragments. Glauconite grains are generally about 0.1 mm in size and slightly rounded, mostly compacted and partly show a pale brown crust. Mica consists predominantly of white mica, with a minor amount of biotite present. The minute interporous spaces are filled with an argillaceous-chloritic and illitic cement.

Sample 3 of the typical sandstone of the Lingulid Sandstone Member from the Djupadalen locality shows a similar composition as the sandstones from
As Hoved and Halleberg, but differs in a number of minor aspects (Fig. 6G, H). Thin sections of the quartz arenite indicate a distinctly higher pore space of c. 10–15 vol.%, which is clearly filled with argillaceous-ferritic cement (illite + goethite) and distinct syntaxial quartz overgrowths. The quartz grains constitute c. 97 vol.% of the rock and range from 0.05 to 0.3 mm in size, with slightly rounded grains of low sphericity, and distinctly platy grains with frequent ferritic coats. Feldspar and mica account together for c. 1 vol.%, glauconite for c. 1 vol.%, and zircon and tourmaline together for c. 0.5 vol.%. Alkali feldspar as well as plagioclase grains are fairly fresh, but alkali feldspar grains commonly show a fringe altered to illite or white mica. Glauconite grains are generally around 0.1 mm in size, rounded, and mostly compacted, but are devoid of external crusts. Mica is present as white mica, but also as biotite (partly altered to chlorite).

It should be emphasized that the samples from the Lingulid Sandstone Member of Västergötland studied by Karlsson (2001) have a feldspar content between 2.3 and 6 vol.%, with some samples having a distinct content of rock fragments up to 5.6 vol.%. However, the samples described by Karlsson (2001) are all devoid of any notable amounts of Fe-hydroxide.

Fossils

Fossils occur predominantly in platy sandstone and occur as external moulds. They are often poorly preserved as fairly eroded imprints due to perennial wave transport on the present-day shoreline. The

![Fig. 6. Thin sections. A–D, sandstone from erratic boulder at the As Hoved Cliff near Palsgård, Jutland, Denmark (sample PMU 28676). A, overview under crossed polarizers, width of image 7.2 mm; B, detail with chloritized contact zone, view under crossed polarizers, width of image 0.6 mm; C, detail of typical composition with relatively large quartz grains, width of image 0.6 mm; D, detail with illitic pore cement, view under crossed polarizers, width of image 0.6 mm. E–F, sandstone representing the typical thick-bedded sandstone of the Lingulid Sandstone Member in the Kvillen section, Halleberg, Sweden (sample PMU 28677). E, overview under crossed polarizers, width of image 7.2 mm; F, detail with glauconite grains near centre, view under crossed polarizers, width of image 0.6 mm. G–H, quartz arenite from the Lingulid Sandstone Member, Djupadalen, Falbygden, Sweden (sample PMU 28678). G, overview under crossed polarizers, width of image 7.2 mm; H, detail with large glauconite grain below centre, view under crossed polarizers, width of image 0.6 mm.](image-url)
best preserved fossil remains come from the larger, massive blocks, in which scattered trilobite remains occur, but unfortunately are often destroyed during splitting of the rock. Internal and external moulds, typical for preservation in sandstone, rarely display the characteristics necessary to determine the species (Table 1). Only cranidia of *Epichalnipsus* and *Berabichia* are preserved fairly completely. Other trilobite remains are fragmentary. Holmiid trilobites were found in the As Hoved boulders only as a genal fragment (Fig. 7A). Due to the prevalence of *Epichalnipsus* in the assemblage, it is here termed the *Epichalnipsus* fauna.

Lingulid brachiopods are eponymous for the Lingulid Sandstone of Sweden and occur as well fairly frequently in the collected erratic boulders (Fig. 7B, C, E–I), but are mostly too poorly preserved to be determinable even to the genus. The only well-known genus and species reported from the Lingulid Sandstone of Sweden is *Glyptias favosa* (Linnarsson 1869), which is also represented in the As Hoved samples (Fig. 7I). A rare and relatively surprising constituent of the fauna is an orthothecid hyolith conch (Fig. 7D) found in unequivocally the same type of erratic boulders at Damsdorf in Germany.

Some of the boulders include large-scale trace fossils with a rather peculiar preservation, probably caused in part as a result of specific weathering processes (Fig. 8). Some specimens appear to record different layers of the original trace as shown in Fig. 8B and 8D. Sören Jensen (personal communication to GG) suggested similarities with *Halopoa*, particularly *H. imbricata* Torell 1870, recorded from lower and middle Cambrian sandstones in Scandinavia, particularly the Mickwitzia Sandstone Member; a genus which has been synonymized with *Palaeophycus* in Jensen (1997).

The fauna described derives from 35 blocks of a collection of 50 units. Of these, 43 units are from As Hoved and seven from other localities in Denmark and northern Germany. All figured and listed specimens in this paper are deposited in the Museum of Evolution, Uppsala University, Sweden (PMU).

### Systematic palaeontology

**Superfamily Olenelloidea Walcott 1890**

**Family Holmiidae Hupé 1953**

**Genus Holmiella Fritz 1972**

_Type species._ *Holmiella preancora* Fritz 1972; by original designation.

**Holmiella? sp. A**

_Fig. 7A_

**Material.** Single gena, PMU 28679, from As Hoved, Palsgård area, Denmark.

**Discussion.** The single fragmentary gena has a moderately and evenly curved lateral border that proceeds into a long, moderately tapering genal spine with elliptical cross section. The genal field ("ocular platform") is relatively narrow (tr.), weakly convex. The lateral border and border furrow are obsolescent and the posterior librigenal margin has a distinct, large indentation so that the margin defines a broad curvature towards the genal angle.

The specimen is fairly abraded on the cobbleso that the recognizable characters do not permit a confident determination, but it matches the morphology known from *Holmiella*. The specimen is tentatively assigned to *Holmiella*.

**Superfamily Ellipsocephaloidea Matthew 1887**

**Family Ellipsocephalidae Matthew 1887**

The family Ellipsocephalidae is a notoriously difficult taxon. It includes numerous genera, which are often not only difficult to demarcate from other genera with a similar morphology, but may also pose difficulties in the recognition of species if based on well-preserved material. Geyer (1990) attempted a reappraisal of the group with strong focus on material from the Moroccan Atlas ranges, but emphasized that a large number of taxa described from Baltica are in need of careful revision.

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Table 1. List of the fossil material collected from the As Hoved locality

| Trilobita                  | Material                                                                 |
|----------------------------|--------------------------------------------------------------------------|
| *Holmiella? sp. A*         | 1 gena                                                                   |
| *Epichalnipsus anartanus*  | >100 cranidia, 3 librigenae, 3 thoracic segments                         |
| *Epichalnipsus sp. A*      | 3 cranidia                                                               |
| *Epichalnipsus sp. B*      | 2 cranidia                                                               |
| *Berabichia erratica*      | 8 cranidia, 3 tentatively assigned librigenae                            |
| Brachiopoda                |                                                                         |
| Lingulid gen. and sp. A    | 8 valves                                                                 |
| Lingulid gen. and sp. B    | 2 valves                                                                 |
| *cf. Glyptias favosa*      | 1 ventral valve                                                          |
| Hyolitha                   |                                                                         |
| Orthothecida gen. and sp. incert. A | 1 conch                                                             |
The difficulty in the study of ellipsoccephalid trilobites arises from the coincidence of three particular problems:

Firstly, there is an evolutionary tendency towards a progressive effacement of the cephalic relief that commonly masks important morphological characters. This trend during evolutionary development contributes to the need of well-preserved specimens to permit a confident determination. This trend is also seen during ontogeny of species from the later phase of this development such as *Kingaspioides sanctacrucensis* (Czarnocki 1927) from the Holy Cross Mountains, southern Poland (see Żylińska & Masiak 2007), or *Kingaspioides frankenwaldensis* (Wurm 1925) from the Franconian Forest, Germany, where the cephalic relief becomes largely effaced in large mature individuals.

Secondly, morphologic trends during the phylogenetic history are decipherable in different lineages so that a strong development of morphological convergence can be recorded. Careful biostratigraphic

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**Fig. 7.** *Holmiella?* sp. and examples of non-trilobitic body fossils from the erratic boulders at As Hoved, Jutland, Denmark (except for D). A, *Holmiella?* sp. A, PMU 28679, incomplete gena B, C, E–G, Lingulid gen. and sp. A; B, PMU 28680/1, ventral valve; C, F, 28681, ventral valve, ventral and anterior views; E, G, PMU 28682/1, dorsal valve, lateral and dorsal views; D, Orthothecida gen. and sp. incert., PMU 28683, incomplete conch; from erratic boulder probably from the Lingulid Sandstone collected near Damsdorf, Germany; H, Lingulid gen. and sp. B, PMU 28680/2, dorsal valve; I, *cf. Glyptias favosa* (Linnarsson 1869), PMU 28684, ventral valve. White scale bars equal 1 mm, black scale bars equal 5 mm.
analysis indicates that these trends partly occur at different phases. This is particularly adverse because biostratigraphically reliable index fossils occur sparsely in the stratigraphic interval in which the ellipsocephalids possessed their acme. This, in turn, either helped to obscure biostratigraphic significance or led to erroneous correlations.

Thirdly, the major stratigraphic interval in which the ellipsocephalids occurred in Earth history coincides with the lower–middle Cambrian boundary interval, which is affected on most Cambrian continents and particularly in their major area in the Acadian faunal realm by sea-level fluctuations. These were responsible not only for an unusually large amount of siliciclastic sediments that were deposited during this interval and which are often unsuitable for favourable preservation of trilobites, but also created gaps that further restrict the amount of available material.

The majority of ellipsocephalid trilobites are known only from cranidia, although it is obvious that pygidia provide important additional information necessary to reveal systematic relations. An example of lumping of species into ‘morphotaxa’ is the genus Ellipsocephalus Zenker 1833, which is used since decades to furnish species with a similar effaced cranidium, regardless of a distinctly differing pygidial morphology as illustrated by Ellipsocephalus hoffi Schlotheim 1823, Germaropyge germari (Barrande 1852), and Ellipsostrenua gripi Kautsky 1945.

It is beyond the scope of this article to discuss the taxonomy of the ellipsocephalid species from Scandinavia. However, it is necessary to emphasize that most generic assignments of the ellipsocephalids from Sweden and Norway are in strong need of a revision. None of the species described from the upper to uppermost lower Cambrian strata of Scandinavia can be assigned correctly to Ellipsocephalus, Proampyx, and Ornamentaspis, although the latter has been suggested by Geyer (1990) to be used as a nickname for the index species Strenuella linnaeussol Kjær 1917, to avoid the completely inappropriate assignment to the late middle Cambrian genus Proampyx Frech 1897. Recently, Hoyberget et al. (2015) placed the species in Ellipsocephalus although its pygidia differ distinctly from those of typical species of Ellipsocephalus such as E. hoffi or E. lejostracus. Another species dealt with as Ellipsocephalus lunatus and used as an index fossil of the Coniulida–Ellipsocephalus lunatus Zone is cer-

Fig. 8. Trace fossil (cf. Halopoa imbricata Torell 1870) from the erratic boulders at As Hoved, Jutland, Denmark. A, PMU 28685, several specimens preserved as negative hyporelief; length of figured view c. 7 cm; C, detail; B, D, latex cast of PMU 28685, illustrating coating with grains on the wall. All scale bars equal 5 mm.
tainly not a true species of the genus. It is probably more closely related to species of *Kingaspidoides* and (pending future studies) it is termed “*Ellipsocephalus*” *lunatus* herein, awaiting a careful revision.

The subdivision of the family into the subfamilies Antatlasinae, Ellipsocephalinae, Protoleninae, and
Strenuellinae appears to be appropriate to date. The subfamily Kingaspiniidae is a junior synonym of the Ellipsocephalinae.

Subfamily Antatlsinae Hupé 1953

Discussion. The Antatlsinae are the oldest ellipsocephaline trilobites and thus ancestral to all other ellipsocephaloideans. They are unequivocally derived from bigotinid trilobites. Species of Berabichia have a relatively general body plan, although the genus Antatlsia predates Berabichia. A phylogenetic lineage leads towards late early Cambrian genera such as Sectiga and Issafeniella. The Siberian genera Chorbusulina Lazarenko 1962 and Charaulaspias Lazarenko 1962 are closely related to Berabichia Geyer 1990, although the general similarity in the morphology of the genae is obviously an independent, parallel development in geographically disjunct genera because they can be differentiated by several other characters as discussed in Geyer et al. (2004).

Despite of caveats mentioned in Geyer et al. (2004), Strenuaeva Richter & Richter 1940 is also a genus of the Antatlsinae. However, species of this genus only include the type species S. primaeva (Brøgger 1879) from Norway, S. inflata Ahlberg & Bergström 1978 from the Lake Torneträsk area, Sweden (see Cederström et al. 2012), S. baltica (Wiman 1905) from erratic material of the Gävle Bay, east-central Sweden, S. nefanda Geyer 1990 from the western Anti-Atlas of Morocco, and an unnamed species listed as S. nefanda from south-eastern Newfoundland (Fletcher 2003, 2006). Other species, previously assigned to Strenuaeva, belong to Issafeniella Geyer 1990, including I. orlowinensis (Samsonowicz 1959) and I. trifida (Orłowski 1985), both from the Ociesęki and Kamienieck formations of the Holy Cross Mountains, Poland (Żylińska & Masiak 2007; Żylińska & Szczepanik 2009), and the Spanish species I. sampelayoi (Richter & Richter 1940) and I. melendezi (Gil Cid 1972).

Genus Epichalnipsus Geyer, Popp, Weidner & Förster 2004

Type species. Epichalnipsus anartanus Geyer, Popp, Weidner & Förster 2004; by original designation.

Additional species included: Berabichia inopinata Geyer 1990, from the lower Cambrian Sectiga Zone of Morocco.

Emended diagnosis. Antatlsine genus with shallow furrows and a generalized overall convexity in transverse section; frontal area convex in sagittal section, distinctly separated from glabella; glabella somewhat raised above shallow dorsal furrows, genae somewhat raised ventrally from dorsal furrows; glabella tapering forward, frontal lobe subacute or with low curvature in dorsal view.

Discussion. Epichalnipsus has been introduced by Geyer et al. (2004) for species of the Berabichia clade that are characterized primarily by a subquadrate cephalon with a well-rounded to faintly subarculate anterior margin, with a subequal overall convexity in transverse section, and a glabella that is slightly to moderately raised above the genae. The fixigenae themselves are weakly convex in transverse section, without a transverse or diagonal depression, and gently slope abaxially from the axial furrows. The axial furrows are moderately wide and weakly defined from the fixigenae.

As noted by Geyer (1990), the type species of Berabichia Geyer 1990, B. vertumnia, B. stenometopa Geyer 1990, and four of the forms described in open nomenclature are characterized by a cephalon in which the different cranidial regions (such as the glabella, fixigenae, palpebral lobes, and frontal area) have individual convexities so that these different parts are generally well defined by distinct furrows. In turn, Berabichia inopinata Geyer 1990 differs in having a cephalon with a rather homogenous overall convexity, at least in a transverse section across the glabella, the fixigenae and the palpebral lobes. This species, provisionally assigned to Berabichia in Geyer (1990), has the typical convexities shown by Epichalnipsus anartanus and was thus transferred to Epichalnipsus.

A specimen of the type species from the erratic boulders was first described by one of the authors (Popp 1999) under the name Proampyx? cf. rotundatus.
and Proampyx cf. rotundatus, respectively. The species described under the name Proampyx rotundatus (Kiær 1917) bears indeed a great resemblance in respect to proportions, convexity of the preglabellar field and the pattern of lateral glabellar furrows with species of Epichalnipsus. However, this species has a tapering glabella and a generally strong convexity in the cranidium. Although the exact convexities of the shell exterior are unknown, it appears to share most characters with Berabichia (see below).

Epichalnipsus anartanus Geyer, Popp, Weidner & Förster 2004
Fig. 9A–V, W?, X?

v 1999 Proampyx? cf. rotundatus (Kiær 1917), Popp, p. 3.
v 1999 Proampyx cf. rotundatus (Kiær 1917), Popp, pp. 4–7, figs. 1–2.
v 2004 Epichalnipsus anartanus n. gen., n. sp., Geyer et al., pp. 131, 133–134, figs. 3, 4.1, 4.3–4.15.

Material. More than one hundred cranidia or cranidial fragments, mostly incomplete internal moulds, 13 cranidia studied in detail (in repository: PMU 28686, PMU 28687, PMU 28689, PMU 28691, PMU 28692a, b (part and counterpart), PMU 28693/1, PMU 28695/1, PMU 28696), three librigena (in repository: PMU 28688, PMU 28690), three fragments of thoracic segments attributed to the species (in repository: PMU 28694, PMU 28697, incomplete cranidium, internal mould, dorsal, posterior and lateral views; B, E, H, PMU 28698/1, incomplete cranidium, composite mould, dorsal, lateral and anterior views, scale bar 1 mm; N, slab with PMU 28698/1 and PMU 28698/2 illustrating differences in size.

C, D, I, Berabichia erratica Geyer, Popp, Weidner & Förster 2004?; C, I, PMU 28701, librigena, dorsal and lateral views; D, PMU 28702, incomplete librigena, dorsal views.

J–L, M?, Epichalnipsus sp. B; J–L, PMU 28699, cranidium, dorsal, lateral and anterior views; M, PMU 28700, partial cranidium, dorsal views. All specimens from the As Hoved locality, Jutland, Denmark. Scale bars equal 5 mm except where otherwise noted.
28693/2, PMU 28695/2). All specimens from As Hoved, Palsgård area, Denmark, except for PMU 28695/1 and PMU 28695/2 from Damsdorf, Germany.

Emended diagnosis. Species of Epichalnipsus with frontal area distinctly inflated that forms a conspicuous platform in lateral view; glabella including occipital ring of c. 65–70 % cephalic length; occipital ring with small, subterminal spine; palpebral lobes of about 25 % cephalic length.

Description. Cephalon with strongly curved to well-rounded to faintly subbaricate anterior margin, ranging from 4.0 to 27 mm in the studied specimens. Glabella including occipital ring in adult individuals of 63 to 72 % cephalic length, maximum width across L1 c. 45 % maximum cranidial width across centre of palpebral lobes (slightly less in juveniles); tapers forward to anterolateral corners of frontal lobe to c. 80 to 85 % width across L1; sides weakly curved. Glabella with three pairs of shallow lateral glabellar furrows, which are fairly well visible on internal moulds, but faint to obsolete on the shell exterior; S1 moderately long, curved backward; S2 and S3 comparatively shorter, S2 directed slightly backward, S3 almost normal to axis; front terminates in a subacute tip that is usually well visible on internal moulds, but less well developed on the shell exterior. Occipital furrow relatively broad (sag.) and normal to axis in the middle part. Occipital ring sagittally about 14–19 % cephalic length, extreme lateral parts narrow, with moderately long spine in subterminal position.

Fixigenae close to dorsal furrows of about 40 % cephalic length or slightly less, genal width across centre of palpebral lobes c. 43 to 49 % maximum glabellar width (across L1); with slightly extended posterior limb. Eye ridge weakly defined on exterior, weakly to moderately well developed on internal moulds, faintly connected with anterolateral corners of glabella; tends to bifid (or perhaps even trifid; Geyer et al. 2004, fig. 4.13, also suggested in Fig. 9D, 9M) at dorsal furrows, the anterior thread-like branch of which form an almost obsolete, rarely visible parafrontal line. Palpebral lobes moderately long (exsagittally 22 to 27 % maximum cephalic length in adult individuals), posterior tip located opposite anterior portion of L1 or at about S1, anterior tip opposite L3, faintly oblique to axis.

Preglabellar field long, distinctly convex to slightly inflated, fused medially with anterior border to form an anterior unit of up to more than 30 % cephalic length in adult individuals, distinctly shorter in juveniles. Anterior border narrow, obsolete, occasionally faintly indicated close to the sutures. Posterior border with straight adaxial part, weakly sigmoidally curved distally and bent forward to palpebral lobes. Posterior border furrow well defined, narrow adaxially, broadening abaxially.

Anterior branches of facial suture diverge from anterior ends of the palpebral lobes to border furrow, with strong inward curvature anteriorly. Posterior branches diverge markedly from posterior ends of palpebral lobes.

Librigena with moderately and evenly developed lateral border that defines a fairly long, moderately tapering genal spine with elliptical cross-section. Librigenal field (ocular platform) relatively narrow (tr.), weakly convex, grades into distinctly upturned ocular socle. Lateral librigenal border and border furrow obsolete. Posterior librigenal margin slightly forward directed to narrow curved genal angle.

Rostral plate and hypostome unknown.

Thorax known only from three fragmentary segments assigned to E. anartanus (Fig. 9W, X). Axial ring moderately convex in transverse section, without median node or spine, but with faint lateral swelling adjacent to the axial furrow. Transverse furrow shallow to moderately well impressed. Articulating half-ring lenticular in dorsal view, with distinctly curved anterior margin, moderately elevated. Pleurae directed slightly backward, short in comparison to the transverse width of the axial rings. Pleural furrow fairly shallow adaxially, better impressed toward pleural tips, divides pleura into narrow, lenticular anterior strip and a broader transversely triangular posterior section of about double exsag. width near axial furrow; commences at axial furrow close to the anterior margin, directed obliquely to the axis almost straight to the acute pleural tip.

Pygidium unknown.

Discussion. Epichalnipsus anartanus is distinguished from E. inopinatus (Geyer 1990) from the Sectigena Zone of the Atlas Ranges in Morocco by a strongly inflated frontal area which forms a platform in front of the glabella, whereas the frontal area in the Moroccan species slopes from the glabellar front. Furthermore, E. anartanus has slightly shorter palpebral lobes and an occipital ring with a small, subterminal spine rather than a minute node as in E. inopinatus.

Epichalnipsus sp. A

Fig. 10A, B, E, F, G, H, N

Material. Three cranidia (PMU 28697, PMU 28698/1, PMU 28698/2). Specimens from As Hoved, Palsgård area, Denmark.

Description. Cephalon with strongly bowed anterior margin. Glabella including occipital ring of slightly less than 70 % cephalic length, maximum width across L1 slightly more than 40 % maximum cranidial width across centre of palpebral lobes; tapering forward
or apparently with subparallel sides due to slightly extended anterolateral corners of frontal lobe; sides faintly curved; three pairs of shallow, faint to obsolescent lateral glabellar furrows; S1 moderately long, curved backward; S2 and S3 short and indistinct; frontal lobe with weak curvature anteriorly. Occipital furrow relatively broad (sag.) and normal to axis in the middle part, slightly more distinct laterally. Occipital ring sagittally of 16–18 % cephalic length, reduced to particularly narrow extreme lateral parts, with distinctly curved posterior margin.

Fixigenae close to dorsal furrows of c. 40 % cephalic length or slightly less, genal width across centre of palpebral lobes c. 60 % maximum glabellar width (across L1). Eye ridge weakly defined. Palpebral lobes moderately long (exsagittally to 33 % maximum cephalic length in the studied specimens), faintly oblique to axis.

Preglabellar field long, distinctly convex, fused medially with anterior border to form an anterior unit of up to 30 % cephalic length. Anterior border obsolescent. Posterior border with straight adaxial part, weakly sigmoidally curved distally and bent forward to palpebral lobes. Posterior border furrow well defined, narrow adaxially, widens abaxially.

Anterior branches of facial suture diverge from anterior ends of the palpebral lobes to border furrow, with strong inward curvature anteriorly. Posterior branches diverge markedly from posterior ends of palpebral lobes.

Librigena, rostral plate, hypostome, thorax and pygidium unknown.

Discussion. The As Hoved material includes cranidia that represent a species different from Epichalnipsus anartanus, here termed Epichalnipsus sp. A. Only three more or less completely preserved and fairly well preserved cranidia have been discovered. The large specimen (Fig. 10A, E, G) has a length of 13.5 mm and testifies an adult individual. The other cranidia (Fig. 10B, F, H) is only 7.5 mm long and is regarded as a late immature stage. Both unequivocally represent the same species although they differ in a few aspects, which all can be attributed to ontogenetic development. These characters include a longer (sag.), more strongly extending occipital ring, a more clearly tapering glabella, and slightly longer palpebral lobes in the large specimen.

Epichalnipsus sp. A is well differentiated from E. anartanus in having a strongly curved rather than subarcuate anterior cephalic margin, a less inflated anterior area, broader fixigenae, and the absence of a subterminal occipital spine. Nevertheless, the form shares the typical cephalic morphology of Epichalnipsus with a clearly convex, fairly homogenous frontal area separated from the glabella by only a shallow transverse furrow and without a dramatic ventral drop in front of the eye ridges, and exsagittally as well as transversely moderately convex fixigenae, which slope ventrally from the axial furrows. Epichalnipsus sp. A is distinguished from Epichalnipsus sp. B (described below) by its longer frontal area, broader fixigenae, and a longer (sag.) occipital ring.

Epichalnipsus sp. B
Fig. 10J–L, M?

Material. A single well-preserved cranidium, PMU 28699, and a slightly distorted partial cranidium tentatively assigned to the same form, PMU 28700; both from As Hoved, Palsgård area, Denmark.

Description and discussion. A third species of Epichalnipsus from the As Hoved locality is represented by a single well-preserved cranidium and a slightly distorted partial cranidium tentatively assigned to the same taxon. The well preserved cranidium is characterized by a broad (width across L1 slightly less than half cranidial width across palpebral lobes), slightly tapering glabella with a faintly subacute front; a relatively short (sag.) occipital ring of c. 15 % cephalic length; relatively narrow and thus clearly rectangular fixigenae; a relatively short (sag.); 24 % cephalic length in the well-preserved specimen) and only moderately convex frontal area; and a subequally curved anterior margin of the cephalon. These characters clearly distinguish it from E. anartanus and the form is described as E. sp. B. The partial cranidium (Fig. 10M) only shows the anterior two-thirds of the cranidium with the same proportions but apparently a less clearly tapering glabella and a broader front which, however, may be a result of the slight deformation.

Genus Berabichia Geyer 1990

Type species. Berabichia vertumnia Geyer 1990; by original designation.

Discussion. The genus Berabichia is characterized by a cephalon with the glabella moderately raised over a wavy platform formed by the genae. The fixigenae have their most elevated areas close to the palpebral furrows, but a basal line drawn from the axial furrow to the palpebral furrow dips gently abaxially so that a transverse section is subhorizontal.

The genus has been introduced to encompass three species from the Moroccan Anti-Atlas and High Atlas ranges. Another six forms were attributed by Geyer (1990) to the genus Berabichia in open nomenclature. Nevertheless, all come from the upper lower Cambrian
Antatlasia guttapluviae and Sectigena zones, upper Banian Stage, suggesting that the Moroccan Atlas ranges depict a major area for the diversification of the Berabichia clade.

In addition to the Moroccan species, Geyer (1990) pointed out that Chorbusulina wilkesi Palmer & Gatehouse 1972 and Chorbusulina subdita Palmer & Gatehouse 1972, both from the uppermost lower Cambrian of the Argentina Range, Antarctica, are also species of Berabichia. Chorbusulina cf. subdita, described by Palmer & Rowell (1995) from the Shackleton Limestone of Antarctica, probably represents another species of the genus. An additional species of Berabichia has been described from Sweden under the name Strenuella primaeva var. rotundata by Kiær (1917) and later dealt with as Protolenus rotundatus (e.g., Ahlberg & Bergström 1978). This species, first described from the Gislov Formation at Forsemölla, Scania, agrees well with the Moroccan species but is known only from imperfectly preserved material (see discussion below under B. erratica).

Additional species subsequently assigned to Berabichia include B. milleri Westrop in Westrop & Landing 2000, B. eslaensis Álvaro 2007, B.? kiaeri (Czarnocki 1927) (by Geyer 1990) and B. oratrix (Orłowski 1985) (by Żylińska et al. 2013).

Berabichia milleri has been reported from the so-called Kingaspisoides cf. obliquoculatus Zone of the Long Island Member of the Hanford Brook Formation, New Brunswick, which directly overlies Matthew’s classical Protolenus (P.) elegans fauna and Zone (Westrop & Landing 2000). Despite the overall similarity of B. milleri in the relative sizes of the different areas of the cranidium, fundamental differences exist between it and the unequivocal species of Berabichia. These differences include: (i) the overall convexity, which shows independently inflated genae in B. milleri that do not slope ventrally from the axial furrows; (ii) a relatively strongly convex and slender glabella; (iii) subequally developed, simple and slightly backward directed S1 to S3; (iv) transverse, well developed eye ridges that describe a distinct angle to the palpebral lobes; (v) long palpebral lobes that reach backward and almost reach to the posterior border furrow; and (vi) a distinct ventral slope just anterior to the eye ridges. These characters clearly indicate that B. milleri is a species of the Protolenus clade rather than the Berabichia clade. It does not readily fit into an existing genus, but shows affinities to Latoucheia (Latoucheia) Hupé 1953 and particularly Cambrunicornia Geyer 1990. Both Latoucheia (Latoucheia) and the variably developed species of Cambrunicornia, the latter known from the Anti-Atlas of Morocco (Geyer 1990), the Tröbitz Formation of Saxony, Germany (Geyer et al. 2014), and species tentatively assigned to the genus from the Redlichops fauna of the Dead Sea area, Jordan (Elicki & Geyer 2013) and from the Láncara Formation of the Cantabrian Mountains, northern Spain (Álvaro 2007), differ in several aspects, particularly in the absence of a distinctly inflated anterior area, but appear to be closely related. Both genera, however, occur in strata equivalent to the Protolenus Zone of New Brunswick or even slightly younger strata so that their stratigraphic occurrence would match with the occurrence of B. milleri in the Hanford Brook fauna.

Berabichia eslaensis Álvaro 2007 has been described from a fauna that includes a species assigned to Kingaspis from the Láncara Formation of the Cantabrian Mountains, northern Spain. Although the species strongly resembles some of the species of Berabichia from Morocco, the overall convexity of the frontal area and the manner in which the palpebral lobes are connected with the fixigenae suggest a close relationship with the Kingaspis clade rather than Berabichia.

Strenuella? kiaeri Samsonowicz 1959 from the Protolenus–Issafeniella Zone of the Holy Cross Mountains of Poland has been transferred to Ellipsocephalus by Orłowski (1985) and then tentatively assigned to Berabichia by Geyer (1990). Żylińska et al. (2013) emphasized that the only known specimen of this species is strongly effaced, shows shallow lateral and axial furrows, and it may in fact represent a distorted specimen of Issafeniella orlowinensis (Samsonowicz 1959) that occurs in the same stratigraphic interval of the Holy Cross Mountains ( Żylińska & Masiak 2007).

Comluela oratrix Orłowski 1985 and Comluela igrzycznae Orłowski 1985, both described from the Holmia–Schmidtellus Assemblage Zone of the Holy Cross Mountains, have been subject to a recent morphometric analysis by Żylińska et al. (2013), who showed that the two species constitute a monospecific assemblage representing a single species dealt with as Berabichia oratrix (Orłowski 1985). This species indeed fits very well into the concept of the genus although the relatively strong deformation of the material makes a reliable reconstruction of the species’ original morphology difficult.

Berabichia erratica Geyer, Popp, Weidner & Förster 2004

Fig. 10C?, 10D?, 10I; Fig. 11A–M
v 2004 Berabichia erratica n. sp., Geyer et al., pp. 134–135, figs. 5.1, 5.2, 5.4.

Material. Eight cranidia (repositioned: PMU 28682/2, PMU 28703 (part and counterpart), PMU 28704–PMU 28707). All specimens from Ås Hoved, Palsgård area, Denmark. Tentatively assigned to B. erratica: three librigenae (repositioned: PMU 28701, PMU 28702).

Emended diagnosis. Species of Berabichia with frontal area moderately inflated, anterior margin tends to be
subarcuate; glabella gradually tapering forward; fixigenae with highest elevation abaxially; palpebral furrow obsolete, merely a shallow and wide depression; palpebral lobes of about one-fourth cephalic length.

**Description.** Cephalon with faintly subarcuate anterior margin. Dorsal furrows moderately wide, poorly defined from fixigenae, grading into weakly to moderately convex fixigenal area.

Glabella including occipital ring of 72 to 76 % cephalic length, tapers gradually forward, frontal lobe 66 to 72 % maximum width across L1; front in dorsal view with low triangular tip or shallow curvature. Three pairs of lateral glabellar furrows very faint to obsolescent on the shell exterior; S1 moderately long, distinctly curved backward, relatively broad; S2 and S3 shorter, S2 backward directed. Occipital furrow broad (sag.) medially, shallower laterally. Occipital ring sag. variably of 15 to 22 % cephalic length, fades to narrow lateral portions, posterior margin thus

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**Fig. 11.** *Berabichia erratica* Geyer, Popp, Weidner & Förster 2004. A, D, G, PMU 28703a, incomplete cranidium, internal mould, dorsal, anterior and lateral views; B, E, H, PMU 28682/2, incomplete cranidium, latex casts of external mould, dorsal, anterior and lateral views; C, PMU 28704, cranidium, internal mould, weathered and partly abraded surface, dorsal view; F, I, M, PMU 28705, partial cranidium, internal mould, dorsal, anterior and lateral views; J–L, PMU 28706, immature cranidium, dorsal, lateral and anterior views; scale bar 1 mm. All specimens from the As Hoved locality, Jutland, Denmark. Scale bars equal 5 mm except where otherwise noted.
species of the genus in showing a tendency to develop although the species appears to differ from all other falls within the morphological range of attributable to allometric growth.

and have a slightly more slender glabella which is smaller than the average specimens from As Hoved that the figured specimens from Wilsche are slightly species as described above. Particularly noteworthy is Additional material discovered at the As Hoved lo-
gravel pit at Wilsche near Gifhorn, northern Germany. based on only two well preserved cranidia from a lar platform') moderately broad (tr.), weakly convex, and border furrow obsolescent. Librigenal field ('ocular platform') moderately broad (tr.), weakly convex, grades into distinctly upturned ocular socle.

Discussion. The description of Berabichia erratica was based on only two well preserved cranidia from a gravel pit at Wilsche near Gifhorn, northern Germany. Additional material discovered at the As Hoved lo-
cally slightly complements the information on the species as described above. Particularly noteworthy is that the figured specimens from Wilsche are slightly smaller than the average specimens from As Hoved and have a slightly more slender glabella which is attributable to allometric growth.

As discussed by Geyer et al. (2004), Berabichia erratica falls within the morphological range of Berabichia, although the species appears to differ from all other species of the genus in showing a tendency to develop a subarcuate anterior margin of the cephalon due to a slightly narrower curvature medially. This feature is known, however, from a few specimens of Berabichia vertumnia Geyer 1990 as well, the type species of the genus. The palpebral lobes of B. erratica are defined from the fixigenae by only a shallow and wide depres-
sion, which is known also from B. vertumnia. Further differences between B. erratica and B. vertumnia are discussed in Geyer et al. (2004). Particularly note-
worthy is that the abaxial part of the fixigenae is developed in B. erratica as a rather flat area so that it indicates some similarity to the striking depression that crosses the fixigenae in Sectigena and can be used for generic distinction.

The most similar species formally described to date are Berabichia oratrix (Orłowski 1985) (see discussion under genus and Żylińska et al. 2013) and B. subdita (Palmer & Gatehouse 1972). Berabichia oratrix differs in having broader fixigenae and slightly longer palpebral lobes. However, specimens of B. oratrix may develop a faint subarcuate anterior cephalic margin as well (see Żylińska et al. 2013, fig. 6B, 6D, 6E).

Berabichia rotundata (Kiaer 1917) is also fairly similar to B. erratica. It differs, among other characters, by a sagittally shorter frontal area and a longer occipital ring (see Ahlberg & Bergström 1978, pl. 3, figs. 1, 2).

Stratigraphy

The biostratigraphy of the Scandinavian lower Cambrian (Cambrian Series 2) (Fig. 2) is surprisingly poorly constrained. The major reason is the fairly humble fossil record from scattered localities due to the prevalence of shallow marine, siliciclastic deposits; a dominance of endemic trilobite species and a high amount of endemic genera; and a preliminary stage of generic concepts for the ellipsocephalid trilobites and a preliminary stage of the taxonomic treatment of brachiopods.

A more or less well agreed biostratigraphic framework has been established for the entire Baltica contin-
tent since the monographic correlation chart (Mens et al. 1990). However, almost none of the recognized trilobite zones could be correlated into any other Cambrian continent with satisfactory precision. The recognition of distinct acritarch zones apparently helped to correlate the trilobite zones into distant regions, but correlations entirely based on acritarch assemblages led to surprising results, which partly contradicted correlations based on trilobites as indicated in Landing et al. (2013) and Sundberg et al. (submitted).

A profound reappraisal of the biostratigraphy of Baltica backed by sequence stratigraphic criteria led
to a partial revision of the established biostratigraphic scheme (Nielsen & Schovsbo 2011). Particularly noteworthy is the abandoning of the Holmia inusitata Zone and the partial amalgamation of the Holmia kjerulfi group Zone with the ‘Ornamentaspis’ linnarssoni Zone. This in fact leads to the assumption that a tremendously shorter time interval is represented by the Holmia and ‘O.’ linnarssoni ranges than previously assumed. Nielsen & Schovsbo’s (2011) analyses prove that the profoundly incomplete depositional record in many parts of Scandinavia hampers the construction of a sufficiently detailed biostratigraphic framework. They also show that the acritarch zones may be controlled in part by facies. Correlations based on acritarch assemblages are a helpful tool, but they must be used with caution. Nevertheless, the revised zonal scheme with a Holmia kjerulfi–‘Ornamentaspis’ linnarssoni and a Comluella?–Ellipsoscelpha lunatus Zone sensu Nielsen & Schovsbo (2011) does not allow a direct recognition of the biostratigraphic position for most of the relevant recorded Scandinavian faunas and awaits further revisions of the faunal assemblages and a revision of the ellipsocelphaloid trilobites.

The Epichalnipsus Fauna from the glacial erratic boulders described herein illustrates the problem of the suggested zones. As shown above, there is little doubt that the boulders from As Hoved, Jutland, are derived from the Lingulid Sandstone Member of the Västergötland region so that the Epichalnipsus Fauna portrays a fauna typical for Nielsen & Schovsbo’s (2011) LC2-4 sequence, which the authors place in the suggested Comluella?–Ellipsocelpha lunatus Zone. However, the eponymous index fossils are scarce and almost nowhere distinctive for the fauna in which they are found. In addition, indirect correlation suggests the trilobites of the Epichalnipsus Fauna to be slightly older than the assemblages with ‘Ellipsocelpha’ lunatus due to reasons detailed in the following paragraphs. However, the occurrence of ‘E.’ lunatus in the assemblages does not appear to precisely determine both the lower boundary of the zone, nor can it be proved that the base of Nielsen & Schovsbo’s (2011) LC2-4 sequence coincides with the base of their Comluella?–Ellipsocelpha lunatus Zone. Therefore it is suggested that the Epichalnipsus Fauna is a representative of the boundary interval of the Holmia kjerulfi–‘Ornamentaspis’ linnarssoni to Comluella?–Ellipsocelpha lunatus zones although the fauna is not known with certainty from outcrops in Scandinavia.

Key areas for correlation from Scandinavia and Baltica into other Cambrian continents and for biostratigraphic resolution are the Holy Cross Mountains, southern Poland, and subsurface occurrences in central and northern Poland although the stratigraphic sequences from these regions are as well incompletely known. Recent investigations and taxonomic revisions of the lower and middle Cambrian Holy Cross Mountains faunas (e.g., Żylińska 2013a, 2013b; Żylińska & Masiak 2007; Żylińska & Szczepanik 2009; Żylińska et al. 2013) indicate different faunal assemblages and a possibility to subdivide the ellipsocelphaloid-bearing pre-Paradoxides strata. Nevertheless, the significance of the crucial Holmia–Schmidtiiellus and Protolenus–Is- safenilla faunas from the Holy Cross Mountains also suffer from poor outcrops and unresolved taxonomic problems of the generic concepts.

Nielsen & Schovsbo’s (2011) sequence stratigraphical analyses help to identify the sea-level fluctuations that indicate an extremely varying termination of the lower Cambrian sequences which is partly a result of the late early Cambrian regressional–transgressive events (commonly termed the ‘Hawke Bay regression’; Palmer & James 1979) and partly a result of Neogene and Pleistocene erosion that removed parts of the Cambrian strata. Thus, the young to youngest early Cambrian faunas from various areas of Scandinavia are not necessarily of similar age, and the most diverse of these faunas offer a glimpse into characteristic biota. A few of these faunas merit a brief characterisation.

**(Tomten Member fauna**

The traditional fauna of the ‘Holmia shale’ (now Tomten Member of the Ringstrand Formation; Nielsen & Schovsbo 2006) of the Mjøsa region, Norway (Kiær 1917) includes the trilobites Holmia kjerulfi, Kjerulfia lata, cf. Runcinodiscus index, Strenuaeva primaeva, and Ellipsostrenua cf. gripi (Kiær 1917; Skjeseth 1963; Ahlberg & Bergström 1978; Bergström 1981; Høyberget et al. 2015). The overlying Evjevik Member includes two major limestone beds in the lower and upper part, respectively. Both appear to bear a fairly rich fauna of the ‘Ornamentaspis’ linnarssoni assemblage (earlier termed the Strenuaeva limestone) with trilobites such as Calodiscus lobatus (Münster 1900; Nikolaisen 1986; Cederström et al. 2012; Høyberget et al. 2015). Most determinable material has been collected from weathered loose blocks so that apparently no biostratigraphical distinction between them had been achieved, but Høyberget et al. (2011a, 2011b, 2015) showed that a similar fauna with ‘O.’ linnarssoni, E. gripi and helcionelloid molluscs occurs in both limestone levels. In addition, the upper limestone bed yielded ‘Ornamentaspis’ sularpensis, Strenuaeva spinosa and Calodiscus lobatus, but it remains doubtful whether these indicate a biostratigraphical change in the trilobite spectrum. More significant seems to be the fact that Holmia kjerulfi and Kjerulfia lata occur in the lower limestone bed and H. kjerulfi is found in the shales between the limestone beds but is not found any higher in the succession of
the Ringstrand Formation (Nikolaisen 1986; Høyberget et al. 2011a, 2011b, 2015). However, it should be emphasized that Høyberget et al. (2011b, 2015) report the helcionelloid Helcionella antiqua (Kiær 1917) from the lower limestone bed, which is also known from strata with ‘O.’ sularpensis of the middle part of the Gislöv Formation of Scania (see below). The only trilobite identified from the overlying Skyberg Member in Norway is ‘Ellipsocephalus’ cf. lunatus indicative of the Comluella?--Ellipsocephalus lunatus Zone (Høyberget et al. 2011b, 2015).

Gislöv Formation faunas

A detailed study of the Gislöv Formation of eastern Scania (Bergström & Ahlberg 1981) appears to indicate (despite the strong condensation) a relatively continuous sequence to be present, and the ranges of trilobites portray a slight change in faunal composition from the middle to the uppermost part of the formation. A lower trilobite-bearing assemblage is recognizable in a shaly interval of the middle part of the formation. It bears, according to Bergström & Ahlberg (1981), Holmia? sp., ‘Ornamentaspis’ granidis, ‘O.’ sularpensis, Berabichia? rotundata, Kingaspidoidea? cf. nordensiokeldi and an oboellid brachiopod assigned to Magnicanalis sp. (generic assignment partly revised herein). Nathorst’s (1877) report of fossils from the formation at Forsemölla lists Holmia sulcata, Kingaspidoidea? nordensiokeldi and Lingulella? nathorsti as additional species from probably this interval of the Gislöv Formation. Additional faunal elements from this interval were reported by Troedsson (1917) from the Hardeberga quarry. These include Calodicus cf. lobatus, which was firmly assigned to Calodiscus lobatus in Cederström et al. (2009). The latter authors confirmed a range of C. lobatus from the upper part of the H. kjerulfia assemblage into the lowest part of the ‘O.’ linnarssoni range zone.

The presence of holmiids and the synchronous absence of ‘Ornamentaspis’ linnarssoni prompted the interpretation of these strata and the interval to the Holmia kjerulfia group Zone. As discussed by Nielsen & Schovsbo (2011), the occurrence of Holmia and holmiid trilobites in general is, however, not restricted to the eponymous Holmia ‘zones’. The presence of typical late to latest early Cambrian ellipsocephalid trilobites, in contrast, indicates a distinct faunal turnover so that the fauna represented in the middle part of the Gislöv Formation indeed signifies a new, recognizable zone.

A higher, but not the highest, part of the Gislöv Formation (generally developed as light coloured limestone) is characterized by a low diverse fauna with ‘Ornamentaspis’ cf. linnarssoni, an oboellid assigned to Magnicanalis sp. and additional brachiopods. This part has been regarded as the lower part of the ‘Ornamentaspis’ linnarssoni Zone, but its faunas are insufficient to distinguish it biostratigraphically from the underlying strata.

The uppermost part of the formation, generally developed as a light or dark limestone with phosphoritic nodules, bears a fauna with ‘Comluella’ scanica, ‘Ellipsocephalus’ lunatus, ‘Strenuaeva’ sp., Amphigeisina danica, Magnicanaldis sp., and Hyolithellus cf. micans (Bergström & Ahlberg 1981; Cederström et al. 2009, 2012).

Remarkably, the well-known ‘Ornamentaspis’ linnarssoni fauna from the dark grey shales at Forsemölla includes additional trilobites such as a new species of Strenuaeva and a species of Protolenus s.l. that will be described elsewhere. They appear to indicate a distinctly younger age of the fauna than previously assumed, probably related to the earliest Protolenus s.l. bearing strata in Avalonia and West Gondwana (Geyer, unpublished data). A similar development with Holmia spp., ‘Strenuaeva’ and Berabichia occurs in the Holmia--Schmidtiellus Zone of the lower parts of the Ocieseki and Kamieniec Formations and is replaced by species of Kingaspidoidea and Issafeniella in the shallower marine facies of the Ocieseki Formation and Protolenus and Issafeniella in the deeper marine facies of the Kamieniec Formation. These are followed by a typical middle Cambrian fauna with species of Paradoxides s.l. and ellipsocephalines (Zylińska 2013b).

Torneträsk Formation faunas

A fauna from the Torneträsk Formation in the Luobåkti section near Lake Torneträsk, northern Sweden, assigned to the Ornamentaspis? linnarssoni Assemblage Zone includes Geyerorodes? lapponicus, Strenuaeva inflata, Neocobboldia aff. dentata and Chelediscus acifer (Axheimer et al. 2007). An earlier report of an assemblage from the Torneträsk Formation by Ahlberg (1980) reported Strenuaeva inflata together with S. triangularis, Ellipsostrum cf. gripi, and Geyerorodes? lapponicus. Geyerorodes, first introduced as Orodes Geyer 1990 and replaced because of homonymy (Özdikmen 2009), is a genus indicative of late sub-Paradoxides strata in Avalonia (Fletcher 2006) or latest sub-Paradoxides to earliest Paradoxides-bearing strata in Moroccan West Gondwana (Geyer 1990; Geyer et al. 1995). The specimen illustrated by Axheimer et al. (2007, fig. 4r) has been re-examined by P. Cederström and appears to be a deformed cranidium of G.? lapponicus (P. Ahlberg, personal communication 2015). Although a confident generic assignment is difficult, it is tentatively assigned to Cambrunicornia, a genus known from the lower–middle Cambrian boundary interval in West Gondwana, where it ranges from the Hupeolenus Zone to the Morocconus notabilis Zone of the Moroccan biostratigraphical zonation in the lowermost Agdzian Stage (see discussions in Geyer et al. 2014).
Grammajukku Formation faunas

The traditional *Ellipsostrenua gripi* fauna of the upper part of the Grammajukku Formation from a ravine at Mount Aistjakk (now commonly spelled Assjat) in the Laisvall region (Kautsky 1945) includes the trilobites *Holmia ljungneri* and *Ellipsostrenua gripi*, and a bradoriid, the helcionelloid mollusc *Helcionella antiqua*, and three species of linguliform brachiopods. Two additional faunas slightly below Kautsky’s original horizon have been reported by Ahlberg (1984a), Cederström in Nielsen & Schovsbo (2011, p. 222) and Cederström et al. (2012) from the Mt. Assjat and the nearby Delliknäs sections. According to Cederberg et al. (2012) these include also *Holmia ljungneri* and *Ellipsostrenua gripi* as in the upper faunal horizon, and a fairly diverse assemblage comprising *Ornamentaspis linnarssoni*, *Ellipsostrenua gripi*, *Holmia cf. inusitata*, *Kjerulfia palpebra*, *Strenuacea spinosa*, and *S.? kullingi*.

The fossil assemblages portrayed above accumulate to a consistent succession of trilobites without detectable biostratigraphic gaps. On the other hand, the similarities with faunas of the Holy Cross Mountains, Poland, and the Atlas ranges, Morocco, appear to indicate that the *Epichalnipsus* fauna cannot be younger than the younger part of the traditional *Ornamentaspis linnarssoni* Zone, or Nielsen & Schovsbo’s Comluella–*Ellipsoccephalus lunatus* Zone. Nielsen & Schovsbo’s (2011) assignment of the member to the LC2-4 sequence appears to be accurate. Accordingly, the endemic character of the *Epichalnipsus* fauna must be regarded as result of biofacies differentiation due to depositional settings of the well washed and re-worked, shallow sand accumulations.

Intercontinental and global correlation

A precise, direct correlation of the *Epichalnipsus* fauna with the uppermost part of the *Holmia kjerulfia*–*Ornamentaspis linnarssoni Zone* (lower part of the former *Ornamentaspis linnarssoni* Zone) or lowermost Comluella–*Ellipsoccephalus lunatus* Zone (upper part of the former *Ornamentaspis linnarssoni* Zone) into regions outside Scandinavia is almost impossible. As demonstrated by Sundberg et al. (submitted), who provide a detailed correlation chart for the Cambrian Series 2–Series 3 boundary interval, a correlation of the late early Cambrian trilobites known from Scandinavia is slightly facilitated by a comparison with faunas from the Holy Cross Mountains, Poland, which provides links to faunas from West Gondwana (particularly Morocco) and western Avalonia (southeastern Newfoundland). The *Epichalnipsus* fauna correlates with part of the *Protolenus–Issafeniella* faunal assemblage (Żylińska & Szczepanik 2009) and probably with the lowermost Agdzian Stage of the Moroccan Atlas ranges (*Hupeolenus Zone*; see Geyer & Landing 2004).

An equivalent of the *Epichalnipsus* level in Avalonian Newfoundland is probably Fletcher’s (2006) *Orodus howleyi* Zone in the upper Branchian Stage. All other correlation must be derived from indirect correlations of these stratigraphic intervals, e.g. with the *Acimetopus bilobatus* Zone of the upper Dyeran in the Taconic Allochthon of eastern Laurentia and coeval strata in the upper, but not uppermost *Olenellus ‘Zone’ of western Laurentia; the mid-Toyonian of the Siberian Platform; and the mid-Duyunian *Arthri-ccocephalus chauveaui–Changaspis elongata* Zone of the South China/Yangtze Platform.

Acknowledgements

Preparation of this article was made possible by research grant GE 549/21-1 of the Deutsche Forschungsgemeinschaft (DFG) to G.G. Thin sections and polished slabs used for this study have been prepared by Peter Späthe at the Institute of Geography and Geology, University of Würzburg. P. Ahlberg (Lund) and A. Żylińska (Warsaw) provided helpful reviews which considerably improved this article.

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### Appendix 1. Petrological characters of the three samples from the studied erratic boulders from the As Hoved cliff, Jutland, and the Lingulid Sandstone Member of Kvillen, Halleberg and Djupadalen, Falbygden

| Grain size | AS HOVED | KVILLEN | DJUPADALEN |
|------------|----------|---------|------------|
| Fine       | Fine     | Coarser than the As Hoved and Kvillen samples |
| Compaction | High     | High    | Low        |
| Grain contact | Poorly visible due to general absence of Fe-oxide coats. | Poorly visible due to general absence of Fe-oxide coats. | Irregularly stepped, straight/linear > concave-convex, << point contacts. |
| Grain bond | Predominantly direct grain contacts and mostly syntaxial quartz overgrowth. | Predominantly direct grain contacts and usually syntaxial quartz overgrowth. | Predominantly direct grain contacts and syntaxial quartz overgrowth. |
| Pores | 1–5 vol.%, syntaxial quartz overgrowths, grain contacts << interporous spaces. | 1–5 vol.%, syntaxial quartz overgrowths, grain contacts << interporous spaces. | 10–15 vol.%, pore cement, prevailing interporous spaces 0.05–0.1 mm, scattered large, branched interporous spaces (L 0.6 mm, B 0.1–0.15 mm). |
| Contact cement | Argillaceous-chloritic, rarely ferritic (goethite) on grain margins | Argillaceous-chloritic, small amounts of goethite pigment. | Locally argillaceous-ferritic (illite + goethite) at grain contacts, scattered glauconite |
| Pore cement | Argillaceous-chloritic, argillaceous-illictic, minute interporous spaces (0.07×0.04 mm to 0.25×0.05 mm), small amounts of goethite pigment. | Argillaceous-chloritic, argillaceous-illictic, minute interporous spaces (0.1×0.03–0.06 mm), small amounts of goethite pigment. | Locally argillaceous-ferritic (illite + goethite) in minute and scattered large interporous spaces. Syntaxial quartz overgrowths. |
| Quartz | c. 94 vol.%, 0.03–0.3 mm, maximum 0.3 mm. Monocrystalline, minor subgrain phenomena. Rare Fe oxide coats. Small grains (0.03–0.1 mm) predominantly isometric, subrounded, irregular shapes, moderate to high sphericity. Large grains platy, poorly rounded (L 0.2–0.3 mm, W 0.05–0.1 mm), angular or splintered grains (L 0.13 mm, B 0.01–0.03 mm), subtrangular in section. | c. 90 vol.%, mostly 0.04–0.1 mm, maximum 0.15 mm. Monocrystalline, minor subgrain phenomena. Rare Fe oxide coats. Small grains (0.04–0.07 mm) predominantly isometric, subrounded, irregular shapes, moderate to high sphericity. Some angular or splintered grains. Large grains (>0.15 mm) platy, poorly rounded (L 0.15–0.25 mm, W 0.04–0.05 mm), no angular or splintered grains observed. | c. 97 vol.%, 0.05–0.3 mm. Monocrystalline, minor subgrain phenomena. Frequent Fe oxide coats. Small grains (0.05–0.15 mm) predominantly subrounded/with rounded corners, irregular shapes, partly very angular, low sphericity. Large grains (>0.15 mm) either with low sphericity and poorly rounded corners or platy. Some grains with Boehm lamellas possible relics of the parent rocks, scarce inclusions of rutile (sagenite). |
| Alkali feldspar | 0.05–0.1 mm. Fresh cleavage fragments with rounded edges or subrounded, microcline (twinning), rare perthitic unmixing. | 0.06 mm. Fresh cleavage fragments with rounded edges or subrounded, microcline (twinning), rare perthitic unmixing. | 0.12–0.17 mm. Fresh cleavage fragments with rounded edges or subrounded, microcline (twinning), fringe altered to illite or white mica. |
| Plagioclase | 0.07–0.09 mm, max L 0.18 mm, B 0.03 mm. Fresh cleavage fragments with rounded edges, platy (L 0.18 mm, W 0.03 mm). | 0.05–0.07 mm. Fresh cleavage fragments with rounded edges, platy (L 0.08–0.18 mm, W 0.05 mm); altered cleavage fragments (L 0.12 mm, W 0.05 mm; sericite, illite, goethite pigment). | 0.15 mm. Fresh cleavage fragments with rounded edges. |
| Glauconite | 0.04–0.12 mm. Subangular, deformed during compaction, partly with pale brown crust. | 0.05–0.15 mm, maximum 0.25 mm (angular). Subangular, with rounded edges and angular, deformed during compaction, partly with pale brown crust. | 0.05–0.15 mm. Subangular, deformed during compaction, no pale brown crust observed. |
| Tourmaline | 0.04–0.07 mm. Cleavage fragments, generally with rounded edges, rarely polygonal. | 0.07–0.08 mm. Cleavage fragments, generally with rounded edges. | 0.04–0.1 mm. With rounded edges. |
| Zircon | 0.03–0.04 mm, with rounded edges, partly with clearly recognizable oscillatory zonal composition. | 0.04 mm, with rounded edges. | 0.07 mm, with rounded edges, partly with clearly recognizable oscillatory zonal composition. |
| Apatite | L 0.1–0.12 mm W 0.03 mm. Long prisms. Transparent. | L 0.05–0.12 mm, W 0.02–0.04 mm. Prismatic, transparent. | Not observed. |
|                       | AS HOVED                              | KVILLEN                               | DJUUPADALEN                           |
|-----------------------|---------------------------------------|----------------------------------------|----------------------------------------|
| Goethite, detritic    | 0.05–0.09 mm.                          | 0.04 mm.                               | 0.06–0.08 mm.                          |
|                       | Rounded.                               | Rounded.                               | Subrounded.                            |
| Dark mica (biotite)   | L 0.07–0.15 mm.                        | L 0.22 mm.                             | L 0.07 mm.                             |
|                       | Scarcely present, pleochroism yellow brown to pale brown, altered. | Pleochroism dark yellow brown to pale brown, altered to chlorite and goethite. | Pleochroism yellow brown to pale brown, partly altered to chlorite. |
| White mica (muscovite)| L 0.06–0.17 mm, maximum 0.3 mm.       | L 0.15–0.25 mm, maximum 0.6 mm (bent by compaction). | L 0.04–0.12 mm, maximum 0.3 mm.       |
| Chlorite              | L 0.15–0.22 mm, W 0.01–0.04 mm.       | L 0.22 mm, W 0.08 mm.                 |                                        |
|                       | Pleochroism yellowish green, pale green to colourless, lamellar intergrowth with white mica, goethite (altered dark mica). | Pleochroism yellowish green, pale green to colourless, lamellar intergrowth with white mica (altered dark mica). | Pleochroism yellowish green to pale green. |
| Chert grains          | 0.07 mm.                              | 0.04 mm.                               | 0.09 mm.                               |
|                       | Elongated, subrounded.                | Rounded.                               | Subrounded.                            |