Rapporter och meddelanden 128

WOGOGOB 2007

9th meeting of the Working Group on Ordovician Geology of Baltoscandia

Field guide and Abstracts

Jan Ove Ebbestad, Linda Wickström & Anette Högström (eds.)

SGU
Sveriges geologiska undersökning
Geological Survey of Sweden

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IGCP503 Ordovician Palaeogeography and Palaeoclimate Regional Meeting 2007

August 17th–20st, Rättvik, Sweden

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Cover photo: Composite photo showing (upper part, photo by J.O.R. Ebbestad) the east flank of the Osmundsberget quarry in the Siljan District, Dalarna with the Kullsberg Limestone to the right, followed by transition beds of the Fjäcka Shale equivalent, and the flank facies Boda Limestone to the left; (lower part, photo by L.M. Wickström), river section at Sladderforsen, River Långan, with folded and thrusted beds of ramp facies sediments (Isön Limestone).

WOGOGOB 2007 logo: The design follows the WOGOGOB 2004 layout, with the text and trilobite motif added by J.O.R. Ebbestad. The outline represents the cranidium of the trilobite *Tetralichas planifrons* (Angelin, 1854) from the Katian Kullsberg Limestone in the Siljan District, Dalarna, Sweden.

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LINNÉ 2007

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Preface

Last year WOGOGOB (**WO**rking **G**roup on **O**rdovician **G**eology of **B**altoscandia) turned 20 years, and the 9th meeting this year in Rättvik in the Siljan District celebrates this occasion. WOGOGOB was instigated by Maurits Lindström in 1986, and the history is chronicled briefly below. The meeting has over the years developed into one of the more important forums for integrated Baltoscandian research and collaboration, along with The Baltic Stratigraphic Conference and Lundadagarna.

WOGOGOB 2007 is a field meeting, with excursions in the Siljan District and the Östersund area. The reason behind the choice of Rättvik and Östersund as the place for this gathering is twofold. Firstly the Siljan District has a central place in Ordovician geology of Baltoscandia and indeed world wide. We are here thinking of reference sections for units in Sweden, standard conodont zones and even global palaeoclimate changes (e.g. the Boda event). Jämtland is central in WOGOGOB's history as the area served as a meeting place for the intial meeting in 1986, and more recently renewed stratigraphical and sedimentological studies have demonstrated the importance of this area in regional geology.

WOGOGOB 2007 is unique in that it brings together palaeontologists, sedimentologists, geochemists and stratigraphers with research efforts directed at the Ordovician of Baltoscandia primarily, but also with wider ramifications for Ordovician geology. The meeting is held in collaboration with, and is a contribution to IGCP project 503, Ordovician Palaeogeography and Palaeoclimate, which aims to develop a better understanding of the environmental changes that influenced the Ordovician biodiversification, the end-Ordovician extinction and the Silurian radiation (http://sarv.gi.ee./igcp503). WOGOGOB 2007 also serves as the Baltic regional team meeting for IGCP 503.

Jan Ove R. Ebbestad, Linda M. Wickström, and Anette E.S. Högström
(Editors)

WOGOGOB 2007
SWEDEN August 17-20

WOGOGOB – How it began

Maurits Lindström

WOGOGOB was born at 18.00 hrs on May 31, 1985. Although it was declared dead by a couple of truly knowledgeable people a few days before and after this date, its survival into a third decade may be due, among other things, to the circumstance that a sufficient number of people would not just let such a quaint acronym expire. It stands for Working Group on Ordovician Geology of Baltoscandia.

The idea of WOGOGOB was presented to a meeting of Palaeontologisk Klub (DGF) in Copenhagen on the mentioned day and found the approval of the participants. Maurits Lindström, Kent Larsson, Anita Löfgren, Valdemar Poulsen, and Nils Spjeldnaes agreed to be organizers. The event had been prepared for through the distribution of a leaflet. In it, there were words about the geological, biological and oceanographical evolution of northern Europe during the Ordovician Period, and it was stated to be ”important that everything be done in order to avoid that it gets the image of a would-be elite or closed circle”.

Because of its regionally and thematically defined focus the working group would not compete with organizations with wider and global responsibilities and thereby interfere with their activities. Fears in this direction were, however, the reason for the rejection of the idea by a couple of geologists.

After it had been agreed that the working group would have neither board nor budget and would not register as an organization, one of its principal initial activities, to collect information about researchers and ongoing research, began forthwith and was carried on at least until 1988; the principal result of this activity was a newsletter distributed in April 1987. This pamphlet contains a cartoon with the significant inscription ”TO BE CONT:D (PERH:S)”.

The first meeting under the name of WOGOGOB was May 27–30, 1986, in Östersund, and was sponsored financially by the Royal Swedish Academy of Science. The meeting was visited by among others Frans E. Wickman, who suggested for the first time that the Ordovician breccias at Lockne could be due to a meteoroid impact.

In spite (or, perhaps, in a way, because) of its semi-formal status, WOGOGOB proved useful as a means for opening up for a meeting of WOGOGOB members in Tallinn June 29 to July 3, 1988, This was in every respect a most successful meeting, although it took place while the Iron Curtain was still there.

Ordovician of the Siljan District, Sweden

Jan Ove R. Ebbestad & Anette E.S. Högström

Structural setting

The first geological map of the Siljan ring, by Törnquist (1871), outlines the nearly perfectly circular structure manifested by a sedimentary halo of Palaeozoic rocks in an otherwise Proterozoic basement. Nearly 100 years later it was suggested that this represented an impact structure (Wickman et al. 1963, Svensson 1971, 1973, Thorslund & Auton 1975). Subsequent geophysical studies, especially during the Deep Gas Project in the 1980's, firmly established the impact origin (see Juhlin 1991). This interpretation has been confirmed by recent, more detailed studies (see reviews by Henkel & Aaro 2005, Reimold et al. 2005). The most recent age estimates of the impact event are 376.8±1.7 Ma by Ar–Ar dating (Reimold et al. 2004) and with a more conservative estimate of 377±2 Ma (Reimold et al. 2005). This places the impact event in the mid Devonian, at the Frasnian/Famennian boundary (see Reimold et al. 2005). Earlier age estimates by Bottomley et al. (1978, 1990) suggested an age of 361.9±1.1 Ma to 368±1.1 Ma.

Although the original crater is denudated and the prominent ring graben has been subjected to glacial excavation during the Pleistocene, this is clearly the largest known impact structure in Western Europe. Its diameter was originally estimated to be 52 km (Grieve 1988), but this figure has later been increased to 65 km (von Dalwigk & Kenkmann 2000). Recently Henkel & Aaro (2005) suggested a topographically observable diameter of 75 km with an estimated 75–85 km diameter for the original impact structure. The central uplift is about 30 km wide, with Lower Palaeozoic sedimentary rocks preserved in the surrounding irregular ring structure which has a maximum width of about 14 km. Outside the ring, the Palaeozoic sedimentary rocks are completely eroded in the Siljan District and only Proterozoic basement rocks are present. Estimates suggest that somewhere between 500 m (Rondot 1976) to 1 000 m (Grieve 1984), or as much as 2000 m (Collini 1988, Lindström & von Dalwigk 1999), of overburden has been removed since the time of the impact.

The Palaeozoic rocks in the ring graben are tectonically disturbed, commonly being steeply inclined or even overturned. Usually, faults are steep but they have little displacement (von Dalwigk 2003), and they are radially distributed with respect to the central uplift (Wickman 1981, Wickman & Nyström 1984, Kenkmann & von Dalwigk 2000, von Dalwigk 2003, Henkel & Aaro 2005). This structural signature developed with the collapse of the transient crater and was forming before the final crater shape emerged. Near-surface sediments (i.e. the Palaeozoic rocks) at the rim of the transient crater were transported by gravity 6–7 km toward the crater centre as mega-blocks, colliding here with mass-flows from the area of the central uplift (von Dalwigk & Kenkmann 2000, Kenkmann & von Dalwigk 2000, Dalwigk 2003, Henkel & Aaro 2005). In six areas around the ring graben, typically where the width of the ring is narrow, the Proterozoic rocks form structural highs with an average uplift of 500 m (Fig. 1). These are remnants of radial transpression ridges formed as a result of oblique compression during inward movement and collision of blocks (Kenkmann & von Dalwigk 2000).

Earliest history of research

Since the earliest part of the 18th century, the Siljan impact structure has been the focus of scientific studies. These began with the report of the travel of C. Linnaeus through Dalarna in 1734, where he studied the botany as well as the geology of the region. One of his discoveries was the presence of *petroleum* in the Skärbacka quarry (at Osmundsberget). Following Linnaeus (1734, reference in Hedberg 1988), Tilas (1740, in Hedberg 1988) gave an exhaustive account of the geology in the Osmundsberget area, describing what he refers to as the "oil mine" and "Fullers earth quarry". Tilas' work is important in two other respects: it is one of the earliest known bed-by-bed descriptions through a sequence of strata, as well as one of the earliest published lithostratigraphic correlations of beds between adjacent but separated sections (Hedberg 1988). The Siljan ring, and especially the petroleum occurrence described by Tilas, was subsequently dealt with in several

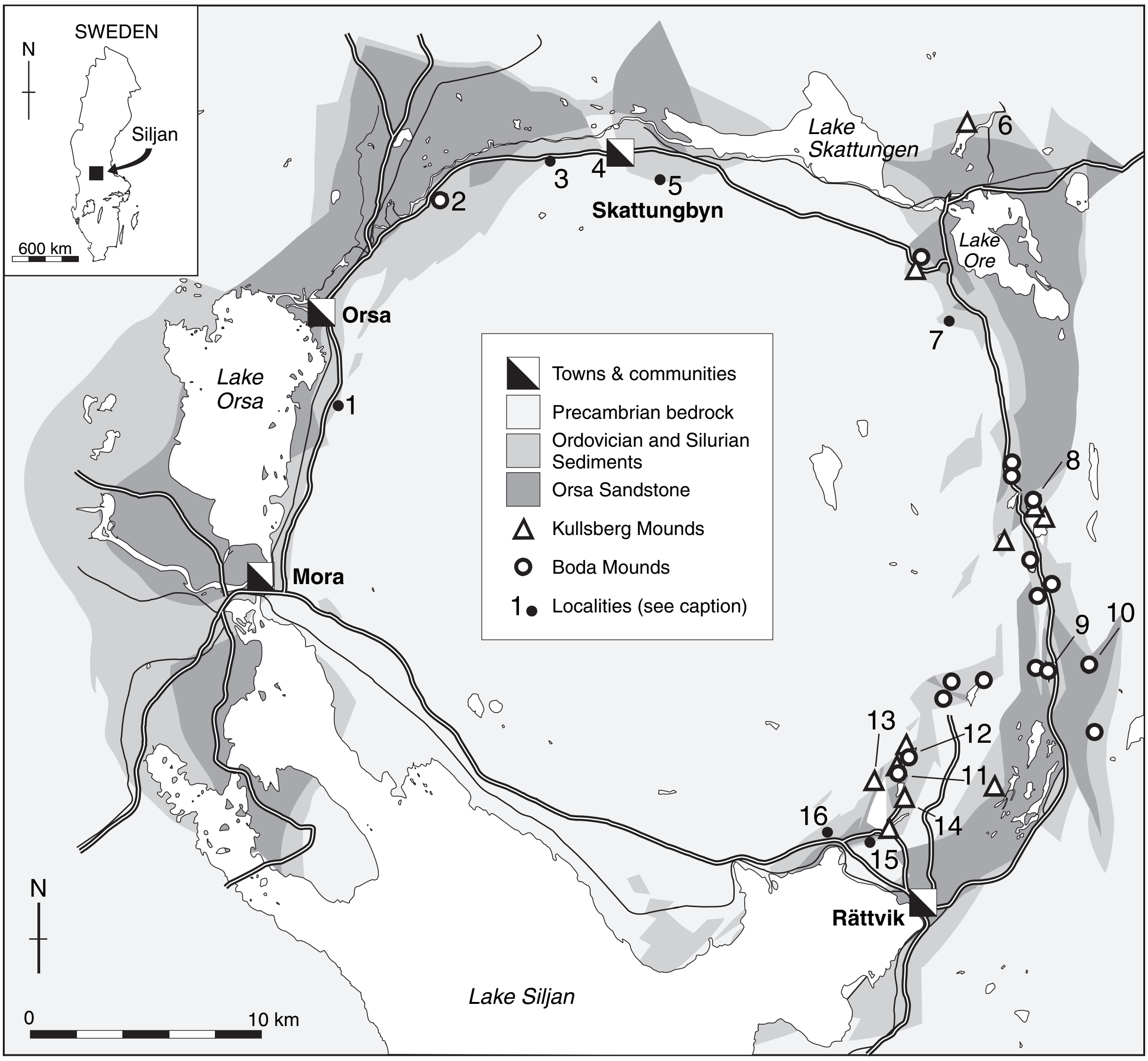

Fig. 1. Map of the Siljan ring structure showing the distribution of Palaeozoic rocks and the Kullsberg and Boda limestone carbonate mounds. The Orsa Sandstone (Late Silurian? – Devonian) has been marked out. Six areas with transpression ridges are shown (modified from Kresten et al. 1991, Kenkmann & von Dalwigk 2000). The following localities mentioned in the text have been marked: 1 Amtjärn, 2 Kallholn, 3 Djupgrav, 4 Talubäcken, 5 Leskusängen, 6 Furudal, 7 Fjäcka, 8 Osmundsberget, 9 Solberga, 10 Jutjärn, 11 Skålberget, 12, Dalhalla (Unkarsheden), 13 Amtjärn, 14 Kullsberg, 15 Nittsjö, 16 Vikarbyn (Kalkbacken-Sätravägen).

papers during the later part of the 18th century (see Hedberg 1988 for the following references: Wallerius 1747, Hülphers 1762, Bergman 1766, 1773–1774, Cronstedt 1752, 1781, 1787, and Rinman 1788, 1789).

Wilhelm Hisinger published extensively on the geology of the Siljan ring. In 1804 (Hisinger 1804, see Hedberg 1988) he comments on the work of Tilas (1740) and says: "*The rock-oil is thick, but fluid, dark brown, and burns with much smoke*" (see Hedberg 1988). Hisinger's most significant geological contribution to the geology of the Siljan ring is a series of papers (Hisinger 1819, 1831, 1837, 1840) describing the distribution and appearance of the sedimentary rocks and their fossil content. The latter includes a number of species of trilobites, gastropods, and cephalopods for which the Siljan District is the type area. In 1831 Hisinger comments on the steeply dipping beds observed by him, especially at Öja and Wikarbyn near Rättvik, and conclude that these are connected with the Siljan ring structure that is clearly seen in the distribution of lakes and rivers.

It was Leonard Törnquist who in reality started the era of modern geological investigations in the Siljan District. On the first geological map of the Siljan region (Törnquist 1871), the ring structure mentioned by

Hisinger (1831) is distinctly outlined and a modern picture of the appearance of the Siljan ring structure begins to emerge. Studies into the stratigraphy and fauna of the sedimentary succession in the Siljan district by, among others, Wahlenberg (1818), Murchinson (1847, se Hedberg 1988), Angelin (1852), Törnquist (1867, 1884), and Stolpe (1872) lay the foundation for more modern interpretations and regional correlation of the geology in the area.

Interestingly, a stratigraphic issue spurred much of the early modern research interest in the Siljan District. The stratigraphical position of the *Leptaena* Limestone (term by Törnquist 1871, p. 89, now the Kullsberg and Boda limestones) was highly controversial and gave rise to a rather fierce geological debate in Sweden. In a series of papers L. Törnquist maintained until 1892 (see Törnquist 1892, 1919) that the *Leptaena* Limestone was situated above the dark graptolitic Siluran shales, whereas Stolpe (1872, 1884) and many others (for extensive list of literature see Moberg 1910, Törnquist 1919) suggested that the limestone was situated between the *Tretaspis* shale and the Silurian shale. Only when large scale industrial quarrying started in the 1920's and 30's, the issue was settled permanently, especially through the works of Isberg (1917) and foremost Warburg (1925).

Following this era in the history of the geological investigations of the Siljan District, Per Thorslund and later Valdar Jaanusson made monumental efforts into understanding the geology of the Siljan District (see Fig. 2 for summary of stratigraphic nomenclature). The following review of the stratigraphic succession demonstrates the central and active position the Siljan District holds for a broad spectrum of geological subjects and the number of people who have and are contributing to the understanding of the area.

The stratigraphic succession

The Ordovician succession in the Siljan District is remarkably complete and unaltered. Conodont Color Alteration Index values show for instance that the rocks have not been heated above 90°C, even though they are tectonically disturbed (Bergström 1980). The entire Ordovican succession is no more than 100 m thick in the so called intermound facies (Jaanusson 1982b).

The present overview provides a summary of current stratigraphical and faunal information about the Ordovician succession in the Siljan District. No attempt has been made to revise the stratigraphy, sedimentology, or biozonations, as this is beyond the scope of this paper (but see Bergström 2007b). Consequently, the topostratigraphic scheme defined for the Swedish Ordovician succession by Jaanusson (1960a, p. 218, 1982b) and later defined as topoformations (Jaanusson 1976, p. 310) is followed although it is realised that it is a mixture of biostratigraphically and lithostratigraphically defined units and hence does not follow the modern separation of biostratigraphic and lithostratigraphic classification schemes (see also discussion in Tjernvik 1972, Tjernvik *in* Tjernvik & Johansson 1980, Nielsen 1995). The stratigraphy and biozonation presented in Fig. 3 is tied into the current classification of the Ordovician System and Estonian Ordovician stratigraphy (Webby et al. 2004, Nõlvak et al. 2006, Bergström 2007b). Dronov & Holmer (1999) developed a number of provincial depositional sequences for Baltoscandia, and these are referred to where relevant.

Large scale composite faunal and sedimentological facies zones or belts are recognized in the Ordovician of Baltoscandia (Jaanusson 1963a, Männil 1966), termed confacies belts by Jaanusson (1976, p. 308). In Sweden, the Scanian and Central Confacies Belts of Jaanusson (1976) correspond to the Scandinavian Basin (Ainsaar et al. 2004). The latter term is used here, to better conform to a sedimentological nomenclature for the baltoscandian epicontinental palaeobasin.

Jaanusson (1952) used the terms calcarenite and calcilutite for carbonate rocks on Öland and in the Siljan District with more than 20% sand-sized grains (usually skeletal material) or less than 20% sand-sized grains respectively. These terms have later been consequently used by e.g. Jaanusson (1982b) and Holmer (1989).

References to type sections and/or type localities are made based on the literature, although some of these are no longer accessible. Kresten et al. (1991) introduced a Swedish spelling of unit names following names and spelling on the 1:50 000 topographical maps. That is in line with the recommendations given by Nystuen (1986, 1989), but for the purpose of this guide the traditional unit names are conserved. Terms previously used for a unit are also summarized (see also Magnusson 1958), although these are not always a direct equivalent owing to the often imprecise stratigraphical precision and or definition of the older terms.

Oldest Palaeozoic strata

Exposed Cambrian strata are missing in the Siljan District, but Upper Cambrian (Furongian, *Olenellus* Zone) sediments have been identified in erratic boulders at Gärdsjö based on well preserved phosphatic brachiopods. These were earlier attributed to *Obolus triangularis* Mickwitz (Moberg & Segerberg 1906, Thorslund & Jaanusson 1960, Jaanusson 1982b), but later revisions by Puura & Holmer (1993) showed the species to be *Ungula inornata* (Mickwitz). In the erratics this species co-occurs with the acrotretacean *Ceratreta tanneri* (Metzger), reported by Holmer (1989) and Holmer & Popov (1990).

	Törnquist 1883	Warburg 1910	Up to 1982, for references see caption	Jaanusson 1982b, 1973, 1976, 1995, Present
				Glisstjärn
	Klingkalk; Leptaena Lst. (but see caption)	Klingkalk Brachiopod Sh.; Læptena Lst.	*Dalmanitina* Beds; Boda Lst.	Tommarp Beds; Boda Lst.
Trinucelus Beds	Red Shale; Leptaena Lst. (but see caption)	Red *Trinucleus* Sh.; Læptena Lst.	*Staurocephalus* Sh.; Red *Tretaspis* Sh.; Boda Lst.	Jonstorp Fm.: Nittsjö Bed, Öglunda Lst.; Boda Lst.
Trinucelus Beds	Grey Lst.	Grey Lst.; Læptena Lst.	*Tretaspis* Lst.	Jonstorp Fm.; Boda Lst.
Trinucelus Beds	Black Shale	Black *Trinucleus* Sh.	Black *Tretaspis* Sh.	Fjäcka Shale
Trinucelus Beds	Masur Lst.	Masur Lst.	Slandrom Lst.	Slandrom Lst.
Chasmops Lst.	Bryozoan Lst.	*Macrourus* Lst.	Upper *Chasmops* Lst. & Sh.; Kullsberg Lst.	Freberga Fm.: Moldå Lst., Skagen Lst.; Skålberg Lst.; Kullsberg Lst.
Chasmops Lst.	Cystidékalk	*Cystidean* Lst.	Lower *Chasmops* Lst. or *Ludibundus* Lst.	Dalby Lst.
Chasmops Lst.	'Flagkalk'	*Ancistroceras* Lst.	*Crassicauda* Lst.	Furudal Lst.
Ortocheras Lst.	Upper Grey Orth. Lst.	*Chiron* Lst.; Upper Grey Orth. Lst.	*Schroeteri* Lst.	Folkeslunda Lst.
Ortocheras Lst.	Upper Red Orth. Lst.	Unnamed; Upper Red Orth. Lst.	*Schroeteri* Lst.	Seby Lst.
Ortocheras Lst.	Upper Red Orth. Lst.	Unnamed; Upper Red Orth. Lst.	*Schroeteri* Lst.	Skärlöv Lst.
Ortocheras Lst.	Upper Red Orth. Lst.	*Platyururs* Lst.; Upper Red Orth. Lst.	*Platyururs* Lst.	Segerstad Lst.: Vikarbyn Lst., Kårgärde Lst.
Ortocheras Lst.	Upper Red Orth. Lst.	*Gigas* Lst.; Upper Red Orth. Lst.	Vaginatum Lst.: *Gigas* Lst., *Obtusicauda* Lst., *Raniceps* Lst., *Expansus* Lst.	Holen Lst.
Ortocheras Lst.	Lower Grey Orth. Lst	*Asaphus* Lst.; Lower Grey Orth. Lst.	Vaginatum Lst.	Holen Lst.
Ortocheras Lst.	Lower Red Orth. Lst.	*Limbata* Lst.; Lower Red Orth. Lst.	*Limbata* Lst.	Lanna Lst.
Ortocheras Lst.	Green Lst. *Phyllograptus* Sh.	*Planilimbata* Lst. *Phyllograptus* Sh.; Green Orth. Lst.	*Planilimbata* Lst.	Tøyen Fm.; Latorp Lst.
Obolus Lst.	*Obolus* 'gruskalk' *Obolus* Congl.	*Obolus 'gruskalk'* *Obolus* Congl.	Obolus beds	Obolus beds

Fig. 2. Nomenclature of older terms. Törnquist (1871) originally placed the Leptaena Limestone above the Rastrits and Retiolites shales (= Kallholn Fm.), but the diagram has been simplified to accommodate the term. Key references up to 1982; Thorslund 1935, Hadding 1958, Thorslund & Jaanusson 1960, Jaanusson & Martna 1948, Jaanusson & Mutvei 1951, 1953, Tjernvik 1956, Jaanusson 1951, 1963a, 1963b, 1973, 1982b. Lst. = Limestone, Sh. = Shale, Orth. = Orthoceras.

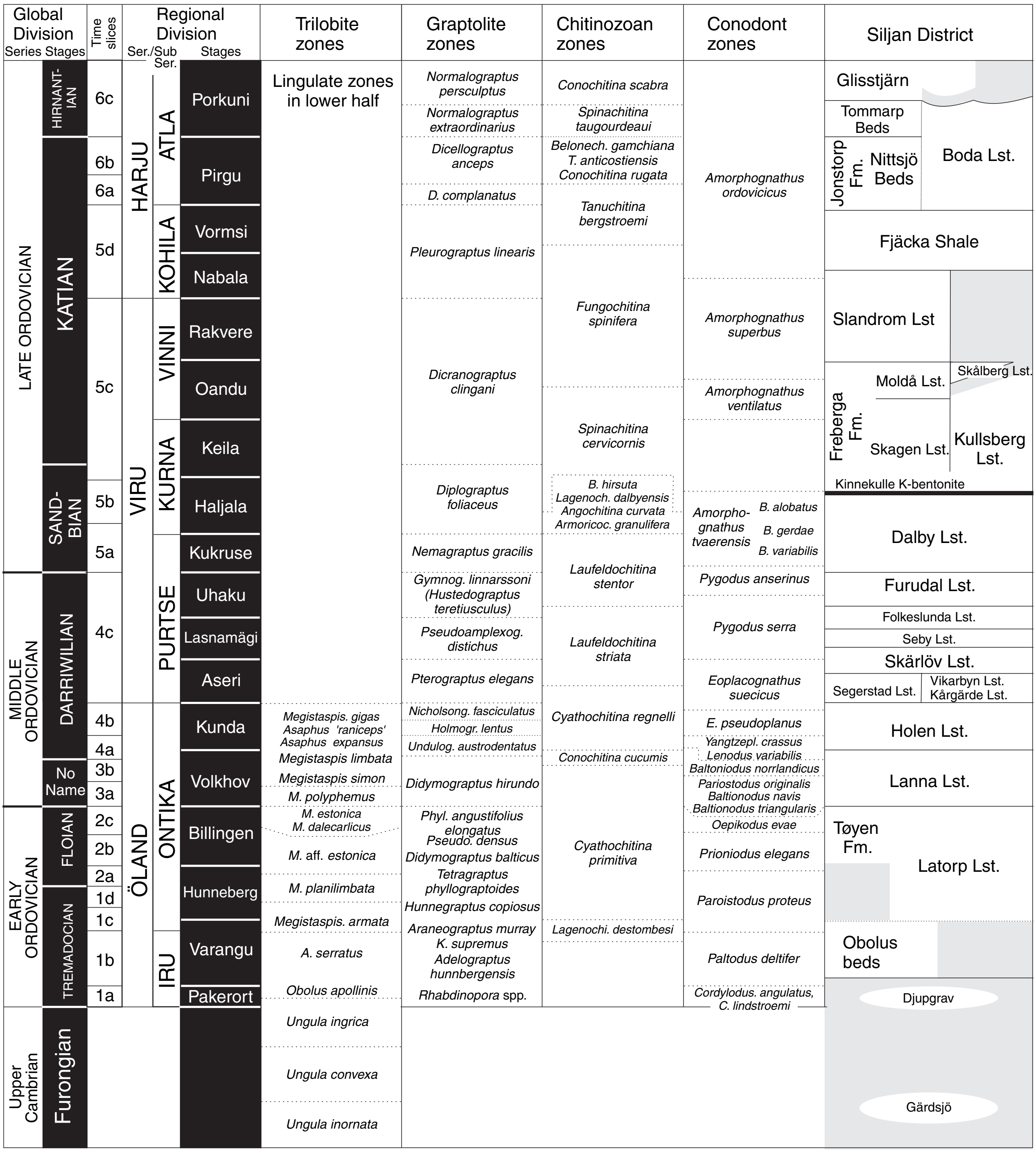

Fig. 3. Correlation chart of Ordovician regional zonation with the international standard, times slices, and stage names (Webby et al. 2004, Bergström et al. 2006b). Regional series, sub-series and stages, and their spelling, follow those of Nõlvak et al. (2006). Included in the chart are trilobite zonation (Tjernvik *in* Tjernvik & Johansson 1980, Löfgren 1994, Nielsen 1995, Pärnaste 2004a), graptolite zonation (Lindholm 1991, Nõlvak & Goldman 2007), chitinozoan zonation (Laufeldt 1967, Nõlvak & Grahn 1993) and conodont zonation (Bergström 1971, 1988, 2007b, Löfgren 1993, 1994, 1994, 1995a, 2000). Data on graptolites in the basal beds at the Djupgrav section (Thorslund *in* Thorslund & Jaanusson 1960) and basal phosphatic brachiopod distribution (Puura & Holmer 1993) are included.

‘Obolus’ *beds*

Previously termed: *Obolus* Sandstone, *Obolus* Beds or Limestone, *Obolus* Conglomerate, *Obolus apollonis* Zone, *Obolus* ‘gruskalk’ (*pars*).

Main lithology: Polymict conglomerate.

Thickness variation: The unit is 3 m thick in the section at Djupgrav (Thorslund 1936b), about 1.8 m at Vikarbyn (Törnquist 1883), and 0.15–0.80 m at Sjurberg (Hedström 1894).

Discussion: In the Siljan District, conglomeratic strata directly in contact with the Precambrian bedrocks have traditionally been referred to the ‘*Obolus*’ Bed/Conglomerate (Törnquist 1883, Hedström 1894, Wiman 1906, Moberg & Segerberg 1906, Hadding 1927, Westergård 1947, Tjernvik 1956, Puura & Holmer 1993). The basal beds were, however, formed during several Late Cambrian and Early Ordovician transgressive phases as shown by variations in lithology (Hadding 1927, p. 90, 1958, Thorslund 1936a, Wickman & Nyström 1984) and fauna (Puura & Holmer 1993, p. 235). At the classic Sjurberg section the Late Cambrian brachiopods *Ungula ingrica* (Eichwald) [identified as *Obolus apollonis* by Wiman (1906), Moberg & Segerberg (1906), Warburg (1910), Tjernvik (1956), Thorslund & Jaanusson 1960] and *U. inornata* (Mickwitz) are reworked, but the lingulid fauna as a whole shows a range of ages from the Late Cambrian (Furongian) to the Early Ordovician Hunneberg Stage (*Armata* trilobite Zone, lowermost *Paroistodus proteus* conodont Zone: Tjernvik 1956, Puura & Holmer 1993 figs. 1, 10, Löfgren 1994). At other localities, the ‘*Obolus*’ Beds are absent and Hunneberg strata (Latorp Limestone) lie on the Precambrian basement (e.g. Nittsjö at the locality of Warburg 1910, p. 443), Talubäcken (Bergström 1988), and Kårgärde (Wiman 1906, Jaanusson & Mutvei 1953, Tjernvik 1956, Jaanusson 1963b, Holmer 1989). Higher in the conglomerate section at Djupgrav, an occurrence of *Rhabdinopora socialis* demonstrates an early Pakerort age (Thorslund *in* Thorslund & Jaanusson 1960, p. 23, Jaanusson 1982b, Puura & Holmer 1993). Conodonts of the Hunnberg *Paroistodus proteus* conodont Zone have been found in the overlying Latorp Limestone beds (Löfgren 1994).

Latorp Limestone

Previously termed: Green Orthoceratite Limestone, *Planilimbata* Limestone.

Type area: The quarry ‘Stora brottet’ at Latorp in Närke, Central Sweden (Tjernvik 1956, pp. 130–133, Jaanusson 1960a, p. 299, 1982b).

Thickness variation: In the Sjurberg section the unit is about 3.7 m thick (Tjernvik 1956, fig. 23). At Kårgärde the unit is partly faulted out and not separated from the overlying Lanna Limestone (L. Karis *in* Jaanusson 1982b, p. 41, Holmer 1989, fig. 5b). In Jämtland the Latorp Limestone is 2.1–5.4 m thick (Tjernvik 1956).

Discussion: Jaanusson (1960b, p. 299) proposed the term Latorp Stage to replace the term *Planilimbata* Limestone, but these were then used interchangeably (Jaanusson 1960a, Tjernvik *in* Tjernvik & Johansson 1980), before the term Latorp Limestone was introduced and used by Jaanusson (1982a, b) for the first time. In the Siljan District the Latorp Limestone is developed as grey and red argillaceous calcilutitic limestones, which are glauconitic in the lower part of the unit (Tjernvik 1956, Hadding 1958). Numerous discontinuity surfaces are present, and these are outlined by yellow goethitic mineralisation (Hedström 1894, Wiman 1906, Thorslund 1936a, Tjernvik 1956, Jaanusson 1982b). Because of the transgressive nature of this deposit, it exhibits an irregular thickness variation. Dronov & Holmer (1999) included this part of the section in their Latorp depositional sequence.

The Latorp Limestone contains biostratigraphically diagnostic trilobites (Törnquist 1884, Holm 1882, Tjernvik 1956, Tjernvik *in* Tjernvik & Johansson 1980). Phosphatic brachiopods were described by Puura & Holmer (1993), and the conodont fauna by Löfgren (1993, 1994). Biostratigraphically, the unit is within the *Megistaspis armata* to the *Megistaspis estonica* trilobite zones (Tjernvik 1956, Tjernvik *in* Tjernvik & Johansson 1980) and the *Paroistodus proteus* to the *Oepikodus evae* conodont zones (Löfgren 1993, 1994, 1995b, Tolmacheva & Löfgren 2000). The former conodont zone was subdivided by Löfgren (1993) into four subzones, largely based on data from the Sjurberg section.

Tøyen Formation

Previously termed: *Phyllograptus Shale*, Lower *Didymograptus* Shale (see Owen et al. 1990, p. 9, for further details).

Stratotype: Hagastrand, Oslo–Asker district, Oslo area, Norway (see Owen et al. 1990, p. 9).

Discussion: In the Talubäcken section about 2 m of graptolitic shale equivalent to the Tøyen Formation is developed above the 20–40 cm basal beds of conglomerate and limestone with glauconite and porphyry clasts (Törnquist 1877, 1879, 1883, 1891, Holm 1882, Skoglund 1968, Bergström 1988). The basal beds of the section belong to the Latorp Limestone (*Megistaspis planilimbata* trilobite Zone and *Paroistodus proteus* conodont Zone (Jaanusson 1982b, Bergström 1988), and as shown by the presence of the zonal index trilobite *Megalaspides dalecarlicus* (Holm, 1882), the Tøyen Fomation at this outcrop represents the *M. dalecarlicus* trilobite Zone. The Tøyen Formation here yielded also the types of *Pseudophyllograptus densus* and *Didymogaptus minutus*, both described by Törnquist (1879), who later described these and other species from the Talubäcken locality (Törnquist 1891). Conodonts (Bergström 1968, 1988) place the exposed shale unit within the *Prioniodus elegans* to *Oepikodus evae* conodont zones. The topmost Latorp Limestone at Talubäcken has produced the best preserved and most abundant conodont fauna of the *Prioniodus elegans* Zone known anywhere in Baltosandia (Bergström 1988).

Lanna Limestone

Previously termed: Lower Red Orthoceratite Limestone, *Limbata* Limestone.

Type area: Lanna in Närke, Central Sweden (Tjernvik 1956, pp. 133–137).

Main lithology: Red calcarenitic calcilutite (Jaanusson 1952, p. 127). See also Hadding (1958, p. 162).

Definition: Topoformation. The lower beds consist of red limestone, lithologically similar to the underlying beds. A series of discontinuity surfaces are conspicuous just below the lower boundary (Tjernvik 1956, p. 167). The top of the unit is marked by a discontinuity surface at the base of the Holen Limestone (see below).

Discussion: Tjernvik *in* Tjernvik & Johansson (1980, p. 174) proposed the term Lanna–Volkhov stage to be used for the limestone unit earlier known as the *Limbata* Limestone. The term Lanna Limestone was used by Jaanusson (1982a, b), seemingly for the first time in the literature. This interval of the Ordovician succession in the Siljan District is poorly investigated biostratigraphically, while it is considerably better understood in other parts of Sweden (Tjernvik 1956, Tjernvik *in* Tjernvik & Johansson 1980, Löfgren 1994). Dronov & Holmer (1999) included this part of the section in their Volkhov depositional sequence.

The zonal trilobite species was earlier named *Megistaspis limbata* (Boeck) *lata* (Törnquist) as described from the Vikarbyn section (Törnquist 1884, p. 93, Tjernvik 1956, p. 165), but the species was considered a junior synonym of *Megistaspis polyphemus* Brøgger by Nielsen (1995). In addition to large asaphids and nileid trilobites (Tjernvik 1956), there is one species of agnostid known from this formation (Ahlberg 1990). Hessland (1949a) described ostracodes from the Lanna Limestone. The *Incisua ventroincisurata* and *Brezelina palmata* ostracode assemblages from this unit and the following Holen Limestone, place the Siljan District in the outer ramp facies, being slightly deeper than in Estonia (Tinn et al. 2006).

Löfgren (1994) recorded conodonts indicative of the *Baltoniodus triangularis* to *Paroistodus originalis* zones in the Lanna Limestone interval in the Sjurberg section. This zone was later refined through subdivisions and correlated against the trilobite zonation (Löfgren 1995a). The *B. norrlandicus* conodont Zone was identified at two localities in Dalarna by Löfgren (2000). The trilobite *M. polyphemus* [earlier *M. lata*] appears in the same section close to the top of the *Oepikodus evae* conodont Zone (Tjernvik 1956, Löfgren 1994), while *M. simone* first appear in the basal part of Phase 1 of the *P. originalis* conodont Zone (Löfgren 1995a).

Holen Limestone

Previously termed: Upper Red Orthoceratite Limestone (*pars*), Lower Grey Orthoceratite Limestone (*pars*), *Gigas* Limestone (*pars*), *Obtusicauda* Limestone (*pars*), *Raniceps* Limestone (*pars*), *Expansus* Limestone (*pars*), *Asaphus* Limestone (*pars*), Vaginatum Limestone, Täljsten (*pars* – lower part).

Main lithology: Red and grey calcarentic limestone (Jaanusson 1952, 1982b, Tjernvik 1956, Hadding 1958).

Type section: Kårgärde, Orsa Parish, the Siljan District, Sweden (Jaanusson 1982b, pp. 18, 40).

Thickness variation: The unit is 7.1 m thick at the type locality, and its thickness is more than 5 m in an incomplete and faulted section at Röjeråsvägen at Vikarbyn (Jaanusson & Mutvei 1951). On northern Öland the unit is 7.6 m thick (Jaanusson & Mutvei 1982, p. 6).

Definition: Topoformation. The base of the unit is marked by a discontinuity surface lined by limonitic mineralisation (Jaanusson 1982b). Following the discontinuity surface is 1.2 m of grey oolitic limestone containing large chamositic and limonitic ooids (Hessland 1949d, Thorslund *in* Thorslund & Jaanusson 1960, Jaanusson 1982b, Sturesson 1988), which is overlain by a shell bed composed of disarticulated trilobites and broken cephalopod shells. The upper 4.8 m of the unit consist of thick bedded calcilutites that become red toward the top. The upper boundary is biostratigraphically defined (see section on the Segerstad Limestone below).

Discussion: Jaanusson (1982b, p. 18) replaced the term Vaginatum Limestone with the topostratigraphic term Holen Limestone. Apart from the type section at Kårgärde (Jaanusson & Mutvei 1953, Jaanusson 1982b), the Vikarby section (Jaanusson & Mutvei 1953, Jaanusson 1982b), and old outcrops at the Fjäcka section (Törnquist 1883, Jaanusson 1947, Jaanusson & Martna 1948, Jaanusson & Mutvei 1953) few exposures of the unit are known in the Siljan District. Warburg (1910) mentioned several occurrences of Orthoceratite limestone at Nittsjö and surrounding areas, but separation of the various, basically biostratigraphical, units (e.g. *Asaphus*, *Gigas* and *Platyurus* limestones: Warburg 1910, pp. 429–431) is possible only by fossils. Sturesson (1988, 2003) described and discussed the up to 2.5 m thick sequence of oolites occurring in this level in the Siljan District, suggesting derivation from volcanic activity. Dronov & Holmer (1999) included the Holen Limestone in their Kunda depositional sequence.

Fauna and age: Asaphid trilobites (Angelin 1854, Törnquist 1884, Jaanusson & Mutvei 1951, Jaanusson 1953a, b, 1954, 1957a, Bohlin 1960) as well as other trilobites (Dalman 1827, Holm 1883, Warburg 1939, Bruton 1967) and nautiloids (Angelin & Lindström 1880, Törnquist 1883, Holm 1896, 1897, Jaanusson & Mutvei 1951, Kröger 2004) dominate the macrofauna. Gastropods were described by Wahlenberg (1818), Koken (1897) and Koken & Perner (1925). Hessland (1949a, b, c, e) described ostracodes, algae, a conularid, and brachiopods from the Holen Limestone, and Regnéll (1945) described echinoderms. Holm (1893) described several species of hyolithids from the Holen Limestone. Holmer (1989) described phosphatic brachiopods from the Holen Limestone at Kårgärde, noting up to 92% dominance of the species *Numericoma*? *spinosa* (Biernat). From the same locality Holmer & Popov (1994) described the acrotretacean *Acrotreta nobilis*. The characteristic mottled fabric of the Holen Limestone seems to come from the presence of *Thalassinoides* trace fossils (see Ekdale & Bromley 2003 for discussion on these traces on Öland). In Jämtland these traces were interpreted as originating from habitually burrowing asaphid trilobites (Cherns et al. 2006).

The *Leonodus variabili–Yangtzeplacognathus crassus* conodont zones at the base of the Holen Limestone were studied by Löfgren (2003). The upper part of the Holen Limestone was defined by Jaanusson (1982b) by the presence of *Megistaspis (Megistaspidella) gigas*.

Segerstad Limestone

Including the Vikarby and Kårgärde limestones

Previously termed: Upper Red Orthoceratite Limestone (*pars*), *Platyurus* Limestone, Transition beds (*pars*), *Lituites* Limestone (*pars*).

Main lithology: Deep reddish brown calcarenites and calcareous calcilutites (Jaanusson 1952, 1960a, 1972, 1982b, Jaanusson & Mutvei 1953, Hadding 1958).

Type area: Parish of Segerstad on Öland, southern Sweden (Jaanusson 1960a, p. 214).

Thickness variation: The maximum thickness of the Segerstad Limestone on Öland is 5.13 m (Böda Hamn boring, see Jaanusson 1960a, p. 271), and the largest known thickness of the unit in Sweden is 6.22 m, recorded in the Ekön boring in Östergötland (Jaanusson 1962, p. 25). The maximum thickness in the Siljan District is 3.7 m (Vikarby section, Jaanusson & Mutvei 1953), followed by a thickness of 3.1 m in the Kårgärde section (Jaanusson & Mutvei 1953, Jaanusson 1982b). In the Fjäcka section, thickness of about 2.5 m was measured by Jaanusson and Mutvei (1953), who noted tectonical distortion of the beds. In Jämtland the Segerstad Limestone is 3.52–6.12 m thick (Larsson 1973).

Definition (in the Siljan District): Topoformation. The lower beds are indistinguishable lithologically from the underlying Holen Limestone (see also Jaanusson 1960a, p. 219), and these units are separated based on the presence of *Megistaspis (Megistaspidella) gigas* in the lower unit and *Asaphus (Neoasaphus) platyurus* in the upper unit. The boundary between the two subdivisions of the Segerstad Limestone (see below) is marked in the Vikarbyn section also by a horizon of "mud cracks" which is overlain by a thin conglomeratic bed. This is not present in the Kårgärde section; the transition is as well marked by a change from a nautiloid dominated (*Lituites* (= *Angelinoceras*) *latus* Angelin) fauna to trilobite dominated (*Illaenus* aff. *sulcifrons* Holm) fauna (Jaanusson & Mutvei 1953, p. 28, Jaanusson 1982b, 1972, p. 222). The upper boundary of the Segerstad Limestone is well marked lithologically by the change to the nodular limestones of the Skärlöv Limestone. In a detailed analysis of the carbonate matrix of the Segerstad Limestone, Jaanusson (1972) found that the skeletal grains were poorly sorted, and consisted largely of echinoderm remains

Discussion: In the Siljan District the Kårgärde and Vikarbyn limestones have been recognized, in ascending order, as subdivisions of the Segerstad Limestone (Jaanusson & Mutvei 1953, subsequently formally named by Jaanusson 1963b, p. 2). The type section for the thick-bedded to finely nodular Kårgärde Limestone is at the Kårgärde section, where the unit is 2.4 m thick. A stromatolitic-like bed occurs at the base of this unit, and this bed is 6 cm thick at the Holen–Segerstad boundary in the Vikarbyn section (Jaanusson 1982b, pp. 20, 41, Holmer 1989); these features may be diagenetic (see discussion in Holmer 1989, p. 13). Similar structures have been found in the Holen Limestone in Jämtland (Larsson 1973).

The type section of the 70 cm thick (70 cm *in* Jaanusson & Mutvei, 1953; 50 cm *in* Holmer 1989) mottled red and grey calcarenites of the Vikarby Limestone is at the Vikarbyn section (Jaanusson and Mutvei 1953, Jaanusson 1963b). Stromatolitic-like structures occur also at this locality (Holmer 1989).

Fauna and age: Jaanusson (1947, 1984) and Jaanusson & Mutvei (1953) presented lists of the macrofossils of the Segerstad Limestone in the Siljan District. Large trilobites, for instance, *Asaphus* (*Neoasaphus*) *platyurus* Angelin, and species of nautiloids dominate the fauna of the unit (Angelin 1854, Angelin & Lindström 1880, Törnquist 1884, Holm 1891, Jaanusson 1947, 1953b, 1957a, 1976, Jaanusson & Mutvei 1953, Kröger 2004), while other macro remains are rare. Ostracodes (Jaanusson 1957b) and especially phosphatic brachiopods (Holmer 1989) abound among the microfauna.

Biostratigraphically the Segerstad Limestone is within the *Eoplacognathus suecicus* conodont Zone (Löfgren 2004), which extends into the lower and middle part of the overlying Skärlöv Formation (Bergström 1971, 2007b).

Skärlöv Formation

Previously termed: *Chiron* Limestone, *Centaurus* Limestone, *Schroeteri* Limestone (lower part), Upper Red Orthoceratite Limestone (*pars*).

Type area: The district east of Skärlöv railway station on southern Öland, southern Sweden (Jaanusson 1960a, p. 214).

Thickness variation: The unit is 1.4 m thick in the Gammalsby boring on southern Öland, otherwise the thickness is poorly constrained on that island (Jaanusson 1960a). The largest thickness (6.29 m) has been recorded in the Ekön boring in Östergötland (Jaanusson 1962, p. 26). In the Siljan District the unit is 3.3 m thick (Jaanusson 1963b, Jaanusson 1982b, Holmer 1989). In Jämtland the unit is 1.10–2.97 m thick (Larsson 1973).

Definition (in the Siljan District): Lithostratigraphic unit consisting of reddish brown, finely nodular limestone with argillaceous intercalations (Jaanusson 1982b, Hadding 1958, Holmer 1989). The unit is bounded by massive, bedded limestone.

Discussion: The unit weathers easily and is poorly exposed both in the Kårgärde and Fjäcka sections, while it seems to be absent in the Vikarby section (Jaanusson 1963b, Jaanusson 1982b, Holmer 1989). Except trilobites (Jaanusson 1953a) few macrofossils are known (Jaanusson 1982b, p. 21), but a rich microfauna of phosphatic brachiopods (Holmer 1989) and conodonts (Bergström 1971, 2007b) are recorded.

The lower and middle part of the Skärlöv Limestone is included in the *Eoplacognathus suecicus* conodont Zone, while the upper part is within the *Pygodus serra* conodont Zone (Bergström 1971, 2007b). The Kårgärde section is the reference section for both these conodont zones (Bergström 1971, p. 91).

Seby Limestone

Previously termed: *Centaurus* Limestone, *Schroeteri* Limestone (middle part), Upper Red Orthoceratite Limestone (top), transition beds (*pars*).

Main lithology: Thick bedded limestone and mottled red and grey nodular calcarenites (Jaanusson 1952, 1963b, 1982b, Hadding 1958, Holmer 1989).

Type area: Within and east of Seby village on southern Öland, southern Sweden (Jaanusson 1960a, p. 215).

Thickness variation: The unit is 1.08 m thick in the Gammelsby boring on Öland (Jaanusson 1960a), while it is 1.6 m thick in the Kårgärde section in the Siljan District (1.7 m in Jaanusson 1963b; 1.55 m in Jaanusson 1982b; 1.6 m in Holmer 1989). In the Vikarbyn section its measured thickness is only 0.4 m. The reduced thickness at this locality has been attributed to a stratigraphic hiatus (Jaanusson 1963b, p. 33). In Jämtland the unit is 0.69–2.22 m thick (Larsson 1973).

Definition (in the Siljan District): Lithostratigraphic unit. Massive bedded calcarenitic limestone is developed in the lower part, changing into finely nodular red and grey calcilutites toward the top (Jaanusson 1952, 1963b, 1982b, Holmer 1989).

Discussion: The Seby Limestone is a thin but distinctive unit in Scandinavia, where it occurs from Jämtland in the north to Gotland in the south (Jaanusson 1982b, Nõlvak & Grahn 1993). In the Vikarby section, the absence of the Skärlöv Limestone makes the boundary to the underlying Vikarby Limestone recognizable only by faunal evidence (Jaanusson 1963b). Holmer (1989, p. 11) reported three levels with hematitic-rich, laminated stromatolite-like domes in the Seby Limestone in the Kårgärde section.

Jaanusson (1963b, 1984) presented faunal lists from the Seby Limestone at Vikarbyn and Kårgärde. In both these works a single hyolithid species was recorded in the Seby Limestone. Phosphatic brachiopods from the Seby Limestone were described by Holmer (1989), while Sutton et al. (2001) described problematic phosphatic sclerites from the Seby Limestone at the Kårgärde section. Species of nautiloid cephalopods were reported by (Holm 1891, 1896, Troedsson 1931, 1932a, Kröger 2004).

Biostratigraphically the Seby Limestone falls within the *Pygodus serra* conodont Zone and the *Eoplacognathus foliaceus* Subzone (Bergström 1971, 2007b), and the *Cyathochitina sebyensis* chitinozoan Subzone of the *Laufeldochitina striata* chitinozoan Zone (Nõlvak & Grahn 1993).

Folkeslunda Limestone

Previously termed: Upper Grey Orthoceratite Limestone, *Chiron* Limestone, *Centaurus* Limestone, *Schroeteri* Limestone (lower part).

Main lithology: Thick and thin-bedded calcarenites (Jaanusson 1952, 1963b, 1982b, Holmer 1989)

Type area: South-eastern part of the parish of Långlöt and the north-eastern part of the parish of Runsten on Öland (Jaanusson 1960a, p. 215). The best section of the unit on Öland is in a quarry close to the road from Vedby to Bäcklunda, E of Hornsjön (Jaanusson 1960a, p. 226).

Thickness variation: The unit is 2 m thick in the Vikarby section and 2.4 m thick in the Kårgärde section (Thorslund & Jaanusson 1960, Jaanusson 1963b, 1982b). Holmer (1989) recorded 2.6 m in the Kårgärde section. In Jämtland the unit is 0.99–3.51 m thick (Larsson 1973).

Definition: Lithostratigraphic unit. The lower boundary is at the base of a 15 cm thick grey calcarentic limestone bed, which is overlain by thin-bedded calcarenitic and calcilutitc limestones. The upper half of the formation consists of thick-bedded calcarentic limestones (Jaanusson 1963b, 1982b, Holmer 1989, p. 11). The upper boundary is placed "where the lithological change is most obvious" (Jaanusson 1960a, p. 215).

Discussion: The Folkeslunda Limestone is the uppermost unit in the traditional Orthoceras Limestone of Sweden (Jaanusson 1982b). With respect to both fauna and lithology, the unit in the Siljan District resembles its development on Öland (Jaanusson 1963b, p. 34). The fauna shares many common species with the Seby Limestone, but is also distinct with respect to the cephalopods and hyolithids (Jaanusson 1982b, p. 21). Jaanusson (1963b, 1984) presented faunal lists from the Folkeslunda Limestone at Vikarbyn and Kårgärde, showing the distribution of the macro fauna in the latter work. Holmer (1989) also found faunal differences in the phosphatic brachiopod fauna, although the dominant species is the same as in the Seby Limestone. A species of hyolithid is also found in the Folkeslunda Limestone, albeit different from the species found in the Seby Limestone (Holm 1893, Jaanusson 1963b, p. 35). Trilobites from the Folkeslunda Limestone were described by Holm (1883) and Törnquist (1884), while Janusson (1957b) described ostracodes. Species of nautiloid cephalopods were reported by (Holm 1896), Troedsson (1931, 1932a), and Kröger (2004).

Biostratigraphically the Folkeslunda Limestone span the *Pygodus serra* conodont Zone and the *Eoplacoghnathus reclinatus* Subzone (Bergström 1971, 2007b).

Furudal Limestone

Previously termed: 'Flagkalk', *Ancistroceras* Limestone, Crassicauda Limestone

Main lithology: Uniform grey calcilutites with argillaceous intercalations (Jaanusson 1952, 1960a, 1982b, Hadding 1958, Holmer 1989).

Stratotype: A quarry close to Kalkbergsbäcken at Furudal, Rättvik Municipality, the Siljan District, Sweden (Jaanusson 1960a, p. 215).

Thickness variation: The Furudal Limestone is 9.2 m thick in the Kårgärde section (8.5 m according to Holmer 1989), more than 5 m thick in the Fjäcka section, and more than 7.55 m thick in the Vikarby section (Jaanusson 1963b, 1982b, L. Karis *in* Jaanusson 1982b, Holmer 1989).

Definition: At the Kårgärde section "The lower boundary is fairly distinct lithologically" (Jaanusson 1963b, p. 12). The upper boundary is transitional to the Dalby Limestone (Jaanusson 1947, 1963b, 1982b, Holmer 1989).

Discussion: Compared with subjacent units, the Furudal Limestone represents a period of more stable depositional conditions in deeper water settings (Jaanusson 1982b, p. 21). Although Jaanusson (1982b) stated that the Furudal Limestone was sparsely fossiliferous, a number of fossil groups have been recorded from the unit (note that some of the older reports may refer to fossils found in the lowermost Dalby Limestone). Some early descriptions of trilobites (Wahlenberg 1818, Dalman 1827, Angelin 1852, 1854, Törnquist 1884, Holm 1880, 1883) were based on specimens from this unit, some of which were revised by Jaanusson (1953a, b) and Jaanusson & Ramsköld (1993). Species of ostracodes were described by Jaanusson (1957b), and detailed faunal logs of ostracodes, trilobites, and brachiopods were presented by Jaanusson (1947, 1963a, 1976). Several graptolite species were described and discussed from localities with the Dalby Limestone the Siljan District (Törnquist 1911, Jaanusson & Strachan 1954). Notably, Nõlvak & Goldman (2007) identified *Nemagraptus subtilis* (restricted to the lower Uhaku Stage) in samples from the Vikarby section. Two paragastropod genera were described by Wängberg-Eriksson (1979) from the Kårgärde and Fjäcka sections.

The boundary between the *Pygodus serra* and *P. anserinus* conodont zones occurs about 5 m below the top of the Furudal Limestone (Bergström 1971, 2007b). The Fjäcka section is the reference section for the latter conodont zone (Bergström 1971, p. 97).

Dalby Limestone

Previously termed: Cystid Limestone, Cystidean Limestone, *Echinosphaerites* Limestone *Ludibundus* Limestone, Lower *Chasmops* Limestone, Older *Chasmops* Limestone.

Main lithology: Greenish grey calcarenites (Jaanusson 1952, 1960a, 1963b, 1982b, Hadding 1958).

Stratotype: Fjäcka section at Moldå, Rättvik municipality, the Siljan District, Sweden (Jaanusson 1960a, p. 216).

Thickness variation: The unit is 19.8 m thick in the Kårgärde section and 19.9 m thick in the Fjäcka section (Jaanusson & Martna 1948, Jaanusson 1963b, 1976, 1982b, Holmer 1989). Especially in the Fjäcka section there are several small structural displacements of the beds (Jaanusson & Martna 1948, Nõlvak et al. 1999). In Jämtland the Dalby Limestone is 88 m thick in the crater deposits of the Lockne crater (Lindström et al. 2005a).

Definition: The base of the formation is lithologically transitional to the underlying Furudal Limestone (Jaanusson & Martna 1948, Hadding 1958). Presently it is defined topostratigraphically by the first occurrence of the Dalby Limestone fauna (Jaanusson 1982b, p. 22). Holmer (1989) placed the boundary at the Kårgärde profile about 1 m below that of L. Karis (in Jaanusson 1982b). The lower 6.6 m (Lower Member, Jaanusson 1982b) consists of greenish grey thick-bedded limestone that is calcilutitic in the lower part and calcarenitic in the upper part. The overlying 13.3 m (Upper Member, Jaanusson 1982b) is more nodular or thin bedded calcarenites and calcarenitic calcilutites. A thin K-bentonite bed is present close to the lower boundary of the Lower Member (Holmer 1989). The upper boundary of the Dalby Limestone is at the top of the thickest K-bentonite bed, the last in a complex of 7 K-bentonite beds (Jaanusson 1960a 1982b, Holmer 1989). This is the Kinnekulle K-bentonite (term introduced by Bergström et al. 1995, p. 4).

Discussion: Jaanusson (1951) introduced the term *Ludibundus* Limestone to replace the older term Cystoid Limestone. The presently used term Dalby Limestone was proposed by Jaanusson (1960a). The Dalby

Limestone is well exposed at its type section at Fjäcka and in the Kårgärde section. In the latter outcrop, a complex of 4 K-bentonite beds is found at the upper boundary of the unit (L. Karis *in* Jaanusson 1982b). Limited outcrops of the Dalby Limestone are found at Orsbleck (Jaanusson 1953a, p. 404, pers. observation Ebbestad). A complete section at Nittsjö was described by Warburg (1910), but it needs to be excavated for detailed study. Several older fossil collections from the Dalby Limestone in the Siljan District came from the now overgrown quarry at Kalkbergsbäcken, 1.3 km W of Furudal Bruk (Jaanusson 1963b, p. 19). Dronov & Holmer (1999) placed the top of their Tallinn depositional sequence approximately at the upper part of the Lower Member.

Fauna and age: The Dalby Limestone is rich in both micro and macrofossil remains. Trilobites are common (Hisinger 1840, Angelin 1852, Törnquist 1884, Holm 1883, Warburg 1939, Jaanusson 1953a, Ahlberg 1990), but the 'crystal apples' of cystoid echinoderms distinguish the unit (Regnéll 1945, 1948). Brachiopods (Hints 1973, Jaanusson 1962, Holmer 1989) and ostracodes (Jaanusson 1957b, Ainsaar et al. 2004) are also commonly present. Holm (1893) described a single hyolithid species from the Dalby Limestone. Jaanusson & Martna (1948) and Jaanusson (1976) showed the biostratigraphic distribution of various ostracodes, trilobites and brachiopods. A number of gastropods, tergomyans and paragastropods are as well found in the Dalby Limestone (Hisinger 1831, Wängberg-Eriksson 1979, Frisk & Ebbestad 2007).

Biostratigraphically the Dalby Limestone falls within some very short-range chitinozoan zones, namely the middle to upper *Laufeldochitina stentor* Zone, the *Armoricochitina granulifera*, *Lagenochitina*? *dalbyensis*, *Belonechitina hirsuta*, and *Spinachitina cervicornis* chitinozoan zones (Laufeld 1967, Nõlvak & Grahn 1993, Nõlvak et al. 1999). This allows the establishment of the boundary between the Kukruse Stage and Idavere Substage of the Haljala Stage at a level of about 2 m above the lower K-bentonite layer (Nõlvak et al. 1999). The Dalby Limestone also encompasses the *Amorphognathus tvaerenensis* conodont Zone with three subzones (Bergström 1971, 2007b). The Fjäcka section is the reference section for these conodont zones and subzones (Bergström 1971, p. 98).

Freberga Formation

With Skagen and Moldå topoformations

Previously termed: Bryozoan Limestone, *Macrourus* Limestone, Upper *Chasmops* Limestone.

Type section: Freberga Formation; interval 87.80–73.85 in the Smedsby gård boring in Östergötland, central Sweden (Jaanusson 1982b, p. 22). Skagen Limestone: the Mossen section situated south of the Norra Skagen farm on Kinnekulle, Västergötland (Jaanusson 1964, p. 11). Moldå Limestone (first used by Jaanusson 1973, fig. 3, p. 20 but without designation): the main Fjäcka section, at Moldå, the Siljan District, Sweden, 0 to 5.75 m below the base of the Slandrom Limestone (Jaanusson 1976, p. 310).

Thickness variation: In the Fjäcka section the Skagen limestone is 5.6 m thick, and the Moldå limestone is 5.8 m thick (Jaanusson 1976, 1982b). In Västergötland the Skagen Limestone is 3–4 m thick (Jaanusson 1964). Both in Västergötland, and Östergötland, and in the subsurface of Gotland and Gotska Sandön, there are stratigraphic breaks at the top of the Skagen Limestone, or the unit may even be missing (Jaanusson 1982a, 1982c, Nõlvak & Grahn 1993, Ainsaar & Meidla 2001). The Moldå Limestone is 5.8 m thick in the Fjäcka section (Jaanusson 1976, 1982b).

Definition: In the Siljan District both the Skagen and Moldå limestones are topoformations. Lithologically the Skagen Limestone in the Siljan District is similar to that of the Dalby Limestone (Hadding 1958, p. 189), while in Västergötland the Skagen Limestone is recognized as a lithostratigraphic unit (Jaanusson 1982c, p. 169). The base of the Skagen Limestone in the Siljan District is the top of the Kinnekulle K-bentonite (Jaanusson 1964). The boundary between the topoformations is marked by a change in palaeocope ostracode fauna (Jaanusson 1976, 1982b). Both units have a dominantly calcarenitic calcilutitic composition (Martna 1955).

Discussion: The term Freberga Formation was introduced by Jaanusson (1982b), but subsequently, the Moldå and Skagen topoformations have had a wider usage. Jaanusson (1982b, 1976) recognized faunal shifts in this interval, which, based on a broader study, Ainsaar et al. (2004) named the Middle Caradoc facies and faunal turnover. This turnover reflects a succession of environmental changes of possible global range. Dronov & Holmer (1999) placed the top of their Kegel depositional sequence at this level. A coinciding, strongly positive $\delta^{13}C$ excursion is recorded in the Skagen and Moldå limestones at the Fjäcka section, and it matches well with the isotopic excursion in coeval Estonian sections (Ainsaar et al. 1999, 2000, 2004) and North America (Bergström et al. 2001a, b, Saltzman et al. 2003); this major global δ^{13} C excursion is referred to as the Guttenberg Isotopic Carbon Excursion (GICE).

Fauna and age: Detailed analysis of the faunal distributions (of mainly ostracodes) in the Fjäcka section in the Siljan District allowed Jaanusson (1976, text-fig. 9, pp. 313–314) to distinguish two successive faunal changes at the base of Skagen and Moldå limestones, respectively. Ainsaar et al. (2004) also recognized the faunal turnover in ostracodes. Trilobites from the Skagen Limestone have been described by several authors (Hisinger 1840, Törnquist 1884, Jaanusson 1953a, Owen 1983, Ahlberg 1990, Jaanusson & Ramsköld 1993), while the conodont fauna was studied by Bergström (1971, 2007b) and Leslie (2000). A number of echinoderms were recorded by (Regnéll 1945).

The base of the Skagen Limestone is marked by the Kinnekulle K-bentonite (at the top of *Baltoniodus alobatus* conodont Subzone; Bergström et al. 1995), while establishment of a conodont zonation within the unit is difficult at present (Leslie 2000, Bergström 2007b), as is also the case with chitinozoans (Laufeld 1967). The base of the *Amorphognathus superbus* conodont Zone occurs in the middle to upper Moldå Limestone (Bergström 2007b).

Slandrom Limestone

Previously termed: Masur Limestone, Upper *Chasmops* Limestone (*pars*), *Macrourus* Limestone (*pars*), 'Knyckelkalk'.

Main lithology: Dense (lithographical, aphanitic), nodular calcilutites (Jaanusson & Martna 1948, Jaanusson 1953c, 1982b, Martna 1955, Hadding 1958).

Type section: The Slandrom Brook at Brunfloviken in Jämtland, central Sweden (Thorslund 1943, footnote on p. 6).

Thickness variation: In the Fjäcka section the Slandrom Limestone is 8.4 m thick (Jaanuson & Martna 1948, Janusson 1953c, 1982b). The unit is about 7 m thick in Jämtland (Thorslund 1940).

Discussion: The Slandrom Limestone is a hard, pure calcilutite with intercalations of calcarenitic calcilutites, where the dense calcilutite occupies about 30% (Jaanusson 1953c, 1982b). Jaanusson & Martna (1948, footnote p. 185) proposed to use the name Slandrom Limestone in the Siljan District for beds previously called Masur Limestone (or 'Knyckelkalk', Warburg 1910, p. 431, Thorslund 1936b, p. 9), recognizing the lithologic similarity to the Slandrom Limestone in Jämtland (Thorslund 1943). Beds of similar age in Västergötland were compared to the Slandrom Limestone in the Siljan District and Jämtland by Skoglund (1963, p. 28), who found it necessary to distinguish the unit in Västergötland as the Bestorp Limestone. Currently, apart from the Fjäcka section, the Slandrom Limestone is exposed at several localities in the Siljan District such as Skålberget and Amtjärn.

The strong positive $\delta^{13}C$ excursion recorded in the Skagen and Moldå limestones decreases gradually through the Moldå and Slandrom limestones (Ainsaar et al. 2004).

Macrofossils are still poorly known in the Slandrom Limestone. Jaanusson (1953c, 1976) showed the distribution of ostracodes, trilobites and brachiopods through the Slandrom Limestone, and trilobites were discussed or described by Jaanusson & Martna (1948), Jaanusson (1953c), and Ahlberg (1990).

Biostratigraphically, most of the Slandrom Limestone falls within the *A. superbus* conodont Zone (Bergström 1971, 2007). The Fjäcka section is the reference section for the latter conodont zone (Bergström 1971, p. 102).

Kullsberg Limestone

With the Skålberg Limestone

Previously termed: *Leptaena* Limestone (*pars*), Lower *Leptaena* Limestone, *Platylichas* Limestone.

Type section: Kullsberg Limestone: the Kullsberg quarry in the Siljan District, Dalarna, Sweden (Thorslund & Jaanusson 1960, p. 32). Skålberg Limestone: Skålberget quarry in the Siljan District, Dalarna, Sweden (Jaanusson 1982b, p. 29).

Thickness variation: The completely excavated Kullsberg mound at the Amtjärn quarry attained a length of about 260 m and a thickness of 34–35 m (Thorslund 1935, 1936b, p. 28). Jaanusson (1982b, p. 27) reported diameters of 300–350 m and thicknesses of about 40–50 m for the Kullsberg Limestone mounds in other localities.

Definition: Lithostratigraphic unit. The Kullsberg Limestone represents mud mounds of pure micritc limestone that are massive (boundstone/packstone) in the centre and have stratified pelmicritic grainstones at the flanks (Tobin et al. 2005). Development of stromatactis is a characteristic of the mounds (Bathurst 1982, Riding 2002), and typically the flank facies consists of pelmatozoan limestone (Hadding 1941, 1958). Kullsberg Limestone mounds are classified as high relief carbonate mud mounds (Riding 2002). The lower boundary is just above the base of the Skagen Limestone (Jaanusson 1982b, p. 27). The Kullsberg Limestone is disconformably overlain by the Skålberg Limestone on the flanks of the mounds and by the Moldå Limestone, Slandrom Limestone, and Fjäcka Shale successively towards the top of the mounds (Jaanusson 1982b).

Discussion: The term Kullsberg Limestone was introduced in a table by Troedsson (1928, p. 179) and subsequently came into common usage (Thorslund 1930, 1935, 1936b, Troedsson 1932b, 1936, Isberg 1934), but not without arguments (Thorslund 1932a, p. 147, 1932b, Troedsson 1932b). Initially the stratigraphical position of the *Leptaena* Limestone was highly controversial (see the historical section), but through the investigations of Isberg (1917) and in particular, Warburg (1925), its stratigraphic position became established. Furthermore, Warburg (1925, p. 412) found that two stratigraphically separate mound generations could be distinguished (now the Kullsberg and Boda limestones, respectively).

Jaanusson (1982b, p. 26) reported 11 Kullsberg Limestone mounds. The same number was recorded by Kresten et al. (1991, see Fig. 1), but they mapped the Vitlingsberg mound as Kullsberg Limestone, whereas Thorslund (1936b, his locality 10) and Jaanusson (1982b) recorded this mound as representing the Boda Limestone (the locality is plotted in the map of Jaanusson 1982b, p. 16 but is not indicated by Kresten et al. (1991). Warburg (1910) recorded an occurrence of the *Leptaena* Limestone southeast of the railroad at the Rättvik isthmus, but this occurrence has later not been confirmed or dated. Occurrences of Kullsberg Limestone mounds have also been reported in the submarine South Bothnian district and subsurface in Östergötland (Jaanusson 1979a, Söderberg & Hagenfeldt 1995).

In the Amtjärn quarry, the beds immediately below the mound limestone are composed of beds with thick (>1–2 cm), sometimes partly articulated, crinoid stems. These beds were formed *in situ* from colonies of crinoids (Ruhrmann 1971). Smaller sized crinoids probably lived on the flanks of the growing mud mound, and the pelmatozoan limestones forming the flank facies was formed through enrichment caused by current activity and re-sedimentation (Ruhrmann 1971). The larger crinoid type is absent in the flank facies, but in places with less turbulence, colonies of cystoids lived (Ruhrmann 1971).

The Kullsberg Limestone falls within a regional lowstand (Nielsen 2004), and sedimentological evidence suggests shallow (< 50 m) deposition above storm wave base within the photic zone (Tobin et al. 2005, p. 189). As is the case in the Skagen and Moldå limestones, the major Early Katian global $\delta^{13}C$ excursion (GICE) is present in the Kullsberg Limestone (Skålberget quarry, Tobin et al. 2005). The diagenetic alteration of the marine calcite cement in the Kullsberg Limestone is slight, and this allows data from these to be used as proxies for seawater temperature (Tobin & Walker 1996, 1997, Tobin & Bergström 2002). The upper part of the Kullsberg Limestone shows a larger positive excursion in both $\delta^{13}C$ and $\delta^{18}O$ than the lower part of the unit at Skålberget (Marshall & Middleton 1990) suggesting a decrease in seawater temperature of up to 15ºC (Tobin et al. 2005).

Jaanusson (1973, p. 20) introduced the term Skålberg Limestone for the first sediments that rest on the Kullseberg Limestone mounds. The Skålberg Limestone is a wedge of the Moldå Limestone, and appears similar apart from slightly larger grain size (Jaanusson 1982b, p. 26).

Fauna and age: Although the Kullsberg and Boda mud mounds share many characteristics, the fauna of the Kullsberg Limestone has not been studied in the same detail. Trilobites are common (Angelin 1854, Holm 1883, Törnquist 1884, Warburg 1925, 1939, Thorslund 1930, Nikolaisen 1982, Owens 1973, Owens 2004), usually forming the main component in the cavities. On the flank facies echinoderm taxa are abundant and diverse (Regnéll 1945, 1948, Ruhrmann 1971, Bockelie 1976, 1979, 1981, Bockelie & Paul 1983). A number of bivalves (Isberg 1934) and gastropods (Koken 1897, Koken & Perner 1925, Ebbestad 1998) are known from the Kullsberg Limestone. Brachiopods have been listed by Jaanusson (1982b) and described by Holmer (1987) and Cocks (2005). Klaaman (1975) identified one of the oldest occurrences of the tabulate coral *Eofletcheria* in the Kullsberg Limestone.

Biostratigraphically, the base of the Kullsberg Limestone is just above the base of the *Baltoniodus alobatus* conodont Subzone (Bergström 1971, 2007b), while its youngest parts are within the *Amorphognathus superbus* conodont Zone. Biostratigraphically the Skålberg Limestone is also within the *Amorphognathus superbus* conodont Zone (Bergström 2007b).

Fjäcka Shale

Previously termed: Black Shale, Black *Trinucleus* Shale, Black *Tretaspis* Shale.

Main lithology: Brownish to black bituminous shale (Schrayer 1978, Vlierboom et al. 1986).

Stratotype: Fjäcka section at Moldå, Rättvik municipality, the Siljan District, Sweden (Jaanusson 1963a, p. 117).

Thickness variation: The unit is 5.8 m thick at the Fjäcka section (Jaanusson & Martna 1948) and 6.1 m at Amtjärn (Ebbestad & Högström pers. obs. 2003, 2007b; measured to be 5 m thick in Isberg 1917, p. 203 and 6 m in Warburg 1910, p. 447), whereas it is only 0.25 m thick at Skålberget (Jaanusson 1982b). At the Kyrkbäcken rivulet, Röstånga in Scania, Pålsson (1996) gave a thickness of 2.2 m.

Definition: Lithostratigraphic unit. Bedded and laminated shale bounded on both sides by calcareous limestone units.

Discussion: The Fjäcka Shale is the source rock for the oil found in spaces in the Kullsberg and Boda limestones (Schrayer 1978, Vlierboom et al. 1986). The sample analysed by Schrayer (1978) showed that the Fjäcka Shale had generated petroleum and also that it is highly enriched in organic carbon. Although the bottom conditions probably were anoxic during deposition of the Fjäcka facies (Vlierboom et al. 1986), periods of more ventilated or dysaerobic conditions allowed for an epi-benthic fauna (Ebbestad & Högström 1999). Spjeldnæs (2000) found that bryozoans preserved in the Fjäcka Shale either had an epiplanctonic or benthic lifestyle.

The Fjäcka Shale in Sweden and Central Estonia and the corresponding Venstøp Formation in the Oslo Region represent a major transgressive sequence (Owen et al. 1990, Dronov & Holmer 1999); the latter authors included this part of the section in their Fjäcka depositional sequence.

Fauna and age: The shale is richly fossiliferous (especially shelly fossils), with rare bedding plane preservation of conodonts and scolecodonts (Ebbestad & Högström pers. obs. 1998 and onwards). The more common fossils are trilobites (Hisinger 1840, Angelin 1854, Holm 1883, Törnquist 1884, Hadding 1913, Bruton 1967, Owens 1973, Owen 1980) and phosphatic and articulate brachiopods (Lindström *in* Angelin & Lindström 1880, Jaanusson 1982b, Ebbestad & Högström 2000). One of the more characteristic fossils of the Fjäcka Shale is the sclerite-bearing machaeridians (Moberg 1914, Ebbestad & Högström 1999, Högström 2000, Högström *in* Hints et al. 2004). Graptolites were described by Törnquist (1891) and Skoglund (1963). A single species of a hyolithid was described by Holm (1893). Spjeldnæs (2000) discussed the ecology of bryozoans found in the normal facies of the Fjäcka Shale and in the transitional beds between the Kullsberg and Boda mud mounds. An enigmatic medusoid-like fossil was discussed by Högström & Ebbestad (2004).

The Fjäcka Shale corresponds to the early *Amorphognathus ordovicicus* conodont Zone, middle to upper Pleurograptus linearis graptolite Zone (Skoglund 1963, Jaanusson 1963b, 1982a).

Jonstorp Formation

With the Öglunda Limestone and the Nittsjö Bed

Previously termed: Grey Limestone (*pars*), Red Shales (*pars*), Red *Trinucleus* Shale (*pars*), *Tretaspis* Limestone (*pars*), *Tretaspis* Shale (*pars*), *Staurocephalus* Shale (*pars*), Middle *Tretaspis* Limestone (*pars*).

Main lithology: Grey and red argillaceous calcilutites (Jaanusson 1982b, p. 24).

Type sections: The Jonstorp Formation: the Jonstorp section on the western slope of Mössberg in Västergötland (Jaanusson 1963a, p. 125). The Öglunda Limestone: the ravine at the Öglunda Cave on the western slope of Billingen in Västergötland (Jaanusson 1963a, pp. 117, 127).The Nittsjö Beds: the Nittsjö section at Nittsjö in the Siljan District (Jaanusson 1963a, p. 124).

Thickness variation: The Jonstorp Formation is more than 6.5 m thick in the Fjäcka section, and 15.5 m thick in the Amtjärn section (Jonstorp Formation + Nittsjö Bed) where the lower member is 5.15 m thick (Thorslund 1935, Jaanusson 1963a, 1982b). In a temporary excavation at Gulleråsen–Sanden, the thickness of the Lower Member was measured to 3.6 m (Jaanusson 1963a, p. 131). In Västergötland and Östergötland the thickness varies between 11 and 20 m (Jaanusson 1963a). The Öglunda Limestone is between 0.8 and 1 m thick in the Siljan District (e.g. at the Kullsberg quarry and the Fjäcka section, Jaanusson 1982b). The Nittsjö Bed is 3 m thick in the Fjäcka section and 2.15 m thick in the Amtjärn section (Jaanusson 1963a, 1982b).

Definition: Lithostratigraphic unit. The lower boundary is marked by the sharp transition from the dark shale of the Fjäcka Formation. The upper part (Upper Jonstorp Member of Jaanusson 1963a, p. 126) is distinctly red coloured followed by the grey coloured Nittsjö Bed. At many localities, the Öglunda Limestone is a distinct, dense and finely nodular limestone bed that separates the grey to green limestone beds of the Lower Jonstorp Member from the upper red coloured Upper Jonstorp Member (Jaanussson 1963a, 1982b).

Discussion: Both the Öglunda Limestone and the Nittsjö Beds were in the Siljan District included as subunits in the Jonstorp Formation (Jaanusson 1982b, p. 24). The Jonstorp Formation is still poorly studied in the Siljan District.

Fauna and age: Few fossils are described from the Jonstorp Formation and its subunits (Jaanusson 1982a). Some trilobites are known (Angelin 1854, Törnquist 1884, Ahlberg 1989), and Neuman (1969a) described corals.

Biostratigraphically the Jonstorp Formation falls within the *Amorphognathus ordovicicus* conodont Zone (Bergström 2007b), but is otherwise poorly constrained (Jaanusson 1982b).

Boda Limestone

Previously termed: *Leptaena* Limestone (*pars*), Upper *Leptaena* Limestone, Kallholn Limestone.

Type section: The carbonate mound at Boda Church in the Siljan District, Dalarna, Sweden (Thorslund 1935, p. 39).

Thickness variation: Hadding (1941, p. 96) and Thorslund *in* Thorslund & Jaanusson (1960, p. 25) reported the diameter for the Boda Limestone to be 1000 m and the thickness to be 100 m. Jaanusson (1982b) gave a thickness of 100–140 m for the mounds.

Definition: Lithostratigraphic unit. The Boda Limestone are mud mounds, similar to those of the Kullsberg Limestone albeit larger (see above). Suzuki & Bergström (1999) distinguished a micritic core of massive whitish to reddish wackstone containing irregular grainstone lenses, a pelmatozoan flank facies, and a terminal bioclastic facies. Boda Limestone mounds are classifed as high relief carbonate mud mounds (Riding 2002). Their base directly overlies the Fjäcka Shale, and/or the Jonstorp Formation, while the top of the mounds are disconformably overlain by the Glisstjärn Formation, and successively the Silurian Kallholn Shale (Schmitz & Bergström 2007).

Discussion: Isberg (1934) rejected the term Kallholn Limestone, because Törnquist (1874, p. 20) had used this name for a different limestone unit. The term was mentioned by Troedsson & Roswall (1926, p. 451) when discussing the Kallholn quarry, and later used by Troedsson (1928, p. 179) for all these limestone bodies. Thorslund (1936b, p. 37), reported 23 localities with Boda Limestone mounds, while Jaanusson (1982b, p. 26) reported 24 localities. Kresten et al. (1991, see Fig. 1) identified 17 mounds.

Jaanusson (1979b, p. A153, 1982b) stated that the *Holorynchus* bearing beds at the top of the Boda Limestone at Osmundsberget indicated an Hirnantian age. Elevated $\delta^{13}C$ values that could correspond to the Hirnantian Isotope Carbon Excursion (HICE) were recorded in the upper part of the Boda Limestone (Marshall & Middleton 1990, Middleton et al. 1991), but Brenchley et al. (1997) reported that the *Holorynchus* bearing beds at the top of the Boda Limestone in the Osmundsberget quarry yielded low pre-Hirnantian $\delta^{13}C$ values suggesting that the entire Hirnantian was missing. However, Schmitz & Bergström (2007) demonstrated both the HICE and conodonts indicative of the Hirnantian in the upper part of the Boda Limestone and the unconformably overlying Glisstjärn Formation.

Fortey & Cocks (2005) used the Boda Limestone carbonate mounds as a key expression for their Boda Event, a short-lived warm period in the late Katian, though this event has recently been re-interpreted (Cherns & Wheeley in press).

Fossils are extremely abundant and well-preserved in the Boda Limestone, and they exhibit strong mound-endemism (Warburg 1925, Isberg 1934, Suzuki & Bergström 1999, Cocks 2005). Fossils are rare in the mound cores (Warburg 1925, Jaanusson 1982b, Suzuki & Bergström 1999) and mostly localized in cm- to meter-sized cavities or pockets in the micritic limestone body (Suzuki & Bergström 1999). Internal sediment with geopetal stratification and marine calcite cement are components of the cavity fillings (Suzuki & Bergström 1999, p. 161). These authors recognized two general type of pockets: 1) narrow open fissures along bedding planes usually with blind possibly cavernous trilobites (Suzuki 2002), and other minute taxa of ostracodes and gastropods, and 2) larger cavities, in-filled from the surface, and usually dominated by sorted disarticulated remains (typically only pygidia or only cephala) of one or two trilobite species. Taphonomically, these accumulations and the peculiar sorting may have come about owing to a strong biotope zonation on the mound surface and selective entrapment of skeletal remains by presumed bacterial mats (Suzuki & Bergström 1999). In addition to the fossil pockets, fissures of variable sizes exist that are filled with the sandstone equivalent to the Tommarp Beds and Silurian graptolitic shale (Isberg 1918, Thorslund 1932a, Jux 1966, Jaanusson 1982b, p. 27).

Limestone mounds similar to the Boda type have been found in the subsurface of Gotland (Klasen mounds, Bergström et al. 2004a, Sivhed et al. 2004).

Fauna and age: More than 90 species of trilobites have been described (Dalman 1827, Hisinger 1840, Angelin 1854, Holm 1883, 1898, Törnquist 1884, Warburg 1925,1939, Skjeseth 1955, Bruton 1967, Owens 1973, 1978, Owen & Bruton 1980, Owen 1981, Bruton & Owen 1988, Kielan-Jaworowska et al. 1991, Suzuki & Bergström 1999, Whittington 2000, Suzuki 2001, 2002, Pärnaste 2004b) and in excess of 100 species of brachiopods (Wahlenberg 1818, Lindström *in* Angelin & Lindström 1880, Isberg 1917, Jaanusson 1956, Wright 1968, 1974, 1981, 1982, 1993, Boucot & Johnson 1967, Sheehan, 1977, 1979, Jaanusson 1982b, Holmer 1987, 1991, Jaanusson & Bassett 1993, Wright & Jaanusson 1993, Zuykov & Egerquist 2005).

Bryozoans have been described or discussed by Brood (1981a, b, 1982), giving an estimate of 31 species occurring in the Boda Limestone. Bivalves and rostroconchs were described by (Isberg 1934), who also discussed possible organic coloration of gastropod and cephalopod conchs (Isberg 1930). Nautiloid cephalopods abound in the Boda Limestone (Frye 1982, 1987), sometimes even forming accumulations in pockets (Suzuki & Bergström 1999). More than 60 species of paragastropods, Tergomyans, and gastropods are found in the Boda Limestone (Wahlenberg 1818, Lindström *in* Angelin & Lindström 1880, Koken 1897, Koken & Perner 1925, Wängberg-Eriksson 1964, 1979, Ebbestad 1997, Ebbestad & Peel 2001, personal observation J.O.R. Ebbestad).

Corals are rare in the fossil pockets, but occur abundantly in the flank facies (Lindström 1873, Lindström *in* Lindström & Angelin 1880, Neuman 1968, 1969a). It is, however, the algae and not the corals that are important builders of the Boda Limestone (Jux 1966). Even within the post-depositional fissures with presumed Tommarp Beds, encrusting algae can be found (Jux 1966).

An exceptionally diverse echinoderm fauna is found in the Boda Limestone, occurring abundantly in the flank facies in particular (Regnéll 1945, 1948, Bockelie & Paul 1983, Bockelie 1976, 1980, 1984, Donovan 1984, 1986, 1987). Among the more rare faunal elements are sclerite bearing organisms (Högström et al. 2007).

Biostratigraphically the Boda Limestone falls within the *Amorphognathus ordovicicus* conodont Zone (Bergström 1971). The upper part of the Boda Limestone in the Osmundsberget quarry (above beds of *Holorynchus giganteus*) is within the Hirnatian (Schmitz & Bergström 2007).

Tommarp Beds

Previously termed: Klingkalk, *Dalmanitina* Beds.

Main lithology: Grey, argillaceous limestone (Hadding 1958, Jaanusson 1982b) .

Type area: Tommarp in Scania (Jaanusson 1963a, p. 132).

Thickness variation: At Kullsberg the Tommarp Beds were 2.35 m thick (Thorslund 1935, p. 13, Jaanusson 1982b, p. 34).

Definition: Lithostratigraphic unit. The Tommarp Formation in the Siljan District is developed as intermound facies composed of calcareous sandstone or calcarenites with the dense 'Klingkalk' at the base (e.g. Kullsberg quarry, Jaanusson 1982b, p. 34). In the Kullsberg quarry the Tommarp Formation is overlain by soft weathering mudstone of the Glisstjärn Formation.

Discussion: The old name 'Klingkalk' comes from the sound created when the rock is hit with a hammer (Hadding 1958, p. 251). In some localities this forms the base of the unit, while calcareous sandstone is developed in other places (Jaanusson 1982b, p. 25). In the Siljan District the Tommarp Formation is defined as a lithostratigraphic unit (Jaanusson 1982b), while in the type area in Scania it is a topostratigraphic unit (Jaanusson 1982c, p. 174). When the term was introduced it replaced the older term *Dalmanitina* Beds in a chronostratigraphic sense (Jaanusson 1963a, p. 132). Later Jaanusson (1982c, p. 174) restricted the term Tommarp Formation in a topostratigraphic sense, suggesting that it was used in the Scanian and Central Confacies belts where the unit could be defined litho- or topostratigraphically.

Fauna and age: Thorslund (1935, p. 13, beds 1–3) and Jaanusson (1982b, p. 34) presented faunal lists of trilobites, brachiopods, bryozoans, gastropods, corals, conodonts, and echinoderms. Both echinoderms (Regnéll 1948) and corals (Lindström *in* Angelin & Lindström 1880, Neuman 1969a) occur in this unit, but are rare. A diverse fauna with 15 species of bryozoans were described from the Tommarp Beds by Brood (1981a). The characteristic trilobite *Dalmanitina mucronata* (Brongniart) is found in the Tommarp Beds at the Kullsberg and Amtjärn quarries (Thorslund 1935, Temple 1952, Jaanusson 1982b).

Glisstjärn Formation

Type section: The Kullsberg quarry, the Siljan District, Sweden (Jaanusson 1982b, p. 33).

Thickness variation: The Glisstjärn Formation at the type locality was measured to be 13 m thick (Thorslund 1935, p. 13, Jaanusson 1982b, p. 34). In the Osmundsberget quarry the thickness of the unit varies due to the undulating surface of the Boda Limestone, but is up to 3.25–3.5 m thick (Grahn 1998, Schmitz & Bergström 2007).

Discussion: The poorly studied Glisstjärn Formation was temporarily considered to be of Silurian age (Grahn 1998), though earlier Jaanusson (1982b) tentatively placed the lower part of the unit in the Hirnantian. Schmitz & Bergström (2007) found that the upper part of the Boda Limestone and the Glisstjärn Formation indeed are of Hirnantian age. Gastropods from the Glisstjärn Formation also support an Ordovician age (Ebbestad et al. 2007). The thickness of the Glisstjärn Formation is highly variable due to the undulating surface of the Boda Limestone (Schmitz & Bergström 2007). In sections at the south and north entrance of the Osmundsberget quarry a distinct layer composed of oriented nautiloid conchs can be correlated (Ebbestad et al. 2007).

Fauna and age: Thorslund (1935) and Jaanusson (1982b) reported trilobite species, and unspecified cephalopods and brachiopods from the unit. Inarticulate brachiopods are fairly common (Larsson & Holmer 2007), and several gastropods and cephalopods are now identified (Ebbestad et al. 2007).

The Ordovician conodont biostratigraphy in the Siljan region, south-central Sweden: a brief review of an international reference standard

Stig M. Bergström

The Ordovician succession preserved in the Devonian astrobleme in the Siljan region, which is one of the stratigraphically most complete in Sweden, has been the subject of investigations by many geologists during more than two centuries and the results of their studies have been published in a large number of papers. Although there are numerous publications dealing with particular aspects of the geology and paleontology of this remarkable region, there is currently no modern and reasonably detailed summary covering its interesting Precambrian and Lower Paleozoic geology. The explanation of the regional map of the Kopparberg County (Hjelmqvist 1966) is focused on Precambrian geology and its treatment of the Paleozoic deposits in the Siljan region is both outdated and very incomplete. As far as the Ordovician is concerned, much more useful general and specific stratigraphic information is presented by, for instance, Thorslund (1935, 1936a), Tjernvik (1956), Thorslund & Jaanusson (1960), and Jaanusson (1963b, 1982b).

The oldest conodont records from the Siljan region are apparently those from the Upper Ordovician by Thorslund (1935) but he did not provide identifications and/or illustrations of his specimens. Many years ago, he informed me that his 'conodonts' were not amber-colored as most Siljan region conodonts (Bergström 1980) but dark brown or black in color. He agreed with my interpretation that in all likelihood, these specimens were scolecodonts rather than conodonts. Hence, there was no confirmed conodont record from this region when I initiated my studies of its conodonts in 1959.

Reconnaissance sampling from some Middle and Upper Ordovician sections was carried out in the summer of 1959 and after the positive results of the analysis of these samples during the following months, a more extensive collection program, which included not only the Siljan region but also some localities in Jämtland, was carried out in the summer of 1960 with the able assistance of Jan Bergström. Additional samples from many Ordovician localities have been collected on numerous occasions in the subsequent years, and I have had the opportunity to visit all significant, and many insignificant, Siljan region localities, often in the company of the late Per Thorslund, whose classic studies added greatly to our knowledge about the geology of the region.

Although much biostratigraphic and taxonomic work was carried out on the conodont collections in the 1960s prior to my move to the USA in 1968, the planned monographic treatment of these and other Swedish conodont collections has never been completed. A few results from the studies of these conodonts have been used in several subsequent publications, some of which deal primarily with other subjects than conodonts and conodont biostratigraphy. Such papers include, for instance, Bergström et al. (1992, in press), Tobin & Bergström (2002), Schmitz & Bergström (2007), and Barta et al. (submitted).

The purpose of the present contribution is to present the conodont species succession in the most important Darriwilian and Katian outcrops in the Siljan region (Fig. 4), including those that are reference sections for zones and subzones. These partly overlapping sections cover the entire stratigraphic interval from the middle Darriwilian Segerstad Limestone to the top of the Ordovician. The changing conodont species associations through the successions are illustrated by detailed, previously unpublished, range diagrams that show the known distribution of most species. Although I have tried to use current taxonomy, there are still

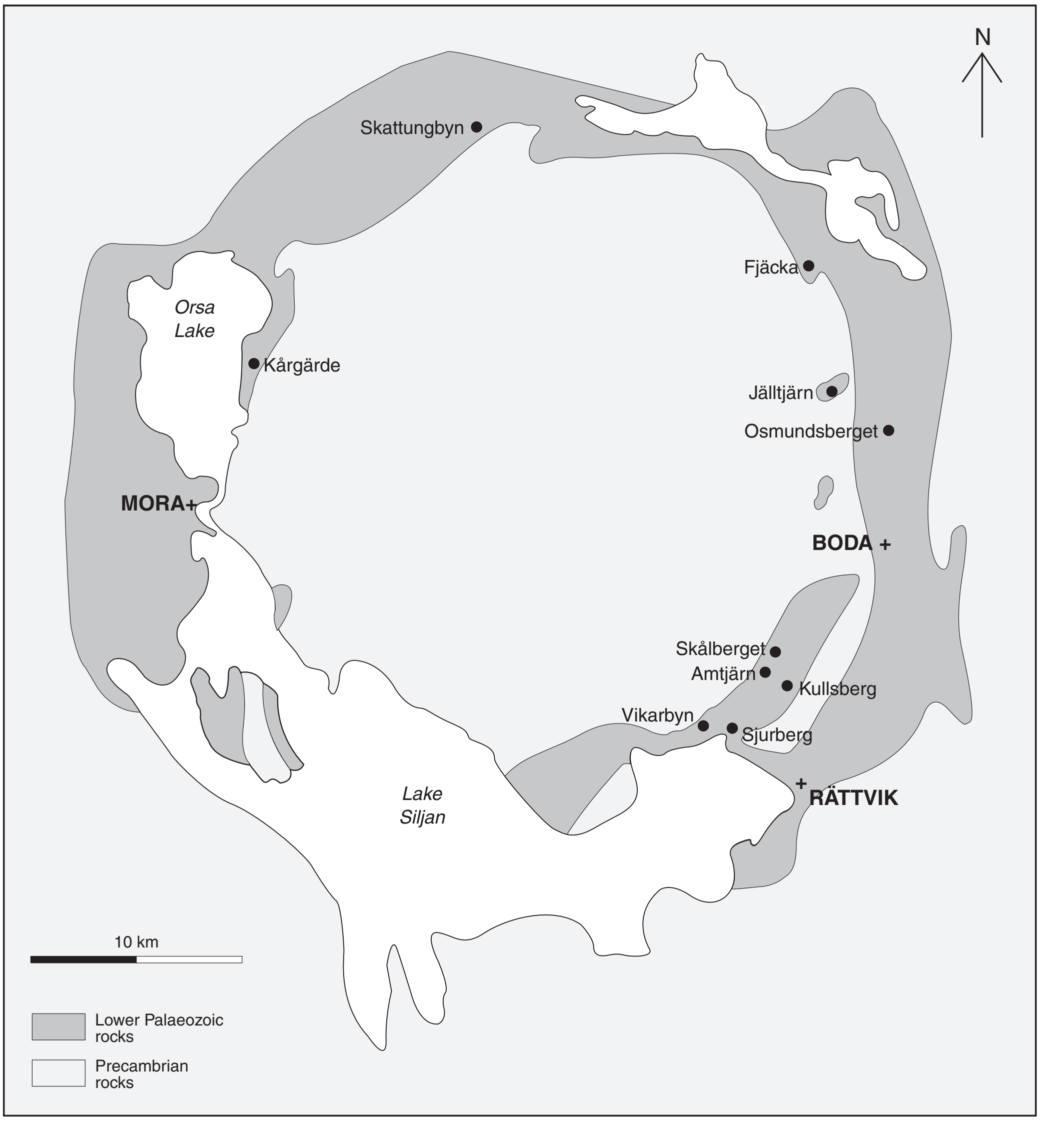

Fig. 4. Sketch-map of the Siljan region showing localities (black dots) mentioned in the text.

taxonomic problems in several genera (such as *Drepanoistodus* and *Panderodus*) and there are also a few undescribed taxa. Most of the species listed have been adequately described in multielement taxonomy by, for instance, Bergström (1971, 1983, 2007a), Löfgren (1978), Dzik (1994), and Rasmussen (2001), and reference is made to these papers for illustrations and taxonomic information. In the present contribution I use the recently ratified global stage and series classification (Fig. 5) although there are occasional references to the standard regional Baltic stages.

Previous conodont studies in the Siljan region

There are relatively few conodont studies that more or less specifically deal with collections from the Siljan region. The first is a contribution to a summary volume on conodont biostratigraphy, in which Bergström (1971) introduced an upper Middle Ordovician and Upper Ordovician (upper Darriwilian through Katian global stages) zone and subzone scheme, now known as the Atlantic conodont zonation. This was originally based largely on conodont data from the Siljan region. Several of the zones and subzones of this scheme have their reference sections in this region; hence, five of these are at Kårgärde, one at Vikarbyn, and six at Fjäcka. For location of these localities, see Fig. 4. This chronostratigraphic framework, which is based on evolutionary changes in lineages of the genera *Eoplacognathus, Pygodus, Amorphognathus*, and *Baltoniodus*, has turned out to be applicable virtually globally in cold/deep water biofacies, and has become an international standard (cf. Webby et al. 2004). The biostratigraphic scheme has remained basically the same as when it was defined more than 35 years ago, the changes being minor and mostly reflecting new developments in the conodont taxonomy. For range diagrams of each of these sections and further information, see the section descriptions below.

The second conodont paper with detailed information from the Siljan region is a study of the Lower Ordovician *Prioniodus elegans* Zone in Baltoscandia by Bergström (1988). In this investigation, the classic outcrop at Talubäcken at Skattungbyn (Fig. 4) was searched for conodonts. This led to the discovery of very abundant and taxonomically diverse faunas as illustrated by the fact that the basal part of the *Prioniodus elegans* Zone at this site had frequencies of up to 40 000 specimens per kg and the fauna included some 20 species. The locality is of special importance because this is the only outcrop known in Baltoscandia where there are graptolites and conodonts occurring together that show that the *Prioniodus elegans* Zone is equivalent not only to the *D. balticus* Zone but also to the lowermost part of the overlying *P. densus* Zone, both these zones being standard units in the Scandinavian graptolite zone succession.

A study by Löfgren (1994) deals with Lower Ordovician conodonts from three localities in the Siljan region, namely Sjurberg, Djupgrav at Skattungsbyn, and a drill-core from Fjäcka. Her collections covered the interval from the late Tremadocian *Paltodus deltifer* Zone to the early Middle Ordovician *Paroistodus originalis* Zone. Significantly, the *Paroistodus proteus* Zone was subdivided into three subzones, each with its reference section at the Sjurberg railroad cut. Her conodont faunas were tied into the standard trilobite zones recognized by Tjernvik & Johansson (1980).

In another investigation, Löfgren (1995a) analyzed the conodont fauna changes within the *Paroistodus originalis* Zone based on many samples from 14 sections in southern and south-central Sweden. Her Siljan region collections came from the outcrops at Sjurberg and nearby Rävanäs, Leskusänget near Skattungbyn, and Kårgärde. Her detailed study led to the conclusion that it is possible to recognize five successive phases within this conodont zone, each characterized by major shifts in the frequency of species in the conodont faunas.

A small number of samples from several localities (Kårgärde, Leskusänget, and Rävanäs) in the Siljan region were also used in another of Löfgren's studies (2000) that deals with lower Darriwilian conodont biostratigraphy (especially the *Baltoniodus norrlandicus* Zone). It is a detailed and valuable assessment of this zone and its conodont fauna but most of the new information is based on sections outside the Siljan region. The same is the case with one of Löfgren's more recent studies (2003), which deals with the *Lenodus variabilis* Zone and its conodonts in southern and central Sweden, and which includes only a small number of samples from three localities in the Siljan region.

Finally, Leslie (2000), in a taxonomic study of Upper Ordovician conodonts of eastern North America, also discussed several taxa based on samples from the upper *Amorphognathus tvaerensis* Zone at Fjäcka and Kårgärde.

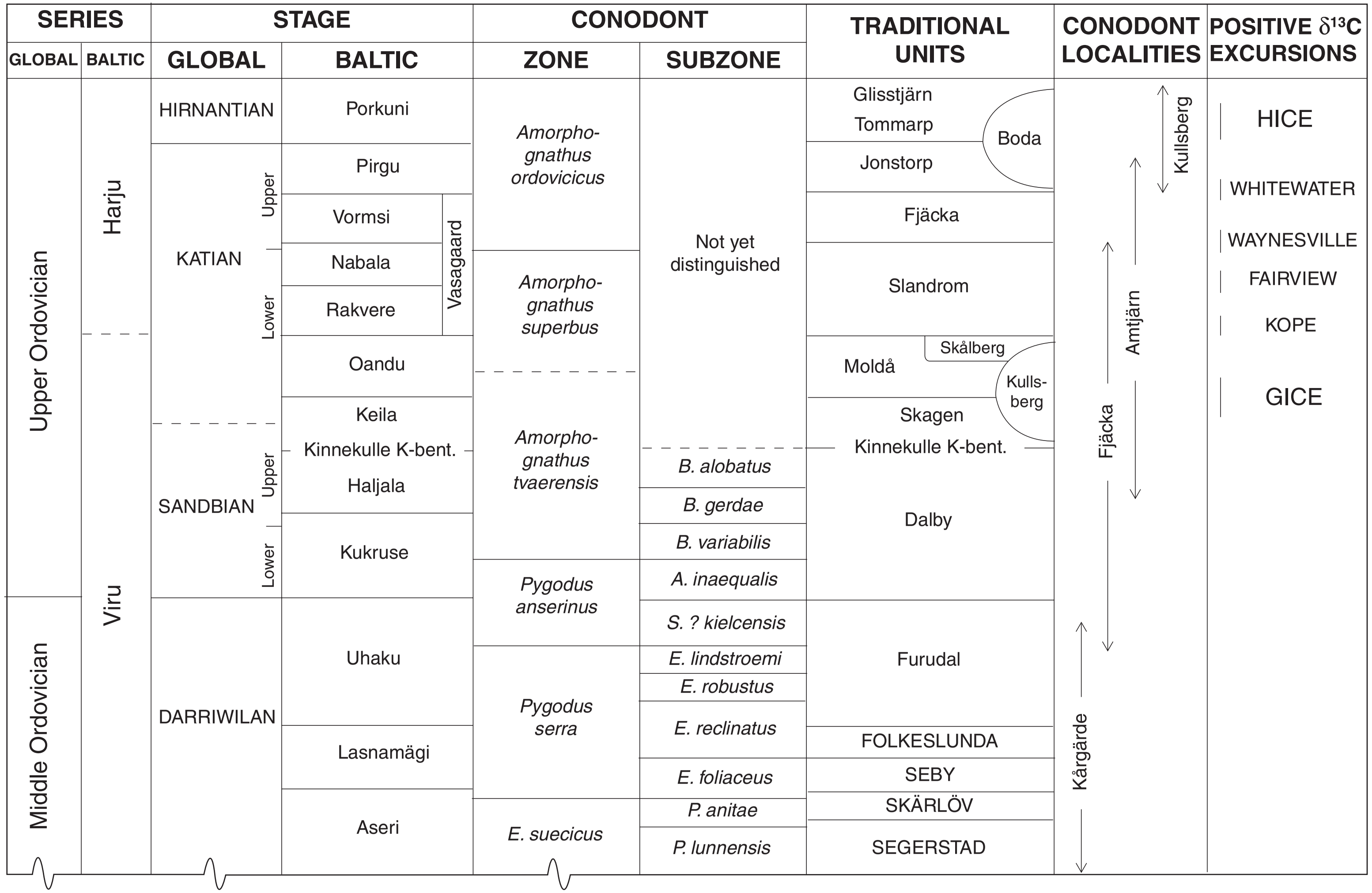

Fig. 5. Chronostratigraphic and lithostratigraphic classification of the upper Darriwilian-Hirnantian succession in the Siljan region, and the stratigraphical ranges of key localities discussed in the text. Also indicated are the stratigraphic positions of the GICE and the HICE isotopic positive excursions, and the inferred positions of four other Katian $\delta^{13}C$ positive excursions.

Conodont biostratigraphy in upper Darriwilian–Hirnantian sections

Kårgärde

Very few representative sections of the upper Darriwilian succession have been recorded from the Siljan region, and the important outcrop at Vikarbyn (Jaanusson & Martna 1953, Thorslund & Janusson 1960, Jaanusson 1963b) is no longer well exposed. The only outcrop currently exhibiting a stratigraphically complete sequence through this interval is at Kårgärde about 4 km south-southwest of Orsa Church (Fig. 4). In an artificial excavation at this site, which is now located within a nature preserve, there is an informative section from strata below the base of the Segerstad Limestone into the upper part of the Furudal Limestone (Fig. 6). In an adjacent small quarry there is an exposure of the upper Furudal Limestone and the lower Dalby Limestone. Because the *Pygodus serra/Pygodus anserinus* Zone boundary is present both in the excavation and quarry sequences, they can readily be tied together, and there is no stratigraphic gap in this composite Kårgärde succession.

The many samples collected through the sequence exposed in the Kårgärde excavation contained relatively abundant and taxonomically diverse conodonts. The vertical ranges of most species are illustrated in Fig. 6, which also shows major stratigraphic units (after Jaanusson 1963b) and the conodont biostratigraphy.

The **Eoplacognathus suecicus** *Zone*

This zone is about 5 m thick in the section studied, and includes the Segerstad Limestone and the lower and middle parts of the Skärlöv Limestone. Following Zhang (1998), this zone is subdivided into the *Pygodus lunnensis* and *Pygodus anitae* Subzones based on the ranges of the subzone indices. Of particular interest among the more than 20 multielement species recognized in this zone is the stratigraphically important and geographically species *Histiodella kristinae* that has been found in two samples from the lowermost part of the Segerstad Limestone. Whereas *P. lunnensis* is currently known only from Sweden, *P. anitae* has a much wider geographic range, being recorded also from Argentina (Albanesi & Ortega 2002), Russia (Melnikov 1999), and northern China (Wang & Luo 1984, An & Zheng 1990).

The **Pygodus serra** *Zone*

The Kårgärde site was designated the reference section of this stratigraphically important zone (Bergström 1971), that has a total thickness of between 17 and 18 m at this locality. This zone has an extraordinarily wide geographic range, being known outside Baltoscandia from numerous localities in the British Isles, North America, Argentina, Australia, China, and other parts of the world. Along with its descendent *P. anserinus*, *P. serra* is one of the key species in global Ordovician conodont biostratigraphy. For comments on the taxonomy of this species, see Bergström (2007a).

Bergström (1971) subdivided the *P. serra* Zone into five subzones based on the vertial ranges of platform conodonts of the genus *Eoplacognathus*. This genus underwent a rapid evolution, probably of mosaic type, in the late Darriwilian and several morphologically distinctive species appeared, each having a short vertical range. The detailed relations between these, and related platform taxa found in other parts of the world, is still the subject of different interpretations. For two slightly different opinions, see Bergström (1983) and Zhang (1998). However, it should be stressed that these different interpretations do not affect the usefulness of the subzones, which have been recognized not only widely in Baltoscandia, Poland (Dzik 1994) and locally in the Appalachians in eastern North America (Bergström 1971, 1973, Bergström & Carnes 1976) but also in Argentina (Albanesi & Ortega 2002) and northern and central China (Wang & Luo 1984, Zhang 1998). As seen in Fig. 6, there is no drastic change in the conodont species association through the *P. serra* Zone and the recognition of the ranges of the subzones and their ranges is based on the presence of their index species.

The **Eoplacognathus foliaceus** *Subzone*

In its reference section, this subzone is a little more than 2 m thick and extends from the upper part of the Skärlöv Limestone to the top of the Seby Limestone. Apart from the presence of the subzone index, the conodont fauna of this subzone is closely similar to that of the *Eoplacognathus suecicus* Zone. Interestingly, *E. foliaceus* is one of the geographically most widespread *Eoplacognathus* species, having been recorded not only

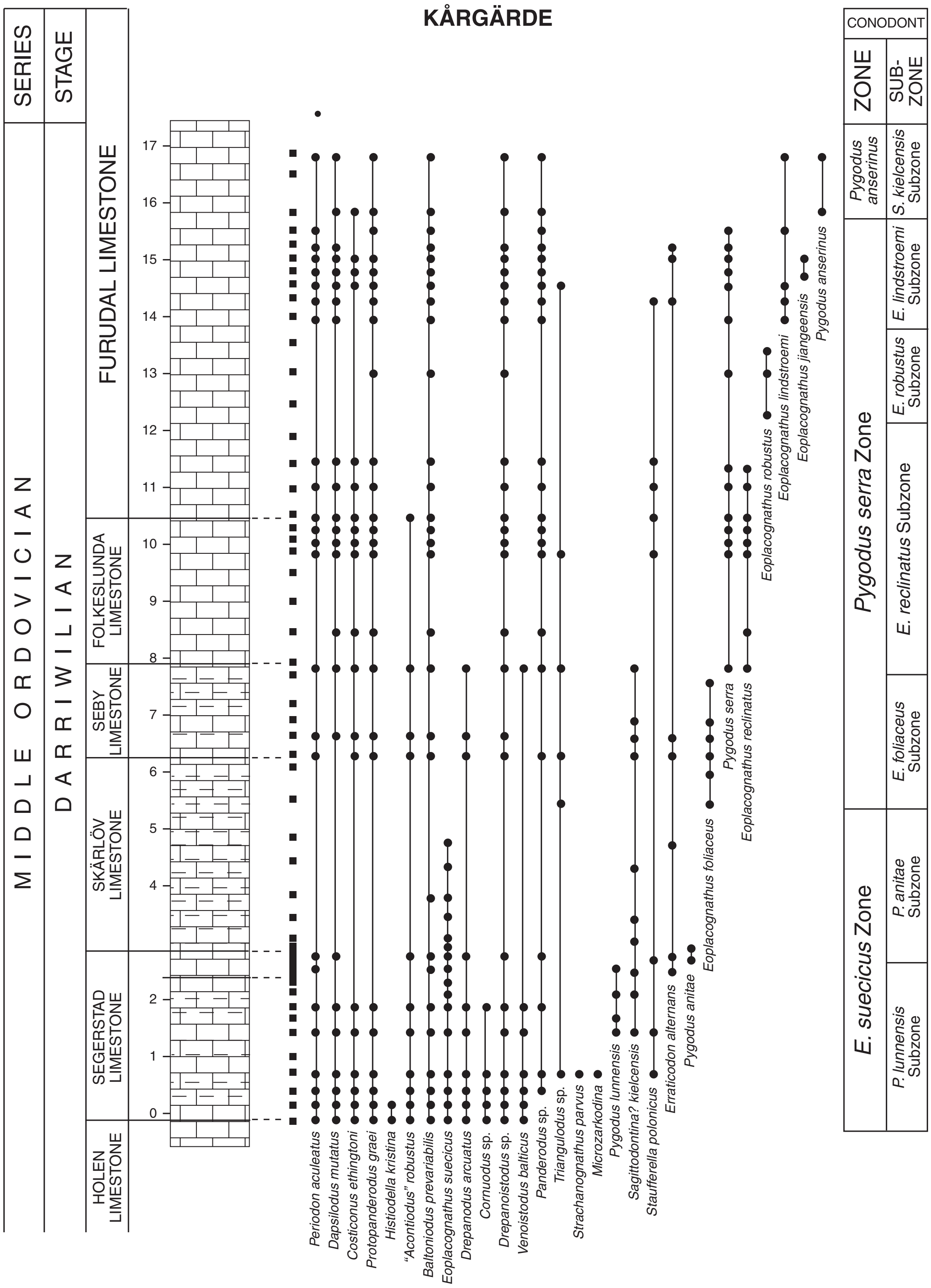

Fig. 6. Stratigraphical ranges of conodont taxa, and condont zones and subzones, in the Kårgärde succession.

at many localities in Baltoscandia but also in eastern North America (Bergström 1971), Argentina (Albanesi & Ortega 2002), Russia (Melnikov 1999), and China (Zhang 1998, Wang & Qi 2001).

The* Eoplacognathus reclinatus *Subzone

This subzone, which has a thickness of about 4 m in it reference section at Kårgärde, extends from the lowermost part of the Folkeslunda Limestone into the lower part of the Furudal Limestone. The subzone index species is not common outside Baltoscandia but has been recorded from a few localities in eastern North America (Bergström 1973), Argentina (Albanesi & Ortega 2002), and China (Zhang 1998).

The* Eoplacognathus robustus *Subzone

Because the designated reference section of this subzone was the Vikarbyn exposure (Bergström 1971), which is now partly covered, it is appropriate to select the Kårgärde outcrop as a replacement reference section. At the latter exposure it covers a less than 2 m thick interval in the lower to middle part of the Furudal Limestone. Outside Baltoscandia and Poland, the subzone index species has been recorded from few localities in eastern North America (Bergström 1976), Argentina (Albanesi & Ortega 2002), and China (Wang & Luo 1984, Zhang 1998).

The* Eoplacognathus lindstroemi *Subzone

A re-assessment of the level of the base of this subzone based on additional collections made since 1971 suggests that at its reference section in the Kårgärde Quarry, the base of this subzone should be moved slightly downward resulting in a subzone thickness of about 2 m rather than less than 1 m. This thickness figure agrees with that at some other localities in Sweden. This subzone includes the middle portion of the Furudal Limestone. The revision of the level of the base of this subzone results in that the occurrence of the notable platform conodont *Yangtzeplacognathus protoramosus* (=*Eoplacognathus* n.sp. *in* Bergström 1971) is in the *Eoplacognathus lindstroemi* Zone rather than in the next older subzone. This species, which is quite rare in Baltoscandia, is common and widespread in China, where it is used as a zone index (Zhang 1998, table 3). Outside Baltoscandia and Poland, representatives of *E. lindstroemi* have been recorded from the British Isles, eastern North America, and Argentina.

The stratigraphically important *Pygodus serra*/*Pygodus anserinus* Zone boundary is about 5 m above the base of the Furudal Limestone and ~15.5 m above the base of the Segerstad Limestone in the excavation. Although not illustrated in Fig. 6, the conodont biostratigraphy has also been investigated in the approximately 15 m thick succession in the adjacent small and long disused Kårgärde Quarry. The strata exposed at that site in the 1960s included the uppermost 8 m of the Furudal Limestone and the lower 7 m of the Dalby Limestone (Jaanusson 1963b). The *Pygodus serra*/*Pygodus anserinus* Zone boundary is approximately 5 m above the base of the quarry sequence, and this important zone boundary is about 3 m below the top of the Furudal Limestone. Rare specimens of the zone index species *Amorphognathus tvaerensis* have been found about 7 m above the base of the Dalby Limestone in the very topmost part of the exposed quarry sequence. This indicates that the local thickness of the *Pygodus anserinus* Zone is approximately 10 m at Kårgärde.

Fjäcka

The now partly overgrown but still easily accessible section at the mill-race at Fjäcka, which is here referred to as the Fjäcka main section following Jaanusson (1963b), has figured prominently in not only Swedish, but international, biostratigraphy and paleontology. This succession, which is now in a nature preserve, has probably been studied in more detail than any other Upper Ordovician sequence in Scandinavia. For key references, see Jaanusson (1963b, 1982b), Bergström (1971), Holmer (1989), and Nõlvak et al. (1999). More recent studies of the Fjäcka locality include Bergström et al. (1995, 2004b, in press), Saltzman et al. (2003), and Ainsaar et al. (2004). Its international importance is shown by the fact that parts of the Fjäcka section have been designated as the reference section for three conodont zones and three conodont subzones in the globally used Atlantic conodont zone scheme (Bergström 1971) as well as for three chitinozoan zones in the Baltoscandic standard chitinozoan zone classification (Nõlvak & Grahn 1993). In addition, it is the type locality of the Dalby Limestone, Moldå Formation and Fjäcka Shale (Jaanusson 1982b).

In 1959 and 1960, with much additional work done in subsequent years, the entire main Fjäcka section was sampled in detail for conodont investigation, some results of which were presented in Bergström (1971). Many of these samples were later used for ostracode (Jaanusson 1976) and chitinozoan (Laufeld 1967) work, and the samples from the upper Furudal Limestone and the Dalby Limestone were utilized by Holmer (1989) in his monographic study of Swedish Sandbian inarticulate brachiopods. Jaanusson & Martna (1953) and Jaanusson (1963b) have provided many macrofaunal data from the Fjäcka succession, and the Dalby Limestone chitinozoan succession was revised by Nõlvak et al. (1999).

Bergström (1971) subdivided the sequence below the Kinnekulle K-bentonite into three conodont zones, namely the *Pygodus serra*, *Pygodus anserinus*, and *Amorphognathus tvaerensis* Zones, and three subzones of the *A. tvaerensis* Zone, namely the *Baltoniodus variabilis, Baltoniodus gerdae*, and *Baltoniodus alobatus* Subzones (Fig. 5). Except the *Pygodus serra* Zone, all of these zonal units have their reference sections in the Fjäcka succession. One additional conodont zone, the *Amorphognathus superbus* Zone, has also its reference section at this locality, but its current stratigraphic scope is slightly different from that tentatively proposed by Bergström (1971).

The **Pygodus serra** *Zone*

Only the very uppermost part of this zone is represented in the oldest portion of the main section at Fjäcka (Fig. 7), where the exposed thickness of the zone is only about 1 m. The top of the zone, which is marked by the appearance of the zone index *Pygodus anserinus*, is about 4.5 m below the top of the Furudal Limestone, hence it is about 1 m lower stratigraphically than at Kårgärde. The composition of the conodont fauna is essentially the same as in this zone at the latter locality.

The **Pygodus anserinus** *Zone*

The species association of this zone is well represented in the uppermost Furudal Limestone and the lower portion of the overlying Dalby Limestone. The zone has a total thickness of about 10.5 m, hence about the same as at Kårgärde. Apart from the presence of the zone index *Pygodus anserinus*, the species association of this zone is closely similar to that of the underlying zone. In the absence of the index species of the upper subzone of the *P. anserinus* Zone, which is known as the *Amorphognathus inaequalis* Subzone, the base of the latter subzone is taken as the level of appearance of typical specimens of *Baltoniodus variabilis*. This level appears to correlate closely with the base of the *Nemagraptus gracilis* Zone and the base of the global Sandbian Stage.

The **Amorphognathus tvaerensis** *Zone*

The base of this zone is taken at the level of appearance of specimens of *Amorphognathus*, which are in all probability *A. tvaerensis*, about 5.25 m above the base of the Dalby Limestone. By and large, the *Baltoniodus*-dominated fauna of this zone shows no great change through the middle and upper Dalby Limestone, and the distinguishing feature of the three subzones of the *A. tvaerensis* Zone is the presence of the subzone index species. For further data on the ranges of these index species, see Bergström (1971). It should be noted that the infaulted repetition of the *L. dalbyensis* Chitinozoan Zone discovered by Nõlvak et al. (1999) at their Subsection 14 does not affect the conodont succession shown in Figs. 7–8. This is because, by chance, the conodont sample collecting in 1960 continued on the quarry floor, which was well exposed at that time, for several m southward of the Locality 8 of Nõlvak et al. (1999), and then it continued along strike in the low quarry wall at their Subsection 13, hence apparently avoiding the faults recognized by Nõlvak et al. (1999, fig. 1).

The **Baltoniodus variabilis** *Subzone*

In its reference section at Fjäcka, this subzone is somewhat more than 4 m thick and occupies an interval between 5.25 and 9.5 m above the base of the Dalby Limestone. Outside Baltoscandia, this subzone has been recognized in several sections in eastern and western North America (Bergström 1971), Argentina (Albanesi & Ortega 2002), and the British Isles (Bergström & Orchard 1985).

The **Baltoniodus gerdae** *Subzone*

The base of this subzone, which is approximately 4.75 m thick in its reference section, is marked by the appearance of the morphologically distinctive subzone index species. The widespread platform conodont *Eopla-*

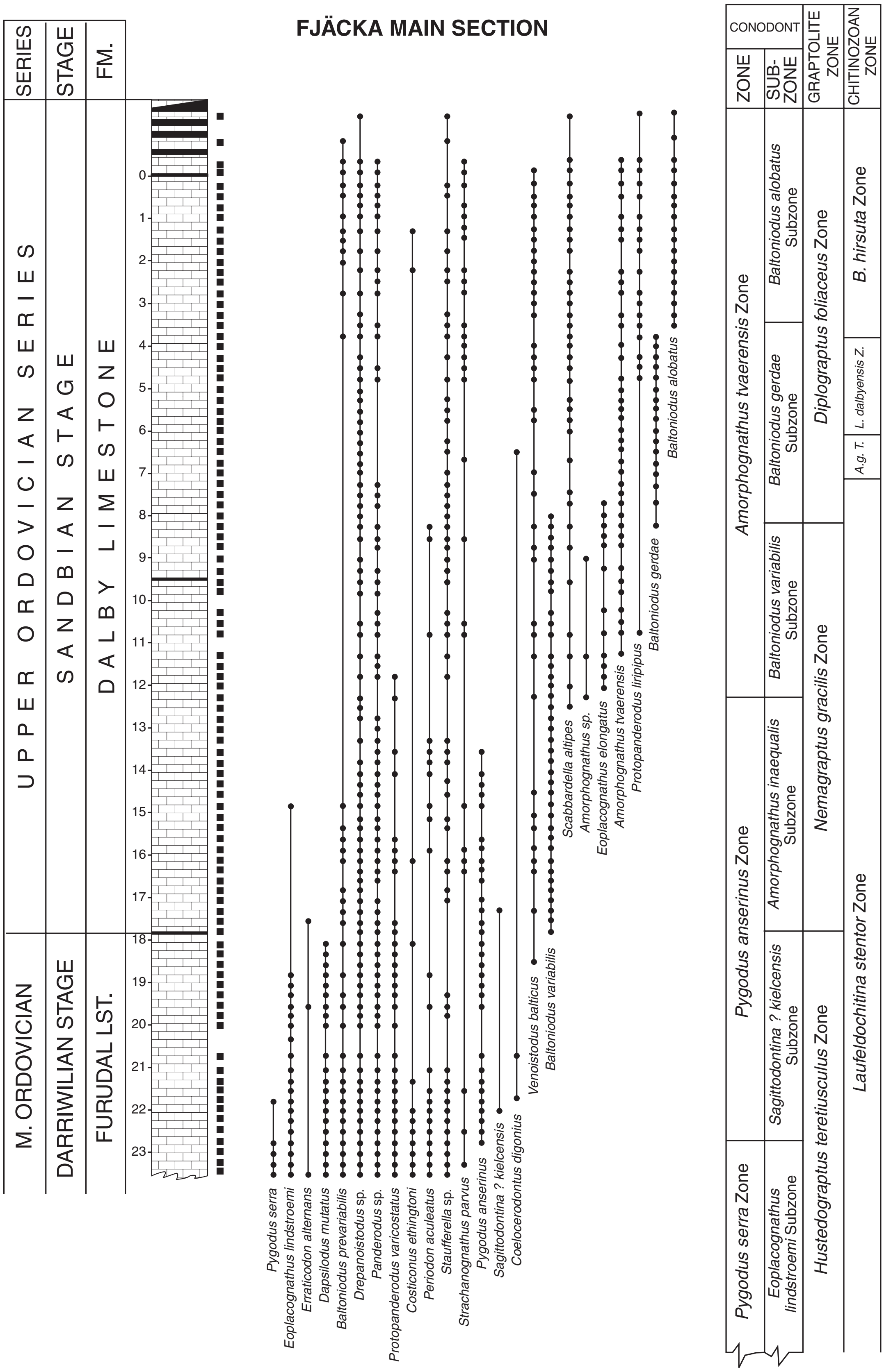

Fig. 7. Stratigraphical ranges of conodont taxa, conodont zones and subzones, and graptolite and chitinozoan zones, in the Furudal and Dalby Limestones in the Fjäcka Main Section. Note that the topmost part of this section overlaps with the basalmost portion of the section illustrated in Fig. 8. A.g.A.c., *A. granulifera* and *A. curvata* zones.

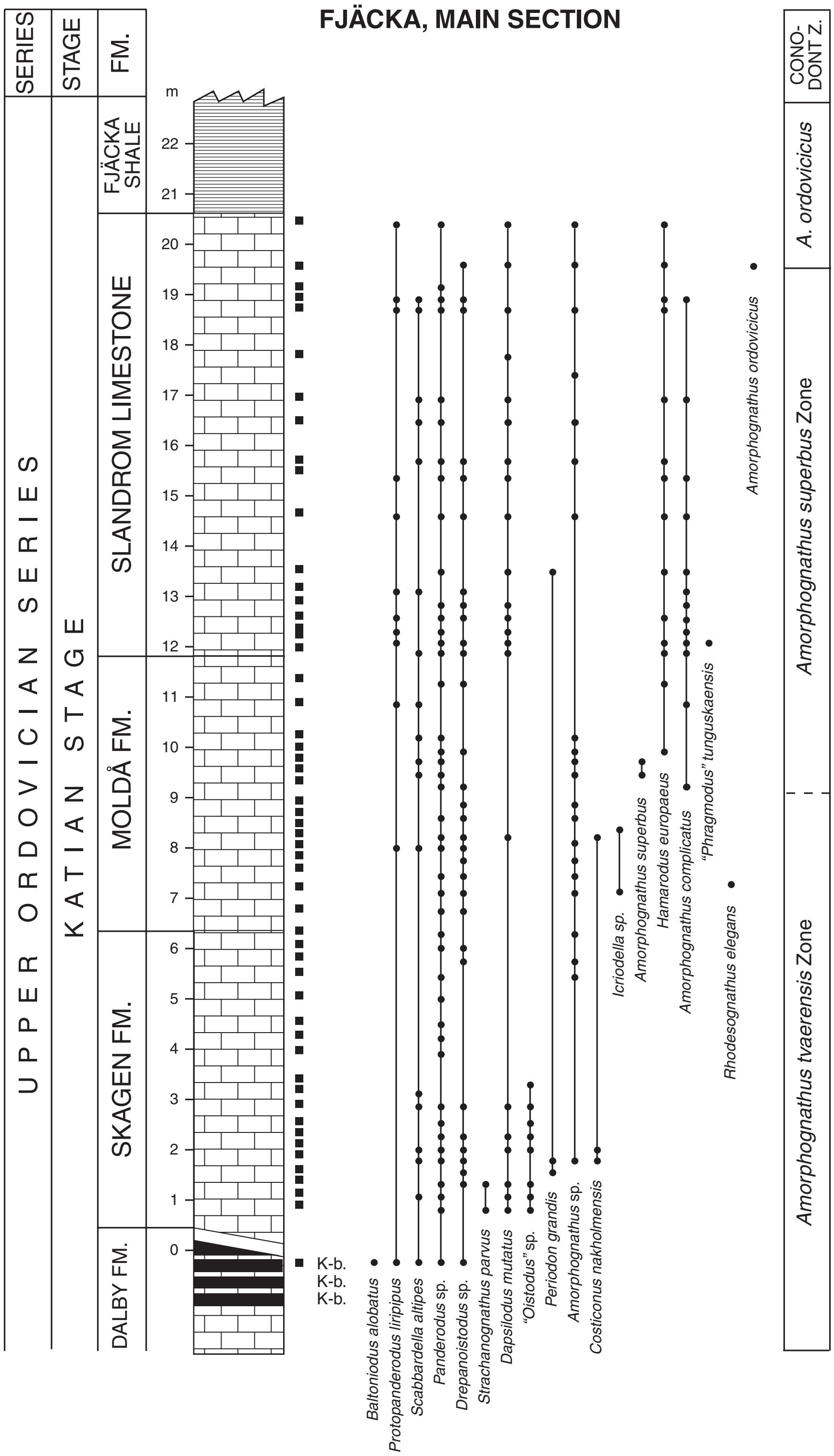

Fig. 8. Stratigraphical ranges of conodont taxa and conodont zones in the Skagen Limestone, Moldå Formation, and Slandrom Limestone in the Fjäcka Main Section.

cognathus elongatus has its last occurrences in the lower part of this subzone. This subzone has been recognized at many localities in Baltoscandia and its index species has also been recorded from several localities in eastern North America (Bergström 1971, Bergström & Carnes 1976) as well as in Nevada (Harris et al. 1979).

The* Baltoniodus alobatus *Subzone

The base of this subzone is at the level of appearance of the subzone index, which is approximately 14.25 m above the base of the Dalby Limestone in the subzone reference section at Fjäcka. At the present time, *B. alobatus* is the only species known to be restricted to this subzone. This subzone, which is characteristic of the upper Dalby Limestone and equivalent strata of the Haljala Stage in the East Baltic, is about 5 m thick at Fjäcka. The subzone index species disappears just below the Kinnekulle K-bentonite but another, much younger and still unnamed, representative of *Baltoniodus* is known from much younger strata in Wales (Lindström 1959). Outside Baltoscandia, representatives of *B. alobatus* have been recorded from many localities in China (Wang & Qi 2001,Wang et al. 2007), and it has also been fund at one site in eastern North America (Kennedy et al. 1979) and recently also in southern Thailand (Agematsu et al. 2007; listed as *Baltoniodus* sp. cf. *B. variabilis*).

The Skagen Limestone conodont fauna (Fig. 8) is less diverse taxonomically than the Dalby Limestone faunas and it includes mainly coniform taxa. Although sporadically present, elements of *Amorphognathus* are quite uncommon and all recovered are too incomplete for safe species identification. Hence, it has not been possible to directly establish the conodont zone reference of the Skagen Limestone in the Fjäcka section, and the same problem prevails at other Skagen Limestone localities studied in southern Sweden. However, in New York State and Ohio (Richardson & Bergström 2003), the boundary between the *A. tvaerensis* and *A. superbus* Zones can be determined precisely, and in the New York succession, it is a little above the Guttenberg Carbon Isotope Excursion (GICE). Because this important excursion ranges into the lower Moldå Formation at Fjäcka (Bergström et al. 2004b, in press), the base of the *A. superbus* Zone should correspond to a level within the Moldå Formation.

Interesting but rare species in the lower part of the Moldå Formation below the base of the *A. superbus* Zone include *Icriodella* sp. and *Rhodesognathus elegans.* Representatives of these genera are common elements in equivalent North American Midcontinent faunas (Richardson & Bergström 2003) and the Fjäcka occurrences may be interpreted as a minor representation of the much more taxonomically diverse 'Midcontinent faunas' previously known from the Svartsaetra limestone in the Trondheim region (Bergström 1997), the Mjøsa Limestone of southeastern Norway (Bergström et al. 1998), and the Vasalemma Formation of Estonia (Viira 1974). These faunas appear to be of Oandu age and correspond to faunas of the Chatfieldian Stage in North America (Richardson & Bergström 2003).

The* Amorphognathus superbus *Zone

At about the middle of the Moldå Formation, there are occurrences of *A. superbus* as well as *A. complicatus* and *Hamarodus europaeus*, and this is here taken as the base of the *A. superbus* Zone. This level appears to be coeval with the base of this zone in Estonia as identified by Männik (2003). In the absence of diagnostic specimens, the *Amorphognathus ventilatus* Zone recognized by Männik (2003) and Männik & Viira (2005) between the *A. tvaerensis* Zone and the *A. superbus* Zone in Estonian drill-cores cannot be distinguished in the Fjäcka succession, and the status of this zone, and also the taxonomy of the poorly known zone index species that was described from substantially younger strata, are in need of further study.

Outside Baltoscandia, the *A. superbus* Zone has been recognized at many localities in the British Isles, North America, and other regions. In a recent paper, Agematsu et al. (2007) recorded *Amorphognathus superbus* (listed as *Amorphognathus* sp.) and *Hamarodus europaeus* about 15 m above a level with *B. alobatus* in the Pa Kae Formation of Thailand. Their conodont fauna is closely similar to that of the very widespread Pagoda Limestone of south China that also contains these three species (An 1987).

The* Amorphognathus ordovicicus *Zone

As is the case at some other localities (Skålberget, Amtjärn) in the Siljan region, representatives of *A. ordovicicus,* the index species of the *A. ordovicicus* Zone, first appears at Fjäcka in the very topmost Slandrom Limestone. Apart from the presence of this species, the fauna of this zone in the Slandrom Limestone is virtually the same as in the older parts of this formation. This conodont zone has an extremely wide geographic range and has been recorded from numerous places in Europe, North America, and Asia.

The overlying Fjäcka Shale and lowermost part of the Jonstorp Formation have not been sampled for conodonts at Fjäcka.

Amtjärn South Entrance Section

The long abandoned limestone quarry near the pond of Amtjärn (Fig. 4), which is now a nature preserve, remains one of the best sections through the Katian Kullsberg Limestone, Skålberg Limestone, Slandrom Limestone, Fjäcka Shale, and Jonstorp Formation in the Siljan region. Conodont samples collected in 1960 were subsequently used also by Laufeld (1967) in his important study of Katian chitinozoans from the Siljan region. Although briefly referred to in several papers (see e.g. Sweet & Bergström 1984, Tobin et al. 2005), the Amtjärn conodont sequence has not been described previously.

Quarrying at Amtjärn began in the 1920s and judging from Thorslund's (1935, 1936b) descriptions, it was active during the 1930s. When I first visited the locality in 1959, the quarry walls were fresh and the sections along the south and east entrances were well exposed. The latter is not now accessible without considerable excavation but the south entrance section is better preserved and readily accessible. In this outcrop there is a virtually continuous outcrop of the uppermost part of the Dalby Limestone through the middle part of the Jonstorp Formation (Fig. 9). Hirnantian strata were formerly accessible by digging along the eastern entrance road to the quarry (Thorslund 1935) but as shown by re-excavation of this section in 1960 (Bergström unpubl.), rapid infilling by water makes detailed study of the steep-dipping rocks at that locality impractical.

The oldest strata now accessible at the Amtjärn Quarry, which are exposed just above the western rock wall at the south quarry entrance, represent the uppermost Dalby Limestone (Thorslund 1935). The approximately 6 m thick succession, which contains conodonts of the *Baltoniodus alobatus* Subzone, is overlain, with gradational contact, by the Kullsberg Limestone that was the principal quarry rock at Amtjärn. This little section, which is currently less than perfectly exposed, is not included in Fig. 9. Samples of the Kullsberg Limestone at this and other localities have proved to contain very few, and stratigraphically undiagnostic, conodonts that are similar to those in the presumably equivalent Skagen Limestone in inter-mound facies. That these units are at least partly coeval is also shown by the fact that $\delta^{13}C$ chemostratigraphy indicates that the beginning of the GICE is in the lowermost Kullsberg Limestone (Bergström et al. in press) as well as in the upper Skagen Limestone.

The **Amorphognathus superbus** *Zone*

The conodont fauna of the Skålberg Limestone, which disconformably overlies the Kullsberg Limestone, is more diverse taxonomically than that of of Kullsberg Limestone (Fig. 9). Although *Hamarodus europaeus* and *A. complicatus* first appear at the base of the overlying Slandrom Limestone, the Skålberg Limestone is referred to the *A. superbus* Zone based on the presence of elements identified as *A. superbus*. Most of the Skålberg Limestone at this exposure consists of a slump breccia composed of a variety of slabs from the Kullsberg Limestone mound.

Apart from the common presence of *A. complicatus* and *H. europaeus*, the conodont fauna of the lower and middle parts of the Slandrom Limestone is essentially the same as that in the upper Skålberg Limestone. A notable occurrence in the middle Slandrom Limestone are few specimens of *Icriodella* sp., a rare genus in the Ordovician of Sweden.

The **Amorphognathus ordovicicus** *Zone*

As is the case at Fjäcka, the first specimens of *A. ordovicicus*, which mark the base of the *A. ordovicicus* Zone, appear in the uppermost part of the Slandrom Limestone. The Fjäcka Shale has not been sampled for conodonts but samples from the lowermost 5 m of the overlying Jonstorp Formation contain a conodont fauna that is basically the same as that in the upper Slandrom Limestone. In Sweden unusual taxa include *Belodina confluens*, which is best known from the North American Midcontinent, and *Birksfeldia* sp., which belongs to a genus first described from the British Isles (Orchard 1980). *Belodina confluens* and *Birksfeldia circumplicata* have previously been found in the Jonstorp Formation of Östergötland (Bergström & Bergström 1996).

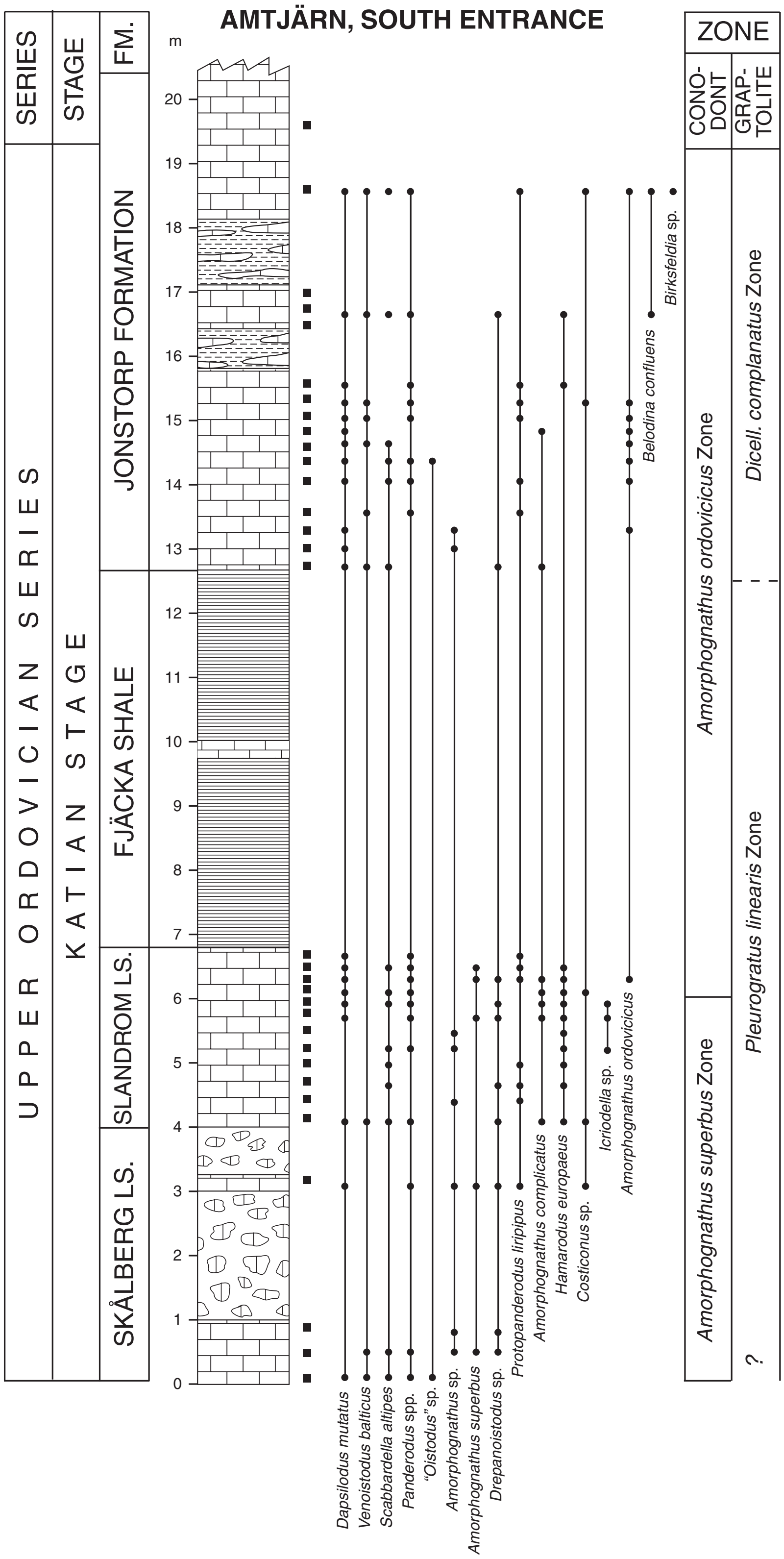

Fig. 9. Stratigraphical ranges of conodont taxa and conodont zones, and inferred ranges of graptolite zones, in the Skålberg Limestone, Slandrom Limstone, and the lower Jonstorp Formation in the Amtjärn South Entrance Section.

Kullsberg Quarry Entrance Section

The best exposure in the Siljan region of the entire Jonstorp Formation, the Tommarp Formation, and the lower Glisstjärn Formation was located along the south side of the entrance road to the Kullsberg Quarry (Fig. 10). This section, which was described by Thorslund (1935, 1936b) and Jaanusson (1982b) and probably was the only section in the Siljan region exposing the entire Jonstorp Formation as well as overlying Hirnantian strata in inter-mound facies, was largely quarried away during the widening of the entrance road and the construction of a limestone processing building. In the summer of 1963, the author, with the valuable assistance of Sven Laufeld, measured and collected conodont samples from the entrance section as its succession was exposed at that time. The fact that this section differs in some details from that published by Jaanusson (1982b) is attributed to the fact that the 1963 section was located tens of m south of the section described by Thorslund (1935) and this is structurally a complex outcrop with lateral changes in the rock succession.

The **Amorphognathus ordovicicus** *Zone*

Conodonts are not abundant or taxonomically diverse in the Jonstorp Formation at this locality (Fig. 10) but the fauna includes *Amorphognathus ordovicicus* as well as *Hamarodus europaeus*, and the whole formation is referable to the *A. ordovicicus* Zone as is the case elsewhere in Sweden. Of particular interest is the presence of single, but typical, specimens of *Belodina confluens* and *Phragmodus undatus*, which are very common in coeval faunas in the North American Midcontinent but rare in late Katian conodont faunas in Baltoscandia. These species can be interpreted as occasional invaders into the Baltoscandic region that otherwise was inhabited by quite different species associations.

The Jonstorp Formation is overlain, apparently conformably, by a 2.5 m thick unit of shales with interbedded limestones that Jaanusson (1982b) referred to as the Tommarp Formation. Thorslund (1935, 1936b) recorded a *Hirnantia* fauna, including *Mucronaspis mucronata,* from this unit. Its topmost part consists of a 35 cm thick bed of calcareous sandstone that in all likelihood represents the so-called 'klingkalk,' This lithologically distinctive bed is known from several Hirnantian localities in the Siljan region (Thorslund 1935, 1936b).

The conodont fauna in the Tommarp Formation is sparse in individuals and of low taxonomic diversity as is the case in Hirnantian strata elsewhere in Baltoscandia. Apart from a few long-ranging taxa, there are rare specimens of a species tentatively identified as *Ozarkodina* cf. *oldhamensis*. This species, which is known from Hirnantian strata at several Scandinavian localities, is present in the latest Hirnantian in Nevada (Sweet 2000), where it is associated with graptolites of the *Normalograptus persculptus* Zone. In recent years, this latest Ordovician interval with conodonts of Silurian aspect (Barnes & Bergström 1988) has been referred to as the *Ozarkodina hassi* Zone. Conodonts of this type have also been recorded from the so-called Glisstjärn Formation that unconformably overlies the Boda Limestone at the Osmundsberget Quarry (Schmitz & Bergström 2007). Another locality in the Siljan region that has yielded conodonts of this type is the Hirnantian outcrop at Jälltjärn (Fig. 4), which was briefly described by Thorslund (1935).

In several respects, the Boda Limestone is one of the most prominent stratigraphic units in the Siljan region. This up to 150 m thick carbonate mound deposit is excellently exposed in several active and inactive quarries, such as those at Osmundsberget, Unkarsheden (Dalhalla), Jutjärn, Solberga, Kallholn, and Östbjörka. Repeated attempts to obtain condonts from this high-calcium limestone have met with very little success, most samples being barren or only containing coniform taxa. However, some samples from pockets of abundant macrofossils, such as those recently described by Suzuki & Bergström (1999), have produced representative *Amorphognathus ordovicicus* Zone faunas, including, apart from the zone index, *Protopanderodus liripipus, Strachanognathus parvus, Scabbardella altipes, Venoistodus* sp., *Drepanoistodus* sp. and *Panderodus* sp.

Relations to $\delta^{13}C$ chemostratigraphy

Recent work in the Ordovician of northern Europe and North America has firmly established the great value of $\delta^{13}C$ chemostratigraphy for both local and long-distance correlations. Whereas it appears to be only one positive, regionally recognizable, $\delta^{13}C$ excursion in the Darriwilian Stage, which is centered in the Segerstad Limestone and coeval units in Estonia and Sweden and known as the mid-Darriwilian excursion (Meidla et al. 2004, Kaljo et al. 2007), there are several significant positive excursions in the Katian to Hirnantian inter-

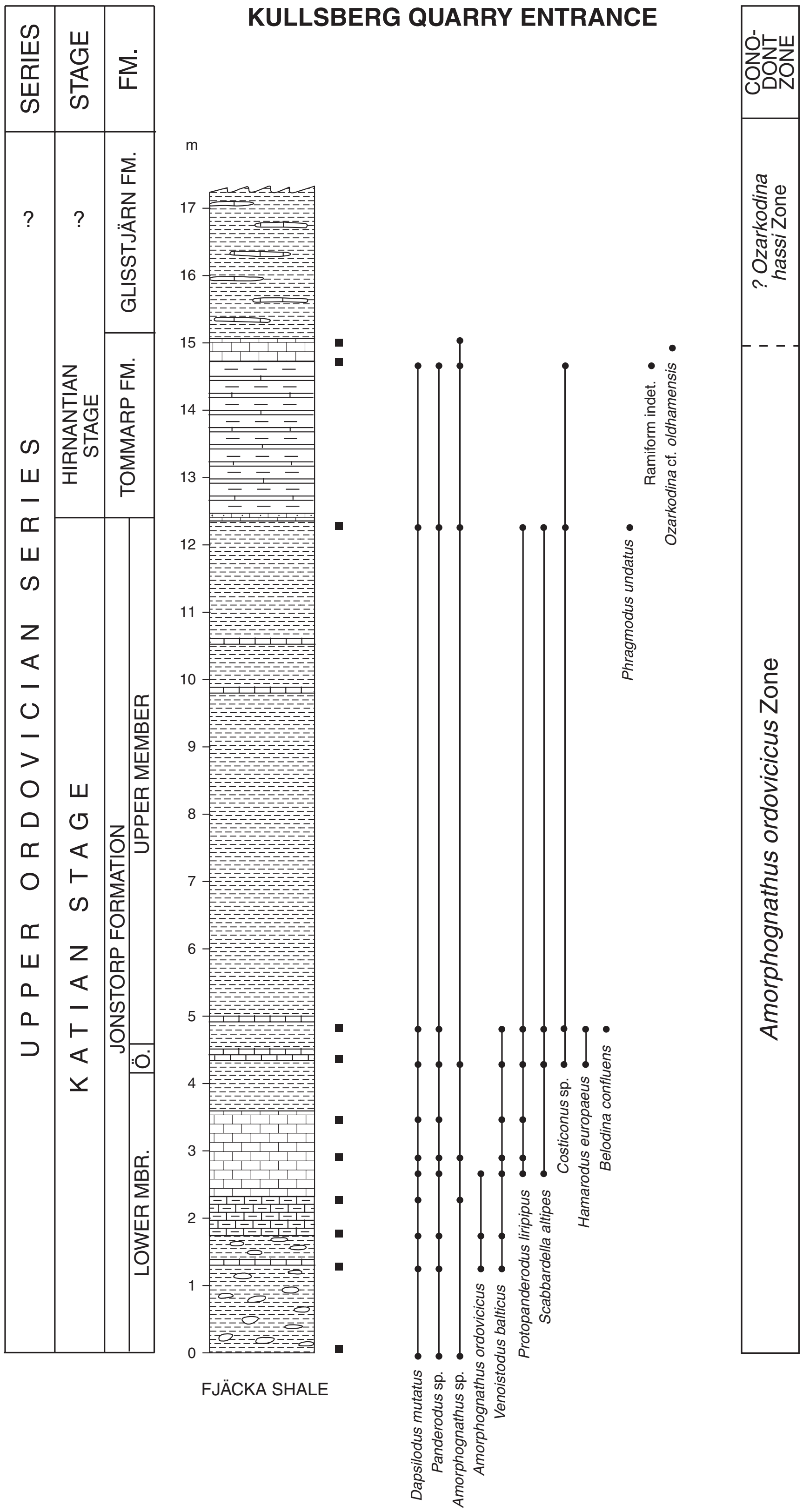

Fig. 10. Stratigraphical ranges of conodont taxa and conodont zones in the Jonstorp and Tommarp formations in the Kullsberg Quarry Entrance Section. Ö, Öglunda Limestone.

val. The most prominent of these are the Guttenberg Isotope Carbon Excursion (GICE) and the Hirnantian Isotope Carbon Excursion (HICE), both of which having an apparently global distribution.

The GICE occurs in the uppermost portion of the *Amorphognathus tvaerensis* Zone in the upper Skagen Limestone and lower Moldå Formation at Fjäcka as well as in the Kullsberg Limestone at Amtjärn and Skålberget (Bergström et al. 2004b, in press). It is also well documented from the upper Keila – Oandu interval in the East Baltic (see, for instance, Kaljo et al. 2004, 2007). This excursion is widely recognized in the coeval interval in the lower–middle Chatfieldian Stage in North America (Ludvigson et al. 2004, Young et al. 2005, Bergström et al. in press, Barta et al. submitted) and it is quite useful for detailed trans-Atlantic correlations (Bergström et al. 2004b, in press).

An even more prominent positive $\delta^{13}C$ excursion is the HICE, which occurs in the lower–middle Hirnantian Stage and has a global distribution. This excursion, which is well known from Estonia, Norway, Scotland, China, and North America has recently been investigated in the Boda Limestone at Osmundsberget, where it occupies an approximately 25 m thick interval in the uppermost Boda Limestone (Schmitz & Bergström 2007). The HICE has been widely recognized in North America, for instance, on Anticosti island, Quebec, in southern Ontario (Bergström et al. 2007), north-eastern Illinois and eastern Iowa (Kleffner et al. 2005), south-eastern Missouri and south-western Illinois (Bergström et al. 2006a), central Nevada (Finney et al. 1999), and the Canadian Arctic (Melchin et al. 2003). Being located in strata corresponding to the *N. extraordinarius* and lower *N. persculptus* Graptolite Zones, it is of major importance for trans-Atlantic correlations of that stratigraphic interval.

Between the GICE and the HICE there are at least four additional positive $\delta^{13}C$ excursions. They were first recognized in Estonia (Kaljo et al. 2004) and recent work (Bergström et al. 2007) has proved the presence of four, apparently coeval, positive $\delta^{13}C$ excursions in the Cincinnatian Series (North American Upper Ordovician) standard section in Ohio and adjacent states. Hence, these excursions have great potential for not only regional Baltoscandian but also trans-Atlantic detailed correlations. None of the latter four excursions has yet been recognized in the Siljan region but their expected stratigraphic positions are shown in Fig. 5. It is important to note that these $\delta^{13}C$ excursions occur in a variety of sediment types and accordingly, they do not seem to exhibit the same problems with environmental distribution control as many fossils. The $\delta^{13}C$ work so far carried out in the Siljan region has yielded exciting results and I plan to expand the previous work to include the Slandrom Limestone–Jonstorp Formation interval using conodont samples from Fjäcka and Amtjärn.

Concluding remarks

The Ordovician conodont succession in the Siljan region must be considered one of the most important in the world, especially as far as the upper Darriwilian and Katian intervals are concerned. Perhaps mainly due to lack of extensive outcrops of parts of the Darriwilian Stage and the clastic nature of the Tremadocian Stage, there are, however, some gaps in the known conodont succession in the Siljan region. Fortunately, these gaps are, or can be, filled by studies in the available cratonic carbonate section elsewhere in Sweden.

Ordovician of the Storsjön Area

Linda M. Wickström

Previous work

The Ordovocian geology of the Storsjön area has been studied since the 1870's. A majority of the earlier studies were undertaken in the 1930's and 1940's by the Geological Survey of Sweden (SGU) in connection to different mapping and exploration projects. Later studies have focused on faunal evolution and understanding of the geological development in a few areas. Examples of published studies are Linnarsson (1875), Wiman (1893), Hadding (1912), Asklund & Thorslund (1934), Thorslund & Asklund (1935), Thorslund (1937, 1940, 1943, 1948), Asklund (1938), Larsson (1973) and Löfgren (1978). More recent studies include Sturkell (1991), Karis (1991), Löfgren (1993), Cherns & Karis (1995), Lindström et al. (1996), Zhang & Sturkell (1998), Karis (1998), Karis & Strömberg (1998), Månsson (1998, 2000a, b), Pålsson (2001), Pålsson et al. (2001), Rasmussen (2001), Dahlqvist (2004), Dahlqvist & Calner (2004), Dahlqvist et al. (2006) and Heuwinkel & Lindström (2007). There are several excursion guides of the area e.g. Asklund (1960), Thorslund (1960), Gee & Kumpulainen (1980) and Karis (1982), serving as comprehensive compilations of the regional geology. The Geological Survey of Sweden has published both regional and local bedrock maps covering the area. The regional map (1:250 000) was published in 1984 and covers the county of Jämtland, however, the associated detailed description was not published until 1998 (Karis & Strömberg). There are also recently published bedrock maps in local scale (1:50 000) of the Storsjön area (Karis & Kero 2002a, b, Lundqvist et al. 2003, Wickström 2006).

Geological setting

A majority of the Ordovician sediments in the central part of Sweden have been deposited in a foreland basin formed in connection to the Caledonian orogeny. The Caledonian orogeny has affected the depositional patterns of the sediments in the area and presumably also the faunal distribution. However, to what extent the faunas were affected is still not very well known. Ordovician strata (e.g. Slätdal Limestone) has also been identified in the Björkvattnet–Virisen area in the county of Västerbotten (Kulling 1933, Neuman 1969b). Because these strata are found in the Köli nappe, preservation status of sediments and fossils is varied. The palaegeographical relation of this area to the Storsjön area is interesting but poorly known. Situated on the edge of Baltica, Jämtland is an important area in order to understand the evolution of Baltica, the development of the Caledonian orogeny and the palaeogeography of the Iapetus Ocean.

The lithological units of the Storsjön area can be found in either the Autochthon or Lower Allochthon, the two lowermost tectonostratigraphical units of the Swedish Caledonides. Herein, we follow Karis (1998), and terms such as autochthon refer only to the tectonostratigraphical units of the Caledonides. Autochthoneous Palaeozoic sediments are present along the entire Caledonian margin and so also in the Storsjön area. However, most of the Palaeozoic sediments in Jämtland belong to the Lower Allochton.

The degree of metamorphism have been studied by Kisch (1980; illite crystallinity and vitrinite), Löfgren (1978; CAI, i.e. Conodont Alteration Index) and Bergström (1980; CAI). Kisch divided the area around Storsjön into four zones, based on an increase in illite-crystallinity. CAI values in the autochthon has been identified to range between 3 and 5, whereas in the Lower Allochthon, CAI values of 5 have been identified, indicating a temperature of above +300°C, following the scale in Epstein et al. (1977).

The sediments in the Autochthon and their fossil content are in general well preserved. Regarding the Lower Allochthon, preservation status is heavily dependent on the local structural geology, but is still rather good. Two of the fieldtrip localities are situated within the Autochthon, (the Lockne impact crater and the quarry in Brunflo) and two are situated within the Lower allochthon, (i.e. Rannåsen and Kälom; Fig. 11)

The sediments deposited in the Storsjön area are, based on differences in palaeoenvironment, divided into 'platform facies' and 'ramp facies'. Platform facies is dominated by limestones and mudstones with interfingering shales in the west (Karis 1998) and it has been correlated to the central confacies belt of Jaanusson. Platform facies sediment is found along the easternmost part of the Caledonian front and was deposited from the Floian to the upper Katian. In central Jämtland, it has, for instance, been identified in Åsarna, Lockne and Brunflo (Fig. 12). The Brunflo area is known to have the most complete stratigraphic sections of platform facies, including a known stratigraphic gap covering the lower Sandbian (Karis 1998). The following Ordovician lithological units have been identified in platform facies; i.e. Latorp Limestone, Töyen Shale, Lanna Limestone, Holen Limestone, Segerstad Limestone, Skärlöv Limestone, Seby Limestone, Folkeslunda Limestone, Furudal Limestone, Loftarsten, Lockne Breccia, Tandsbyn Breccia, Ynntjärns Breccia, Dalby Limestone, Örå Shale, Slandrom Limestone and Fjäcka Shale. The stops in Brunflo and Lockne will both display platform facies.

Ramp facies is more widely spread and covers a larger area than platform facies. It has for instance been found on the islands in Storsjön, near Östersund, Föllinge, Häggenås and Alsen/Offerdal (Fig. 12). Ramp facies sediments in Jämtland are dominated by greywackes, limestones, black shales to clastic sediments com-

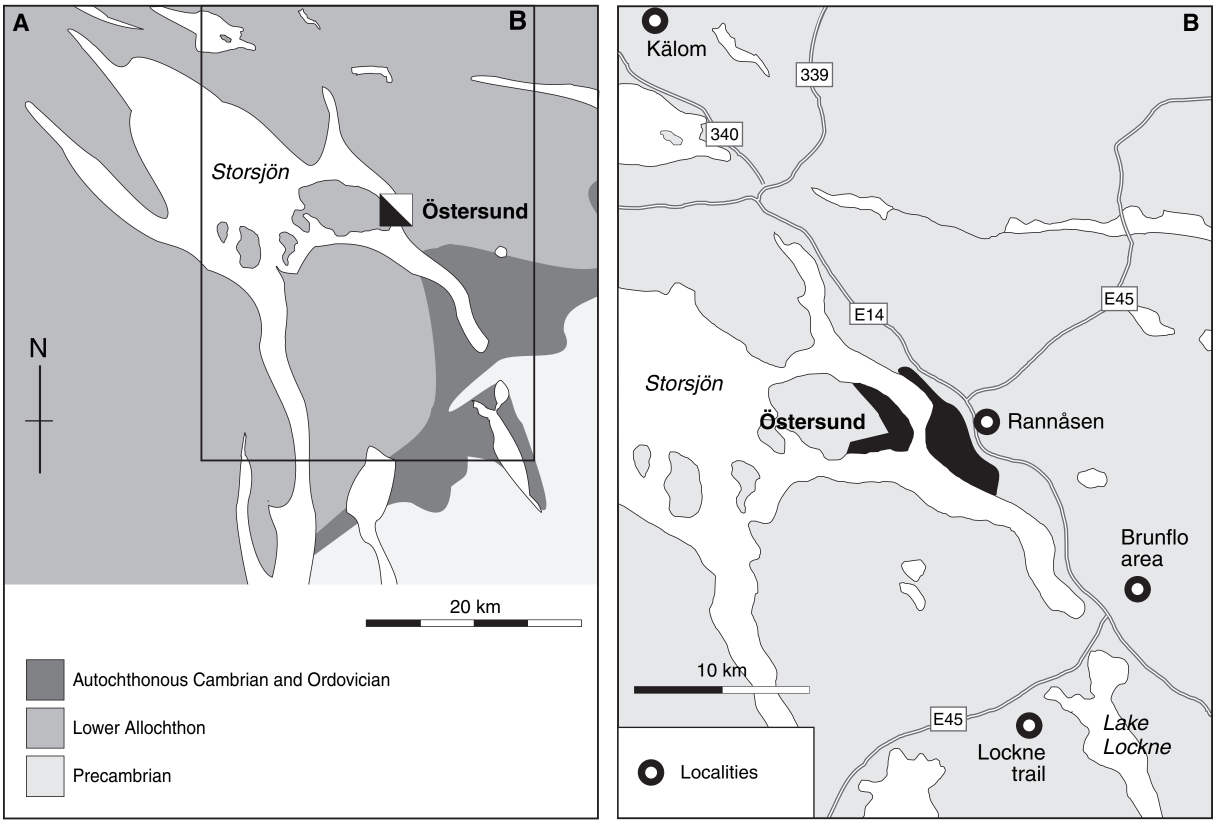

Fig. 11. Generalized map with major geological features of the Storsjön Area (A)- Two of the fieldtrip localities are situated within the Autochton, (the Lockne impact crater and the quarry in Brunflo) and two are situated within the Lower allochton, (i.e. Rannåsen and Kälom; Fig. 11B). Map prepared by J.O.R. Ebbestad.

posed of sand and coarse silt. A majority of the sediments are turbidite sequences of the Middle Ordovician Föllinge Formation. Ordovician ramp facies sediments are known to have been deposited from the Floian throughout the Ordovician and they have been correlated to the Oslo region (e.g. Rasmussen 2001). The Following Ordovician lithological units in Jämtland have been deposited in ramp facies, i.e. Latorp Limestone, Töyen Shale, Isön Limestone (Stein Formation), Föllinge Formation, Andersön Formation, Dalby Limestone, Örå Shale, Furulund Limestone, Slandrom Limestone, Fjäcka Formation, Kogsta Siltstone Formation, Ede Quartzite Formation and Kyrkås Formation. The stops at Rannåsen and Kälom are both characterised by sediments of ramp facies sedimentation.

Faunas

Relatively few detailed studies have been undertaken of the Ordovician faunas in Jämtland, considering the space in time that is represented and the geographical distribution of the sediments. Published studies include conodonts (e.g. Bergström 1971, Löfgren 1978, 1993, Sturkell 1991, Zhang & Sturkell 1998, Rasmussen 2001, Pålsson et al. 2001), trilobites (e.g. Linnarsson 1875, Thorslund 1940, Owen 1987, Nikolaisen 1991, Ahlberg 1995, Månsson 1998 and Pålsson et al. 2001), graptolites (Cooper & Lindholm 1990, Pålsson et al. 2001), hyoliths (Holm 1893, Malinky 2002), ostracodes (Thorslund 1940), brachiopods (Dahlqvist et al. 2007), medusoids (Cherns 1994), cephalopods (Reyment 1970, Chen & Lindström 1991) and chitinozoans (Grahn & Nõlvak 1993).

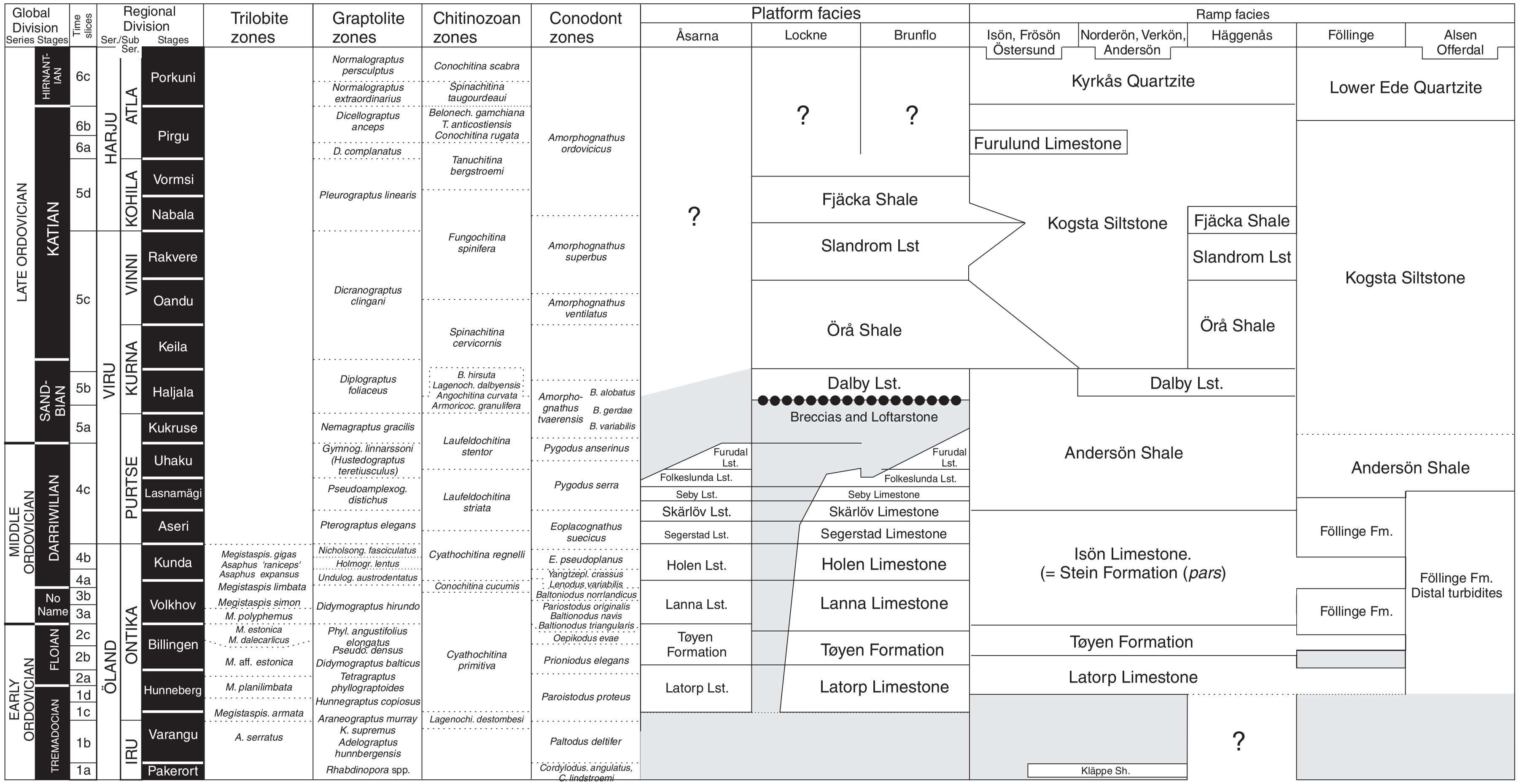

Fig. 12. Correlation chart for the Ordovician of the Storsjön Area, including zonation with the international standard, times slices, and stage names (Webby et al. 2004, Bergström et al. 2006b). See Fig. 3 and Rasmussen & Bruton (1994) for details on regional zonation. The differentiation between platform facies and ramp facies is included (modified by J.O.R. Ebbestad from Karis 1998).

The Lockne crater

Maurits Lindström

The 7–7.5 km large impact crater at Lockne forms the low agricultural ground about the northern end of the lake Locknesjön (Fig. 13). It is dated by the youngest deposits before and the oldest deposits after the impact, which in both cases belong to the conodont Subzone of *Baltoniodus gerdae* (Simon 1987) and the chitinozoan zone of *Lagenochitina? dalbyensis* (Grahn & Nölvak 1993). The age is thus early Sandbian.

The impact occurred on the eastern slope of the Caledonian foretrough (Heuwinkel & Lindström 2007), at a mathematically modeled water-depth of about 500–700 m (Shuvalov et al. 2005). The impact-related rocks of the area have been known for about a century (Wiman 1899). However, they were initially interpreted as products of erosion of a rocky terrain that was exposed in an archipelago. The islets could be identified as granitic hills in the modern landscape and were surrounded by more or less coarsely clastic shoreline deposits (Thorslund 1940). Not least owing to Thorslund's detailed and accurate descriptions of the stratigraphy and structures of the area, this interpretation was generally accepted as a cornerstone of the reconstructed Ordovician palaeogeography of Scandinavia.

Thorslund recognized three principal lithologies that are now known to be impact-related. One of them is a greywacke-like arenite that he made known under its old (Cronstedt 1763) local name loftarsten, Anglicized *loftarstone*. Another consists of more or less coarse breccia of diverse composition, but frequently with the same lithological components as the grain population of the loftarstone. Thorslund referred to all of these breccias as *loftarstone conglomerate* or Chasmops conglomerate. The third of the lithologies consists of all sizes of fragments of the local crystalline basement, held together by a strongly silicified matrix. The term coined for it by Thorslund was *arkose-like breccia*. It was interpreted as the residue after sub-aerial weathering of the basement. It capped the islets and was itself overlain by loftarstone conglomerate and loftarstone.

Thorslund's interpretation of the loftarstone and loftarstone conglomerate as littoral deposits contradicted Hadding (1927), who believed that these clastics formed on the sea-bed in connection with tectonically released sediment movements and independently of any shoreline. Hadding's interpretation was based principally on the abundance of angular clasts, rather than rounded ones, and their non-weathered nature.

It was, indeed, possible to question Thorslund's archipelago model based on the assumption that his described observations were accurate – which they were; they still provide some of the best material for the interpretation of the area. His loftarstone conglomerate was much too poorly sorted and contained too many huge, angular clasts to be at all likely as a shoreline deposit in the very shallow waters of his archipelago.

The loftarstone itself was remarkable for its thick, mostly non-laminated and massive bedding, the structure of which included grading. The crystalline cores of the islets were only visible at the level of the lower Sandbian; nowhere was the Middle Cambrian or pre-Sandbian Ordovician of the area found to be abutting against cliffs of crystalline basement. Every mapped contact between the lowermost Palaeozoic and the underlying crystalline basement showed an exceptionally flat and smooth peneplane that cut the pre-Cambrian structures.

For these reasons Lindström et al. (1983) published an interpretation of the area which was, in effect, a revival of Hadding's (1927) ideas. According to this interpretation Thorslund's loftarstone conglomerate was a debris flow deposit, formed in a considerably deeper water than Thorslund's archipelago. The loftarstone was suggested to be a turbidite that followed upon the debris flow(s), and the more or less brecciated crystalline rock that formed Thorslund's islets was suggested to be large olistoliths in the debris flow(s). This interpretation was presented at the excursion in connection with the first WOGOGOB meeting in Östersund 1987. By then, it had been further elaborated in the doctoral thesis of Simon (1987), who made a special point of the circumstance that the crystalline rock fragments in Thorslund's arkose-like breccia looked crushed, not weathered. He left the origin of the crushing an explicit mystery.

The WOGOGOB 1987 excursion was attended by Frans Erik Wickman, who had concluded from carefully reading Simon's thesis that the debated lithologies at Lockne were related to a major impact. He postulated, however, that this impact centered as far away as Frösön (Wickman 1988), which made his impact crater possibly the largest in Europe, with a diameter of 65 km. Because the geological evidence in the region

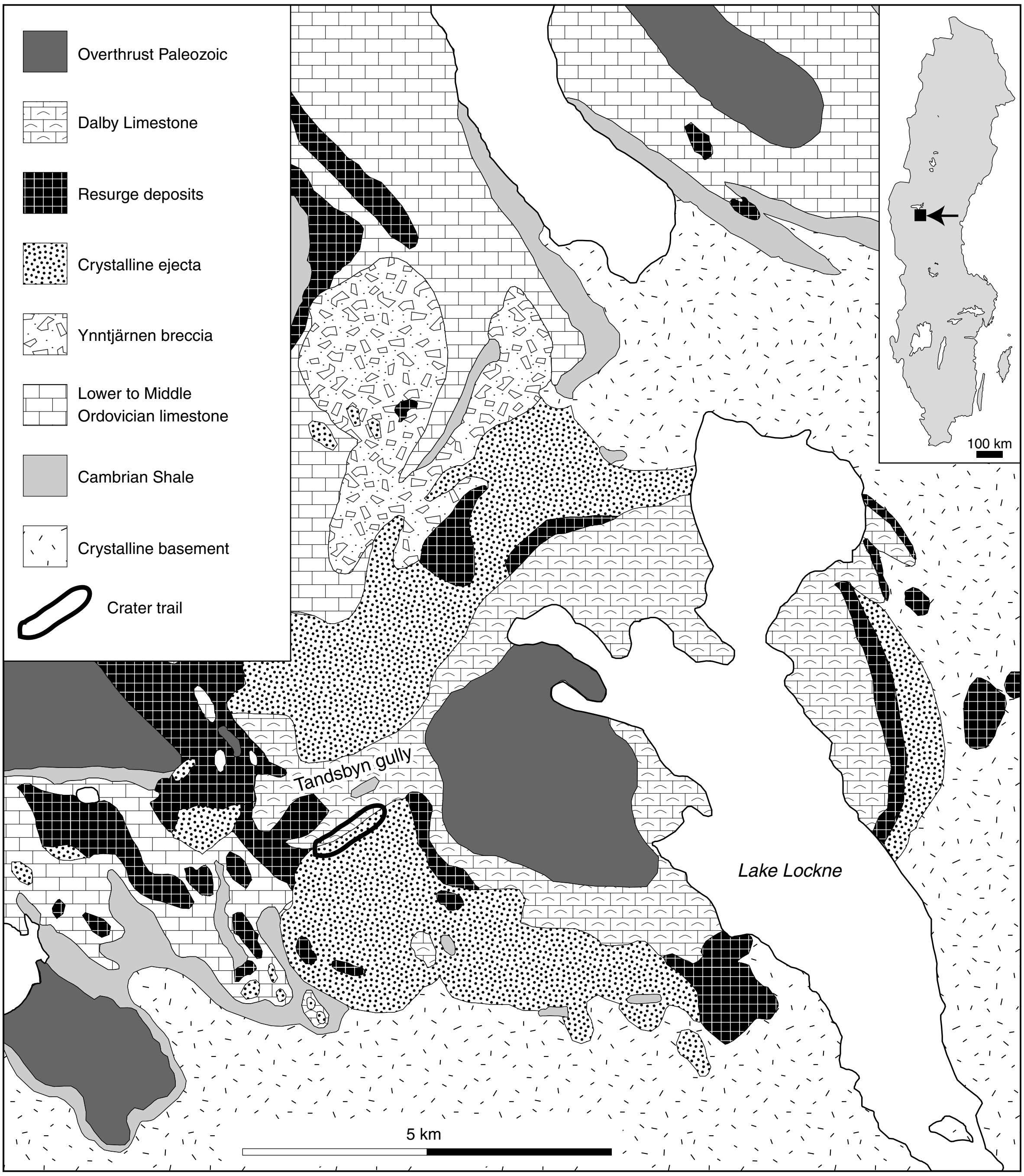

Fig. 13. Geological map of the Lockne area outling the impact facies and the succeding Dalby facies.

is strictly against an impact of this size in the Phanerozoic, this circumstanc caused a minor delay of the acceptance of the impact hypothesis for Lockne.

The three things that soon enough made the Lockne impact crater stand out as a reality were that its existence provided a unique explanation for the intense crushing found in Thorslund's arkose-like breccia, that this breccia had a concentric occurrence about a sub-circular topographic low around the northern end of Locknesjön, and that a roughly 7 km wide crater would fit precisely into the geological structure of the area if situated in this low ground.

The distribution of the arkose-like breccia about the Lockne crater indicated that much of it was ejected from the crater. The only Palaeozoic rock identified beneath such ejecta was black, bituminous ”Alum” shale of apparently Middle Cambrian age (Lindström et al. 1991, 2005a). Because the identification of the crater did not lead to the immediate realization that the mid-Ordovician loftarstone conglomerate and loftarstone (explained as debris flow and turbidite and as such possibly related to Caledonian tectonism in agreement with Hadding 1927) were related to the cratering event, the Middle Cambrian beneath the ejecta was taken as indicative of the age of the crater (Lindström et al. 1991).

However, when in 1991 a considerable thickness of rocks precisely corresponding to the loftarstone and loftarstone conglomerate was brought to light in a drillcore from the roughly coeval Tvären crater (Lindström et al. 1994) their connection with the cratering could no longer be overlooked. The concept of resurge was coined, and the loftarstone and its associated ”conglomerate” were recognized as the resurge deposits of the Lockne impact, which therefore must be mid-Ordovician (Lindström & Sturkell 1992, Lindström et al. 1996).

In the meantime the rock units under discussion had to be redefined and renamed. The name Loftarstone (Swedish: loftarsten) has hitherto been kept in use for the greywacke-like resurge arenite, and it appears reasonable to do so even in the future. Thorslund's loftarstone conglomerate was first renamed Lockne Conglomerate (Larsson 1973) and thereafter Lockne Breccia (Lindström et al. 1983). The last-mentioned name was intially used for all breccias with Lower to Middle Ordovician clasts that occur in the area. However, Hadding (1927) realized that there are two different breccias, with different modes of origin, for which this generalization holds, one of which he called Loftarstone Conglomerate, the term later adopted by Thorslund, whereas the other was called *Orthoceras* limestone Conglomerate. The last-mentioned contained only clasts of the local limestone, whereas the Loftarstone Conglomerate contained abundant crystalline clasts in addition to the limestones.

According to Lindström et al. (2005a) the name Lockne Breccia should apply to the polymictic clast deposit that includes more or less abundant fragments of crystalline rock. Hadding's (1927) *Orthoceras* limestone Conglomerate should be called Ynntjärnen Breccia. It is characterized as a monomictic limestone breccia with a marly matrix and consisting of clasts derived from immediately adjacent limestone beds. It mostly lacks crystalline clasts but occasionally contains a few of them. It apparently formed while cratering was still going on, and before the resurge. Thorslund's arkose-like breccia was renamed Tandsbyn Breccia (Lindström & Sturkell 1992).

The geometry of the crater and the ejecta distribution indicate that the impactor came obliquely from the east, with a likely inclination of about 45° (Lindström et al. 2005b; Fig. 14A). Therefore, the ejecta spread mostly westwards, toward the Caledonian foretrough. Immediately after touchdown there developed a water crater that grew to an ultimate diameter of about 10 km (Fig. 14B). Most of the 80 m thick Cambrian and Ordovician sediments were swept away from the area covered by the water crater. This crater was surrounded by an over 1 km high rim wall of water. The central crater, excavated into the basement bedrock, was near to its ultimate width of 7 km and nearly 2 km deep when excavation culminated (Shuvalov et al. 2005), after which it equilibrated at somewhat over 7 km width and a depth of over 200 m but definitely less than 400 m. (Fig. 14C–E) The basement ejecta formed a 1–2.5 km wide and well over 50 m thick brim round the central crater, except in the easternmost sector, where the brim is practically absent. After downcutting by Caledonian overthrusting and later erosion, the thickness of the reamainder of the brim commonly reaches about 50 m but probably not more than this.

Isolated cobble-sized ejecta reached as far as 40 km southwest of Lockne (Sturkell et al. 2000). Ejecta clasts weighing about 500–1000 kg have been observed at Torvalla 16 km northwest of the center of the Lockne crater. Because clasts of this mass are unexpected even at smaller distances from the crater than this, this occurrence could not have been farther from Lockne at the time of the impact than it is now. Therefore the Torvalla outcrop cannot belong to the overthrust terrain but must be essentially autochthonous. Other outcrops with ejecta clasts of the order of a thousand kilograms occur at localities 9–11 km north of the impact center (Lindström et al. 2005b). West of the central crater there are large bodies of ejected Tandsbyn Breccia for instance at 6 km (at least 10^7 m^3) and 9 km (at least 5000 m^3) from the center of the crater.

Assuming an east–west trajectory of the impactor, the main spread of ejecta should have been in the north, northwest, southwest, and south sectors, with relatively little in the east and a focal downrange minimum about west (Lindström et al. 2005b). The western minimum corresponds to the location of the excursion target at the so-called Tandsbyn Gully (Lindström et al. 1996).

The excavation and ejection stage of cratering was accompanied by forceful outward flow of water that culminated at 130 m/s 10 s after impact touchdown 5 km from the touchdown point and 40 m/s 30 s after touchdown at 7 km from the touchdown point (Shuvalov et al. 2005). This flow was not only capable of eroding clasts over 10 m in diameter, but of causing vibrating normal and shearing stresses in the substrate through which the underlying orthoceratite limestone could be broken up into Ynntjärnen Breccia (Fig. 14B).

After about 40 s the outward flow was replaced by inward flow reaching respectively 100 m/s and 30 m/s at the mentioned distances from the touchdown point. Thus began the first stage of the resurge that is called resurge proper (Ormö et al. in press). It culminated in the rise of an over 1 km high water mountain where the flow converged at the center of the crater (Fig. 14C). The collapse of this water mountain caused an anti-resurge that was directed outward and was mostly felt inside the central crater (Fig. 14D).

The resurge proper was destructive in the vicinity of the central crater and left mainly coarse deposits within it, and the anti-resurge had its strongest effects within it. However, the last resurge stage, termed oscillating resurge (Fig. 14E), was reduced to velocities that permitted deposition of clast sizes decreasing from cobbles to silt outside the central crater as well as within it. The resulting deposits will be studied at the Crater trail along the south flank of the Tandsbyn Gully.

Secular deposition in the cratered area was diversified owing to the variety of sea-bed that had been created by the event. The Crater trail is an excellent site for the study of some of this diversity.

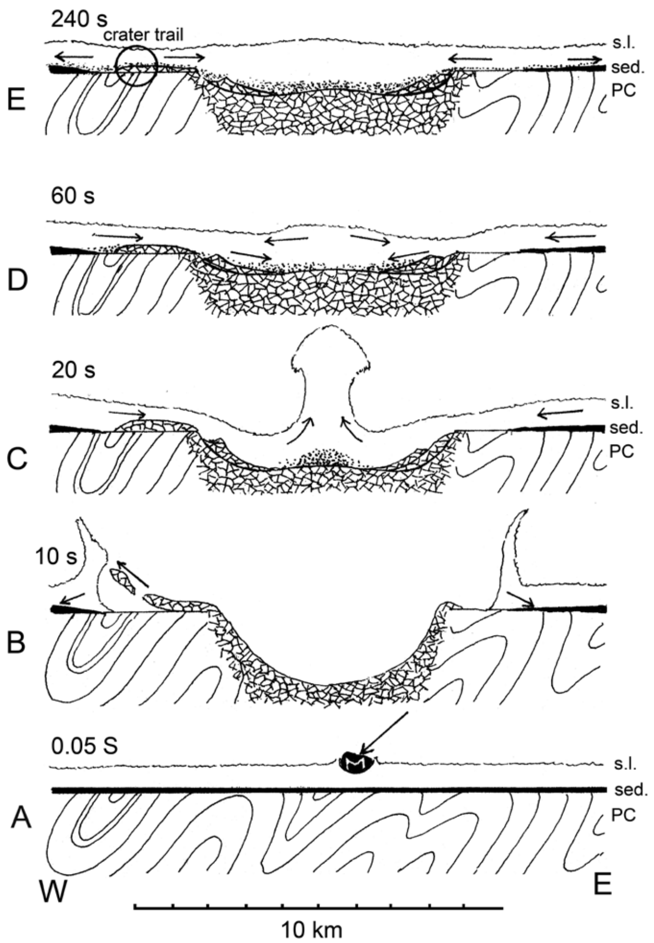

Fig. 14. Successive stages of the cratering at Lockne, sketched in east-west sections. The vertical and horizontal scales are roughly identical. The crystalline basement (indicated by PC at the right margin) is symbolized by a fold pattern in order to bring out the sub-Cambrian unconformity. Cambrian and Ordovician sedimentary rocks (sed. at the right margin) are shown in black. The surface of the sea-water (s.l. at the right margin) is indicated by a finely crinkled line. The Tandsbyn Breccia and crystalline ejecta are shown by breccia signature. Resurge deposits are indicated by stipple pattern over the sea-bed. M = the impactor. 14A shows the situation just after touchdown on the surface of the sea. 14B shows the culmination of crater excavation, with the basement crater inside a considerably wider water crater. The stress exerted by the high-velocity expulsion of water on the surrounding Palaeozoic limestone is indicated by oblique arrows. It decomposes the limestone into monomictic Ynntjärnen Breccia. 14C shows the resurge proper that is too forceful to deposit sediment outside the crater but may deposit coarse sediment under the central plume of water that forms where the resurge converges. 14D shows the current system and beginning sedimentation after collapse of the central plume. 14E shows the oscillating resurge that probably deposited most of the gravel to silt grade sediments of the resurge that are known as Loftarstone.

Stratigraphic succession

Linda M. Wickström, Åsa M. Frisk & Maurits Lindström

Loftarstone

Other terms: Loftarsten (Cronstedt 1763).

Type area: The area in and surrounding the Lockne crater, Jämtland.

Main lithology: The mostly well-sorted, arenitic Loftarstone is built up by material originating from Orthoceratite Limestone (with fossil fragments), crystalline basement, Cambrian claystone, and melts particles (Lindström et al. 1996, Lindström et al. 2005a). The Loftarstone represents the last stage of the resurge after the impact. The grain size ranges from coarse sand to silt. Compared to the resurge sediments of the Lockne Breccia the Loftarstone has smaller grain size and also has more material deriving from the deepest excavated part of the crater. Only in the Loftarstone quartz with PDF, particles of melt rock, and anomalous concentration of iridium have been found (Therriault & Lindström 1995, Simon 1987, Sturkell 1998). At Hällnäset dewatering structures are evident in the Loftarstone.

Thickness variation: Four boreholes from the inner crater indicate that the Loftarstone has a thickness of at least 47 m in the inner crater (Lindström et al. 1996, Lindström et al. 2005a). In the outer crater the thickness is only a few metres, apart from the resurge gullies.

Discussion: The boundary to underlying Lockne Breccia is either sharp and erosional, or gradual in a fining upward sequence. Its distribution is restricted to the area in and around the Lockne crater, Jämtland. The Loftarstone is often succeeded by the Dalby Limestone. It lacks macrofossils.

Lockne Breccia

Earlier terms: Loftarstone Conglomerate (Thorslund 1940), *Chasmops* Conglomerate (Thorslund 1940), and Lockne Conglomerate (Larsson 1973).

Type area: The area in and surrounding the Lockne crater, Jämtland.

Main lithology: The Lockne Breccia (Lindström et al. 1983) is a polymictic sedimentary breccia that was deposited primarily by resurge. The clasts range in size from sub-millimetres to hundreds of cubic meters. The dominant clasts are local Ordovician limestone, but crystalline ejecta clasts are very common and Cambrian mudstone and limestone are represented in several outcrops (Lindström et al. 2005a). The typical, resurge deposited Lockne Breccia tends to be clast-supported, rather than matrix-dominated, and moderately sorted. A widely distributed variety is matrix-supported and poorly sorted. This should probably be defined as a separate unit, because it was deposited before the typical lithology and was not water-laid. Bedding is absent in both varieties. The better sorted, typical Lockne Breccia often shows a gradual transition into the overlying Loftarstone.

Thickness variation: In the centre of the Lockne crater the Lockne Breccia (sensu lato) is more than 155 m thick, strongly thinning outwards.

Discussion: The Lockne Breccia (sensu lato) rests on monomictic Tandsbyn Breccia in the inner crater of Lockne (Lindström et al. 2005a), otherwise it can overlay Orthoceratite Limestone or Ynntjärnen Breccia. Within the Lockne Breccia large clasts of Ynntjärnen Breccia can be present, with volumes over 100 m^3 (for example west of the church of Brunflo; Lindström et al. 2005a).

Tandsbyn Breccia

Earlier terms: Arkose-like breccia (Thorslund 1940) and Lockne Breccia (Lindström et al. 1983).

Type area: The area in and surrounding the Lockne crater, Jämtland.

Main lithology: The monomictic Tandsbyn Breccia (Lindström & Sturkell 1992) consists of crystalline basement rock, mostly granitic, that is crushed to varying degree, from intensely penetrative to moderate. It occurs extensively as ejecta outside the central crater and massively as lowermost filling of the central crater. A finer version of the Tandsbyn Breccia is regularly found with a sharp contact with the coarser sandy-gravelly version. The finer Tandsbyn Breccia is also found as angular fragments in the coarser version (Ormö & Lindström 2006).

Thickness variation: Not over 50 m outside the central crater, over 100 m inside the central crater.

Discussion: Ejected sheets and isolated bodies of Tandsbyn Breccia (with volumes even much exceeding 10,000 m^3) are in places overlying Orthoceratite Limestone and the Ynntjärnen Breccia. Outside the crater brim bodies of Tandsbyn Breccia at distances of 6–9 km from the centre of the crater (Lindström et al. 2005a).

Ynntjärnen Breccia

Earlier terms: *Orthoceras* limestone Conglomerate (Hadding 1927) and Lockne Breccia (Lindström et al. 1983).

Type area: The area in and surrounding the Lockne crater, Jämtland.

Main lithology: The Ynntjärnen Breccia (Lindström et al. 2005a) consists of pre-impact Ordovician beds (Orthoceratite Limestone) that were relatively argillaceous with nodules and beds of limestone, that were shaken up and disintegrated into a breccia after the formation of the water crater. The clast sizes vary in the breccia from a few millimetres to over $100m^3$. The principal feature of this breccia, compared to the Lockne Breccia, is that it is monomictic with respect to the local lithology of Orthoceratite Limestone, whereas totally disparate members of the Orthoceratite Limestone succession occur as clasts in any outcrop of Lockne Breccia. Also, clasts of crystalline ejecta are either rare or absent in the Ynntjärnen Breccia. Detachment of limestone clasts that were being incorporated into the breccia occur frequently (Ormö & Lindström 2006).

Thickness variation: 0–6 m

Discussion: The Ynntjärnen Breccia is situated at successively lower stratigraphic levels in the direction of the crater (Ormö & Lindström 2006). In some localities the Ynntjärnen Breccia is overlain by ejected Tandsbyn Breccia and in others by Lockne Breccia. In difference to the Lockne Breccia it has no gradational contact with the Loftarstone (Lindström et al. 2005a). Its principal occurrence is in the west and northwest sectors of the area nearby to the crater. In a large area on both sides of the road between Nyckelberg and Löfsåsen, as well as northwest of Nordanbergsberget, there is Ynntjärnen Breccia overlying Orthoceratite Limestone.

The Brunflo Limestone

Discussion: Is an informal name including all Ordovician limestone units in platform facies recognised from the Brunflo area. It has only been used by the Geological Survey of Sweden for the purpose of mapping in local scale.

Kogsta Siltstone Formation

Type area: The area surrounding the village of Kougsta, Jämtland.

Main lithology: Shaly siltstone interbedded with distal turbidites (Karis 1998).

Thickness variation: Karis (1998) 30–40 m.

Discussion: The lower boundary of the Kogsta Siltstone appears to be diachronous across Jämtland (see Karis 1998). In the type area it succeeds the Föllinge Formation, and the boundary has been determined to the top of the uppermost bed of turbidite deposition of the Föllinge Formation. In the east, the Kogsta Siltstone overlies either the Slandrom Limestone or Örå Shale. Unpublished material from the type area in Alsen has yielded a fauna indicating the *Dicranograptus clingani* biozone regarding the basal part of the formation (Karis 1998) and the upper part of the formation has yielded moulds of a shelly fauna including brachiopods, trilobites and echinoderms, of Hirnantian age (Dalhqvist et al. 2007). In the Östersund area and on the islands in L. Storsjön, a limestone unit (Furulund Limestone) is locally developed within the upper part of the formation.

The Kyrkås Quartsite Formation

Type area: Rannåsen, Jämtland

Main lithology: Mudstone association, Sandstone/mudstone association, Sandstone association (Dahlqvist 2004).

Thickness variation: Karis (1998) 20–40 m. Dahlqvist (2004) at least 90 meters. Due to erosional and tectonic processes, thickness varies locally.

Discussion: In contrast to the Ede quartzite, there is no unconformity between the Kyrkås Quartsite Formation and the underlying Kogsta Siltstone. Biostratigraphical data has confirmed the Late Ordovician age of this formation (Dahlqvist 2004), however, since its upper boundary never has been established, maximum thickness and stratigraphic distribution remains unknown. Recent provenance studies (Dahlqvist et al. 2006) suggests that the sediments are derived from the Hedmark group or the Southwest Scandinavian domain.

The Ede Quartzite Formation

Other terms: Phacops Quartzite.

Type area: Edefors, Jämtland.

Main lithology: Lower part of the unit is composed of quartzitic sandstone beds. The upper part of the unit is composed of a mixed carbonate–silisiclastic association (Dahlqvist & Calner 2004).

Thickness: Maximum 6 m (Cherns & Karis 1995).

Discussion: The Ede Formation can be found in the west to north-western part of the Östersund –Lake Storsjön area. An unconformity marks the boundary between the Ede Quartzite and the underlying Kogsta Siltstone. The Ordocvician–Silurian boundary probably lies within the Ede Quartzite. It is marked by a hiatus, probably comprising the uppermost Hirnantian and Rhuddanian and has been as an unconformity underlying the favositid biostrome (Dahlqvist & Calner 2004). Recent biostratigraphical dating using conodonts has shown that the upper part of the formation was deposited during the Aeronian (Dahlqvist & Bergström 2005).

Locality descriptions, the Siljan District

Jan Ove R. Ebbestad & Anette E.S. Högström

In this section we present descriptions of the localities included in the pre-meeting excursion for the WOGOGOB 2007 meeting in Rättvik (Fig. 15). For details on the stratigraphic overview and conodont zonations see Bergström (2007b) and Ebbestad & Högström (2007a). Grid references are largely from GPS measurements (Garmin e-trex) and the map series used is the 1:50 000 scale topographic series ('gröna kartan').

Stop 1. Amtjärn quarry

Location: Northwest of Rättvik Municipality, toward Nittsjö and Dalhalla, in the forest on the west side of the pond Amtjärn. Topographical map sheet Rättvik 14F SV, UTM coordinates WH 04112 55728, Swedish Grid 58028 60467.

Age: Upper Ordovician (Katian), Viru regional series, Keila and Oandu stages.

Description: An old limestone quarry in the Kullsberg Limestone, which is now a nature preserve (naturminne). Being one of the earliest commercial quarrying sites in the Siljan District, Amtjärn quarry attracted considerable interest among geologists because the contact between the mound and the surrounding "normal facies"

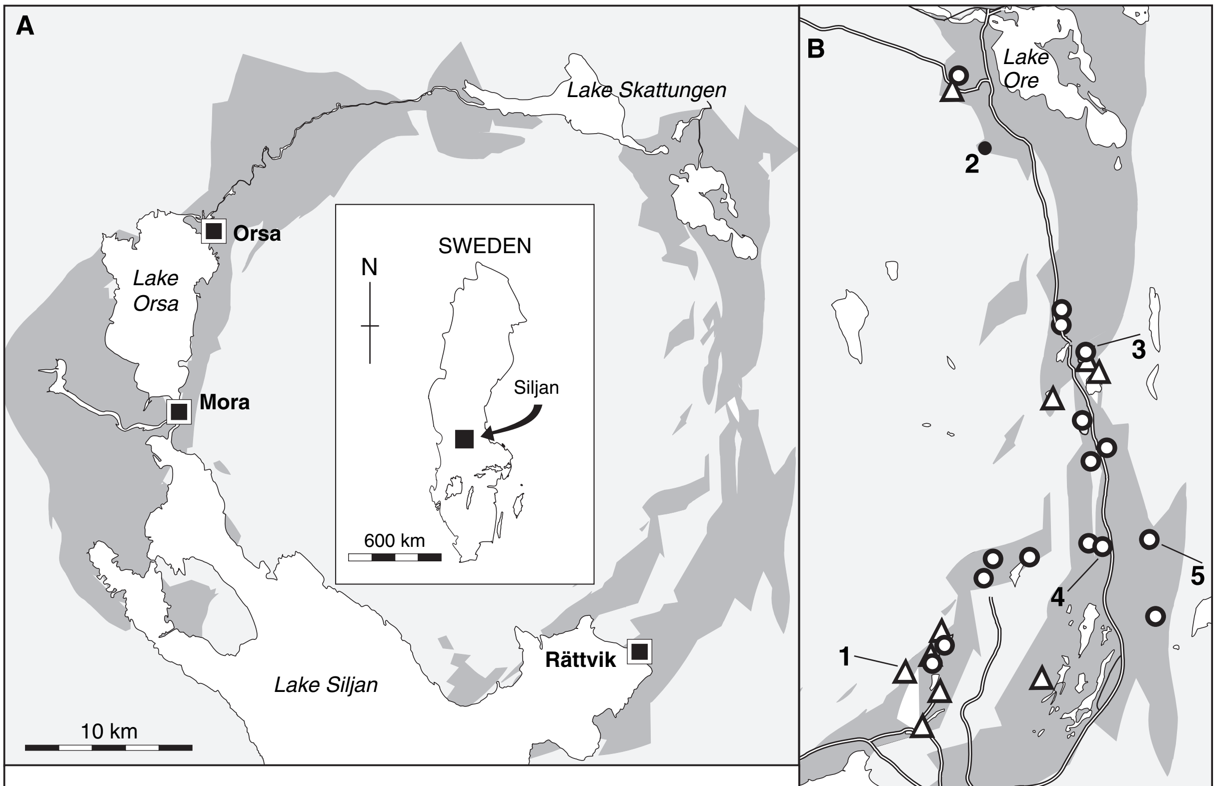

Fig. 15. General geological map of the Siljan ring (A) with localities visited during the pre-meeting field excursion (Fig. 15B).

could be seen (Isberg 1917, Warburg 1925, Hadding 1941, Thorslund 1935, 1936b, Thorslund & Jaanusson 1960). The beds in the quarry dip to the west with an angle of nearly 90 deg.

In the Amtjärn quarry, the beds immediately below the mound limestone are composed of beds with thick (>1–2 cm), sometimes partly articulated, crinoid stems (Fig. 16). These beds were formed *in situ* from colonies of crinoids (Ruhrmann 1971). Smaller sized crinoids probably lived on the flanks of the growing mud mound, and the pelmatozoan limestones forming the flank facies was formed through enrichment caused by current activity and re-sedimentation (Ruhrmann 1971). The larger crinoid type is absent in the flank facies, but in places with less turbulence colonies of cystoids lived (Ruhrmann 1971).

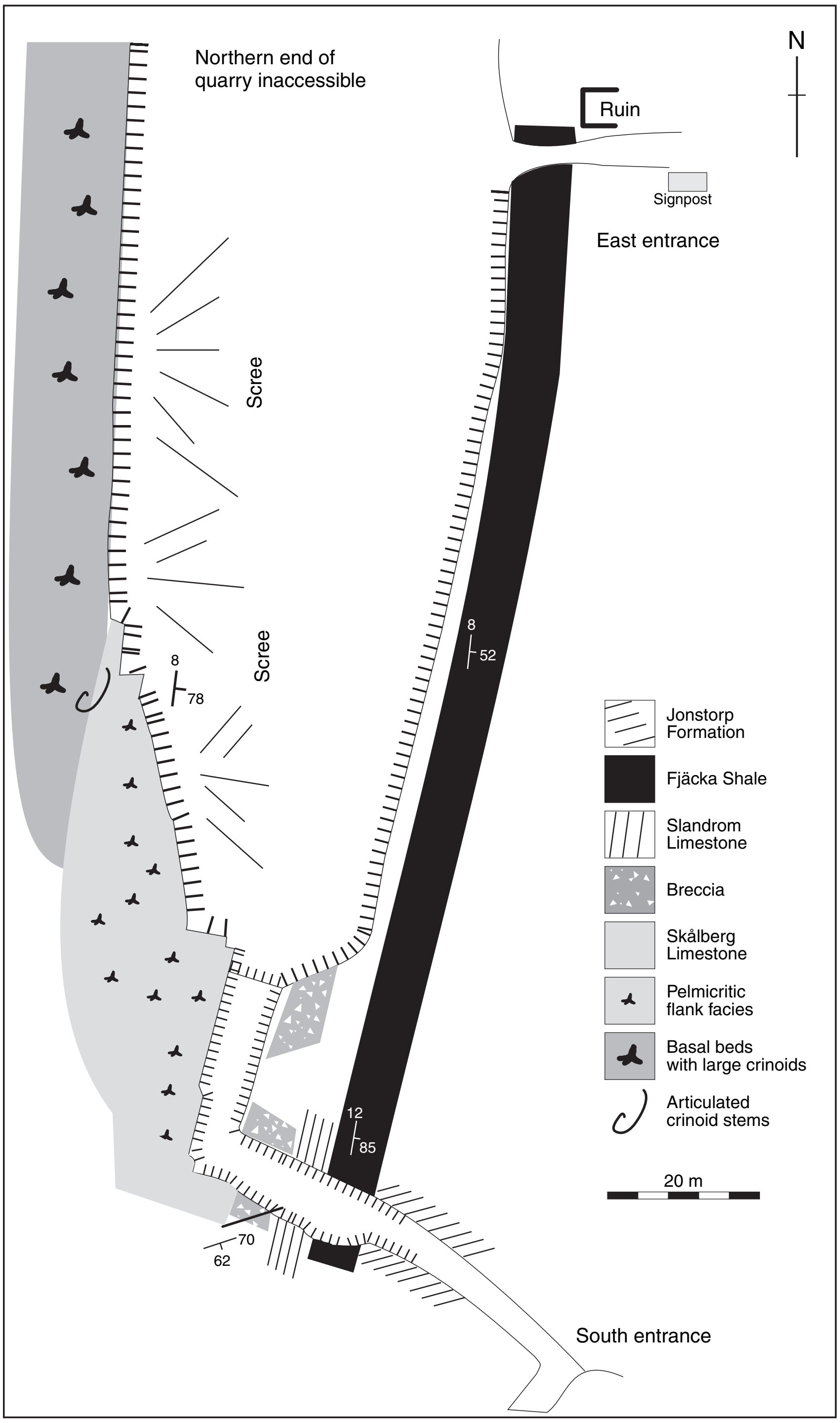

Fig. 16. Map of the southern part of Amtjärn quarry, showing general facies distribution.

Moving laterally along facies, to the south in the quarry, there is a narrow gully going in a south-eastern direction (South entrance in Fig. 16). Here are outcrops from the uppermost part of the Dalby Limestone through the middle part of the Jonstorp Formation (Thorslund 1935, 1936b, Bergström 2007b). The entire section was cleaned for the WOGOGOB 2007 meeting, but the Dalby Limestone is presently not exposed.

The initial beds in the south wall of the gully are pelmicritc limestone attributed to the Skålberg Limestone (Bergström 2007b). A prominent zone with breccia follows, which also can be seen at the entrance of the gulley at the main quarry (see Fig. 16). Bergström (2007b) interpreted this as a slump breccia. The Slandrom Limestone overly the breccia, and is about 3.5 m thick. The overlying Fjäcka Shale is 6.10 m thick, well exposed and appears to be undistorted. Outcrops of the dark shale can be traced over the ridge to the north and can be seen also at the east entrance of the quarry (Fig. 16). Here the thickness was measured to be 6 m by Thorslund (1936b). Above the Fjäcka Shale follows 7.5 m of green and grey beds of mudstone and argillaceous limestone of the Jonstorp Formation.

Stop 2. "Fjäckan"

Location: Section by the Fjäcka rivulet at Moldå, Dalby village, Ore parish, northeastern part of the Siljan district, just west of regional road 301. Topographical map sheet Rättvik 14F NV, UTM coordinates WH 0690 7640, Swedish Grid 7850 6340.

Age: Middle and Upper Ordovician (Sandbian and Katian), Viruan and Harjuan regional series, Uhaku to Pirgu stages.

Description: A nature preserve (naturminne) cut into the bedrock by the Fjäcka rivulet, there is also a small abandoned quarry and traces of old industrial use of the area. These include among others a limekiln and sawmill. First mentioned by Törnquist (1867), the section has been reported continuously thereafter, in 1945–1946 a "complete" section from the upper Furudal to the Jonstorp Formation was exposed by excavations (Jaanusson & Martna 1948), further excavations in 1976 were done for preservation of the section as a nature preserve and geologic site of international interest. The Fjäcka section is the type locality for the Dalby Limestone, the Moldå Formation and the Fjäcka Shale (Jaanusson 1960a, 1963b). Bergström (1971) designated the Fjäcka section as type locality for three North Atlantic conodont zones.

A total of approximately 57 m of partly folded, steeply dipping (50–70°) strata crop out along the small valley where the Furudal, Dalby, Skagen, Moldå, Slandrom, Fjäcka and Jonstorp formations are exposed, whereas the Kullsberg Limestone is missing (Jaanusson & Martna 1948, Jaanusson 1982b, Holmer 1989). Only the upper 5 m of the the Furudal Formation is exposed. The Dalby Formation is 19.9 m thick with a complex of seven bentonite beds, where the thickest is 26 cm, marking the upper boundary. The Skagen, Moldå, and Slandrom limestones are 5.5 m, 5.8 m, and 8.4 m thick respectively. The following Fjäcka Shale is 5.8 m thick. The upper unit exposed is the Jonstorp Formation which is more than 6.5 m thick. Detailed biostratigraphical and geochemical isotope studies (see Ebbestad & Högström 2007a), have demonstrated the remarkable completeness of this part of the Ordovician succession.

Stop 3. Osmundsberget

Location: Non-operational quarry located just off regional road 301 at Osmundsberg, Rättvik Municipality, on the east side of the Siljan ring. Topographical map sheet Rättvik 14F SV, UTM coordinates WH 1070 6840, Swedish Grid: 7040 6730.

Age: Upper Ordovician (Katian), Keila–Oandu regional stages, to the Lower Silurian (Llandovery), Late Aeronian Stage.

Description: The site is owned by Svenska Mineral AB, but no longer quarried. It is one of the largest limestone quarries in the area, exposing both the Kullsberg and Boda limestone mud mounds. These are separated here by a thin unit of transitional facies (Fig. 17). The base of the Kullsberg Limestone is not seen.

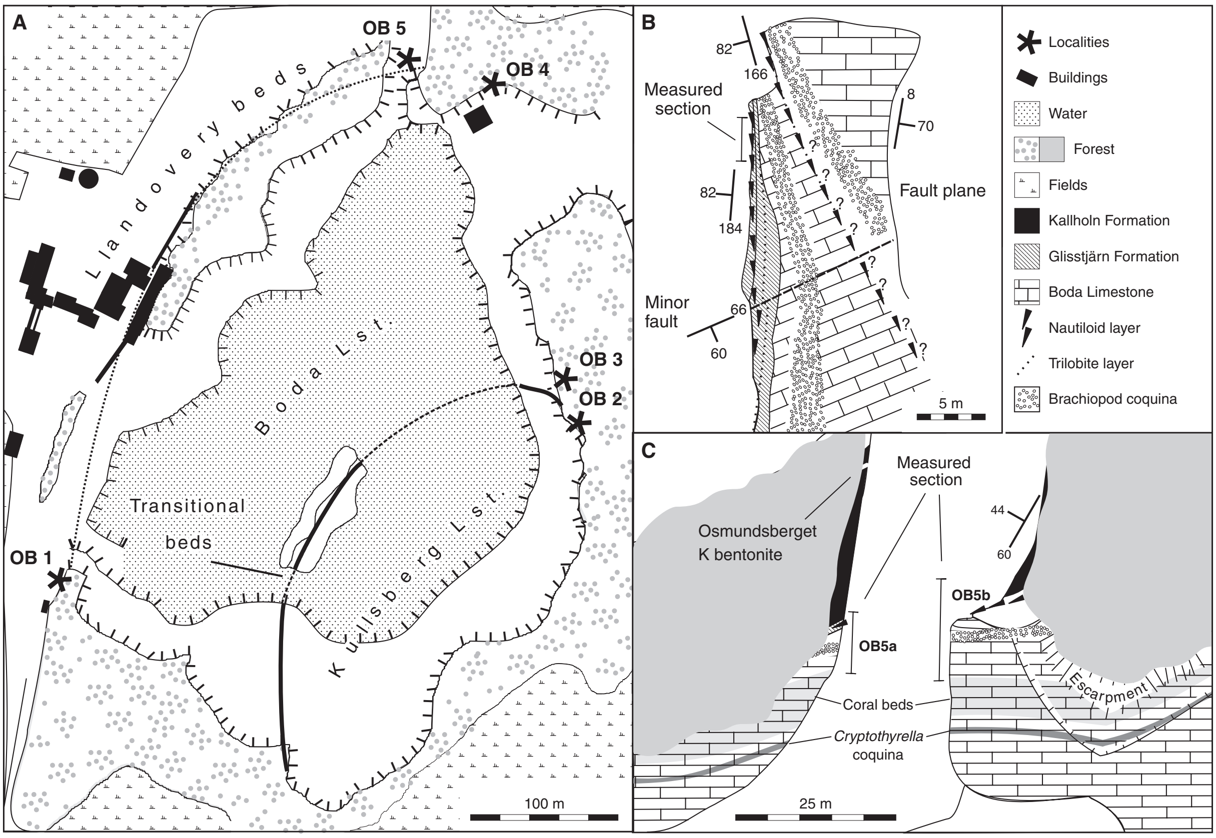

Fig. 17. Map of Osmundsberget quarry (Fig. 17A), showing general facies distribution. Fig. 17B show the O/S section at Osmundsberget 1, while Fig. 17C show the O/S section at Osmundsberget 5 at the northern entrance of the quarry.

Unconformably overlying the Boda Limestone are pelmicritic beds of the Glisstjärn Formation (Hirnantian), followed by black Silurian (Mid-Aeronian) graptolitic shales with carbonate concretions of the Kallholn Formation. The excavated centre of the quarry is an artificial lake used as dump for excess carbonate residues. It is partly filled with gravel at the northern and north-western ends. A broad plateau is leading around the quarry on the east side, while a small islet is sitting in the south central part of the quarry lake, representing sediments of the transitional beds between the mounds.

The beds are steeply dipping (around 65 – 80 degrees) to the west, with several listric normal faults occurring in the carbonate mounds. Maximum width of the Boda Limestone outcrop is about 240 m in a north–south transect while maximum width is about 550 m in a north west southeast transect. Because the present day outcrop represents a cross section through an overturned and tilted oblong body, thickened by a series of normal faults, the original thickness and width would be less. A maximum thickness of 150m is therefore a conservative estimate for the Boda Limestone in this quarry, but structural mapping is needed to elucidate the architecture of the mound body.

Below are some localities of special interest discussed in more detail (see Fig. 17).

Osmundsberget 1

Location: UTM coordinates WH 10654 68128, Swedish Grid 70350 67155.
At the south entrance of the quarry is a 30–35 m long section of steeply dipping beds of massive micritic Boda Limestone overlain with an angular disconformity by thick-bedded pelmicrites of the Glisstjärn Formation. The topography of the Boda Limestone is broadly undulating. A large surface at the north end of the section exposes mass concentration of bi-polarly oriented orthoconic nautiloids (Ebbestad et al. 2007). Two mass

occurrences occur in beds within 10 cm of each other, and these beds can be followed along the section. To the south, where the Glisstjärn Formation is thicker due to the underlying topography, a coquina of disarticulated *Stenopareia* specimens occur 90 cm below the nautiloid beds. The top of the Boda Limestone is at this locality distinguished by a thick series of brachiopod coquinas (Fig. 17B)

Osmundsberget 2

Location: UTM coordinates WH 10979 68295, Swedish Grid 70508 67487.
At this location transition beds between the Kullsberg Limestone to the southeast and the Boda Limestone to the northwest are developed (Fig 17A). Their maximum thickness is about 8–9 m and they are composed of three distinct units. In the middle about 220 cm of the Fjäcka Shale is developed. Above the shale is a 190 cm thick unit of bedded greenish mudstone with thin and thick pelmicritic layers, before the light micritic development of the Boda Limestone starts. Another 4–5 m of mudstone with pelmicritic layers of limestone is as well developed below the Fjäcka Shale at this location. Towards the south in the quarry (high up in the south wall), the black shale thins out and is here only 10 cm thick. The thickness of the overlying section remains about the same, while the thickness of the beds between the Kullsberg Limestone and the Fjäcka Shale is reduced (not measured).

Osmundsberget 3

Location: About 30 m north of Osmundundsberget 2
At this location a large overturned block of thick bedded pelmicritic Boda limestone is seen in the east wall of the quarry (Fig. 17A). The block is tilted to the north, at an angle of nearly 90 deg. relative to the surrounding beds. Green mudstone surrounds the block on the lower and upper surface. According to Riding (2002), steep marginal slopes may be common in high relief carbonate mud mounds such as the Boda Limestone.

Osmundsberget 4

Location: The northeast corner of the quarry. UTM coordinates WH 10909 68461, Swedish Grid 70682 67479.
Highly fossiliferous flank facies developed at the northwest wall, near top of the Boda Limestone (Fig. 17A). At the lower level, to the east in the section, are distinct red and green coloured beds of mudstone between benches of pink micritic limestone and pelmicritic limestone beds. Higher in the section, exposed along the entire western wall face, is a distinct 60 cm thick coquina with the brachiopod *Crypothyrella terebratulina* (Wahlenberg). Stratigraphically above this are beds with rugosan and tabulate corals. From an unspecified level at this locality came the specimens of *Holorynchus gigantea* that were discussed by Brenchely et al. (1997).

Osmundsberget 5

Location: The northern entrance of the quarry. UTM coordinates WH 10886 68478, Swedish Grid 70694 67398.
The *Crypothyrella* and coral beds can be followed around the escarpment to the west, where the northern access to the quarry opens up in a 25 m wide entrance (Fig. 17C). The O/S section on each side of the entrance (west and east) differs in their development, and the following account is based on the eastern outcrop. Near the top of the layered beds of the Boda Limestone a brachiopod coquina occur, which correspond to the several meter thick beds seen at the Osmundsberget 1 locality. At Osmundsberget 5 the bed is only 43 cm thick, and is only 40 cm below the top of the Boda Limestone. Disconformably, with a 10 degree angular disconformity, follows thick pelmicritic beds of the Glisstjärn Formation. Only 76 cm above the top of the Boda Limestone a cephalopod concentration is seen, which corresponds to that found in Osmundsberget, but with somewhat reduced abundance. Above follows 110 cm of soft weathering green mudstone overlain by thick beds of limestone (54 cm thick). The Glisstjärn Formation ends with a 65 cm thick unit of nodular limestone with shaley intercalation, before the succession is capped by the Silurian graptolitic shale of the

Kallholn Formation. In the western outcrop the thick green nodular beds of the Glisstjärn Formation are absent (see also Schmitz & Bergström 2007).

Stop 4. Solberga

Location: Non-operational quarry located just west off regional road 301 at Ovanmyra, Rättvik Municipality, on the east side of the Siljan ring. Topographical map sheet Rättvik 14F SV, UTM coordinates WH 1170 6100, Swedish Grid 6320 6810.

Age: Upper Ordovician (Katian), Keila–Oandu regional stages, to the Lower Silurian (Llandovery), Late Aeronian Stage.

Description: This is a quarry in the Boda Limestone, where the core material has been partly removed (Fig. 18). The mound is essentially flat lying, with Llandovery shale of the Kallholn Formation exposed and in contact on the north-western flank. A number of small wells are situated on the quarry floor (Fig. 18), in which thick oil is still found. The quarry is owned by Svenska Mineral AB.

The uppermost parts of the Boda Limestone is missing in this quarry, and the characteristic *Cryptothyrella* bed is not seen. However, at the northeastern wall of the quarry a horizon with *Holorynchus gigantea* is found near the top of the escarpment, associated with corals (Solberga 1, UTM co-ordinates 11745 61125, Swedish Grid 63327 68116).

At the southern wall an exceptionally large composite pocket is found (Solberga 1, UTM co-ordinates 11764 60861, Swedish Grid 63063 68182). Part of the pocket is filled with layered internal sediment, while

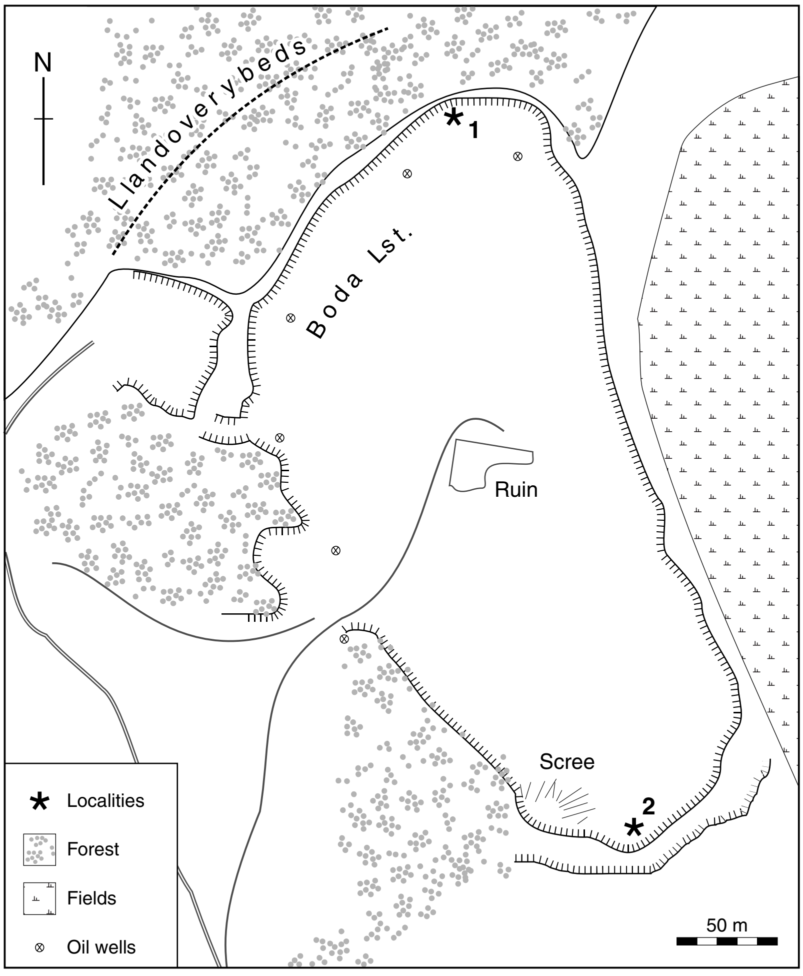

Fig. 18. Map of the southern part of Solberga quarry, showing general facies distribution.

other parts are filled with pygidia of the trilobite *Eobronteus laticauda* (Wahlenberg) in particular. The locality is also rich in gastropods, especially *Platyceras crispum* Lindström *in* Angelin & Lindström which at the O/S boundary at Osmundsberget 5 occurs in association with the *Cryptothyrella* coquina.

Stop 5. Jutjärn

Location: Operational quarry located east of regional road 301, just west of the pond Jutjärnen, Rättvik Municipality, on the east side of the Siljan ring. Topographical map sheet Rättvik 14F SV, UTM coordinates WH 1370 6090, Swedish Grid 6310 7010.

Age: Upper Ordovician (Katian), Keila–Oandu regional stages, to the Lower Silurian (Llandovery), Late Aeronian Stage.

Description: This is a large quarry in the Boda Limestone, owned and operated by Svenska Mineral AB. The limestone is essentially flat lying but is heavily disturbed by numerous faults and cracks. It is presently the only quarry in the Siljan District where the core of the Boda Limestone is still partly present. A number of large pockets have been exposed during the quarrying, essentially filled with cephala of *Stenoparaia* but also rich in other taxa mixed in-between. Suzuki & Bergström (1999) found that nine trilobite species dominate the trilobite fauna of the Boda Limestone. Pockets are usually dominated by fossil of one of these species, and usually by either their cephala or their pygidia. This may suggest a strong habitat distribution on the top of the mounds, and a sorting effect whereby smaller parts of the exuvia are trapped in algal mats on the mound surface (Suzuki & Bergström 1999).

In the layered flank facies of the Boda Limestone on the west side at the entrance of the quarry (UTM coordinates WH 13709 60937, Swedish Grid 63114 70129) a coquina bed with *Cryptothyrella* is seen. This would represent the upper part of the Boda Limestone by comparison with the Osmundsberget quarry.

This quarry was the main site for the study on trilobite ecology of the Boda Limestone by Suzuki & Bergström (1999).

Locality descriptions, the Storsjön Area

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Stop 6. Lockne crater (crater trail)

Location: A foot path known as the "crater trail" is located along the south side of the Tandsbyn gully, near the village Tandsbyn. It starts after going uphill from the parking area and further crossing the railway. The trail is around 2 km long and was re-opened in 2005 with new information signs about the different formations in the crater.

Age: Upper Ordovician (Sandbian, Kukruse and Haljala regional stage).

Description: The brim of the inner Lockne crater, i.e. the zone of ejected crystalline basement (Lindström et al. 2005a), is crosscut by radial channels that channelled the resurging seawater after the impact. Fractured and brecciated basement rocks constitute the *Tandsbyn Breccia,* which occurs in the inner crater as well as outside it, like here, where it forms the ejecta sheet. Deep and wide gullies were formed in the brim due to the resurging seawater. Best preserved and exposed is the Tandsbyn gully. The first resurge deposits to partly fill the gully were *Lockne Breccia* (polymictic clast deposits with more or less abundant fragments of crystalline rock) with a gradational contact with the sandy and silty *Loftarstone*. The Loftarstone is followed by secular deposits belonging to the continued sedimentation of the Dalby Limestone, as prior to the impact. In the Tandsbyn gully the thickness of the Dalby Limestone comprises only about 5–10 m. However, the total thickness of the post-impact part of the Dalby Limestone inside the inner crater exceeds by several times the thickness of coeval limestones in Sweden, which are generally 15–20 m thick. The deposition of the post-impact Dalby Limestone in the Tandsbyn gully has been logged in detail and three facies associations have been defined (Frisk & Ormö in press). First a pure, light grey, and thick-bedded biocalcarenite representing the *Rim facies,* deposited on topographic highs and directly overlying the Tandsbyn basement breccia. Within the lowermost 0–4 m, coarse and angular fragments of crystalline rock, ranging in size from fine pebbles to cobbles, are randomly distributed in the succession. The contact between the rim facies and the Tandsbyn Breccia is particularly well exposed along the southern side of the Tandsbyn gully in the higher terrain passed by the crater trail. Secondly a *Cephalopod facies*, a thick-bedded, light-grey, moderately pure calcilutite with occasional extremely thin argillaceous layers, is distributed in a limited area near the bottom of the gully. It is especially rich in nautiloid conchs that characterize the facies association. The last is the *Argillaceous facies* consisting of nodules of argillaceous limestone set in grey, hard, and slightly cleaved mudstone that rests with gradational conformable contact on fine Loftarstone in the lower parts of the gully. Sedimentary structures as nodules and trace fossils are common in the argillaceous facies, and it is similar to contemporaneous Dalby Limestone occurrences elsewhere in Sweden. Around the parking area and just after crossing the railway the argillaceous facies with limestone nodules is exposed. In a few localities the Dalby Limestone is succeeded by the *Örå Shale*.

Fauna:

Örå Shale: Mostly contains olenid and remopleuridid trilobites and graptolites, but also some articulate brachiopods. Branched bryozoan colonies have been observed with the brachiopods. Grahn (1997) noticed the occurence of *Cyathochitina campanulaeformis*.

The post-impact Dalby Limestone in this area belongs to the *Lagenochitina dalbyensis* and *B. hirsuta* chitinozoan zones (Grahn et al. 1996). The impact event is documented in beds corresponding to the *L. dalbyensis* chitinozoan Zone.

Rim facies: The faunal assemblages of this biocalcarenite are quite different from the facies of the general sea-floor and within the crater and gully depressions. It consists of skeletons of echinoderms, large rhynchonelliformean brachiopods, bryozoans, trilobites, and ostracodes. The microfossil fauna mostly consists of diverse conodonts and lingulate brachiopods. Further up in the succession of this facies, orthoid brachiopod shells are extremely abundant and locally form coquina beds. There is an absence of organisms typical of the photic zone (e.g., calcareous algae), as found in the rim facies of the almost coeval Tvären crater.

Cephalopod facies: The macrofauna is low diversity, with mostly Endoceratid nautiloids, up to 1 m long, as the dominant element preserved. The nautiloid conchs have diameters up to 7–8 cm and have chambers with spar-filled geopetal voids, thus demonstrating that they were only partially filled with mud. They are arranged sub-parallel and the average number of specimens per square meter ranges between ten to several tens. Large coiled cephalopods are also present. Moreover this facies is quite rich in cystoids, but otherwise rather poor in macrofossils, though, crinoids and brachiopods are evident in the successions. The microfossil fauna mostly consists of conodonts, inarticulate brachiopods, and ostracodes.

Argillaceous facies: The interbedded shales demonstrate moderate amounts of bioturbation as vertical traces cutting the bedding planes. Macrofossils are represented by trilobites, mainly *Neoasaphus ludibundus*, cephalopods, and occasional cystoids of *Echinosphaerites* type. Large and well preserved conularids have also been observed. Inarticulate brachiopods (*Eoconulus robustus*, *Acanthambonia* sp., *Acrotretella* sp., *Paterula* sp., siphonotretaceans, and discinaceans), chitinozoans (characteristic index species *Lagenochitina dalbyensis* and *Lagenochitina* sp. A aff. *capax*), and conodonts (*Amorphognathus tvaerensis*, *Prioniodus gedae*, *Strachanognathus parvus*, and *Prioniodus (B.) navis Prioniodus alobatus*) constitute a part of the microfossil assemblage.

Stop 7. Brunflo area

Location: Brunflo

Age: Öland to early Harju

*Description***:** The Ordovician geology of the Brunflo area is characterised by limestones and shales deposited in platform facies from the middle Öland to early Harju (Karis 1998, p. 17). However, at this stop we will focus on the middle Ordovician Segerstad Limestone, Seby Limestone and Folkeslunda Limestone. Although the Brunflo area is part of the Autochton, it is not unaffected by the Caledonian deformation. The limestone commonly undulates due to tension and internal faults, that may cause repetition of the sequence.

The oldest Ordovician lithological unit that has been observed in the area is the Latorp Limestone. It underlies the Tøyen Formation, which was temporarily exposed in the village of Brunflo during construction work (Karis 1998, p. 85). Above the Tøyen Formation, several limestone units follow i.e. the Lanna Limestone, Holen Limestone, Segerstad Limestone, Seby Limestone and Folkeslunda Limestone. None of these are specific to Jämtland, but are also found in other parts of Sweden.

Between the Lanna Limestone and the overlying Holen Limestone, a thin limestone conglomerate has been reported, interpreted as a period of time with interrupted sedimentation and erosion (Karis 1998 p. 85). The Holen Limestone has a large geographical distribution across the Brunflo area and is fossiliferous (trilobites, echinoderms, brachiopods, cephalopods and gastropods). The lower unit of the Holen Limestone is exposed at Lisbetodlingen, whereas the upper part is exposed in several other quarries (e.g. Lundbomsberget, Gusta and Vamsta; Karis 1998).

The Segerstad Limestone, Seby Limestone and Folkeslunda Limestone were described in detail by Larsson (1973). There are several quarries in the area, of which Lunne may be the one that has been studied in most detail (e.g. Larsson 1973). This section is also, from what is known from the literature (e.g. Larsson 1973, Löfgren 1978), the most complete, with a stratigraphic succession from the Kunda to Kukruse stages. However, at the fieldtrip we will stop where these units are more accessible. In Jämtland, the Segerstad Limestone is characterized by reddish calcarenite and calcilutite (Larsson 1973), in its upper part calcarenite that is partly recrystallised dominates. Above the two lowermost discontinuity surfaces of the Kårgärde member, beds with mudcracks and stromatolites can be found (Larsson 1973). However, the present interpretation of these structures have been questioned.

In the Gärde quarry (Rödberget), the upper Holen Limestone and lowermost Sergerstad Limestones have been quarried. Discontinuity surfaces stained with haematite are present and above them, the algal mats mentioned above.

Stop 8. Rannåsen

Location: E144425/N701020, Quarry in operational phase, located ca 2.5 km NE of Östersund, ca 1 km E of the main road (E14).

Age: Rawtheyan? – Hirnantian

Description and interpretation: The Rannåsen quarry contains a folded and faulted sequence of the Kyrkås Quartzite and maybe the youngest part of the Kogsta Siltstone. The succession comprises two sequences, commencing with marine heterolithic shales and siltstones with interbedded sandy tempestites that become more abundant upwards in the sequence. In each sequence there is an upward increase in grain size, of hummocky cross stratificated (HCS) beds, amalgamation and thickness of sandstone beds, frequency of rip-up clasts, textural maturity of sandstones, a shift from HCS to trough and tabular cross bedding, and a decrease in bioturbation. The succession at the nearby Nifsåsen quarry has been logged in detail and three depth-related facies associations have been defined; the *Mudstone association*, deposited in an offshore environment; the *Sandstone/mudstone association*, deposited in the offshore transition zone; and the *Sandstone association*, deposited in a shoreface environment. The two depositional sequences, separated by a transgressive surface, indicate repeated relative shallowing of a storm-dominated proximal shelf setting. Within each sequence the overall shoaling pattern is interrupted by minor deepening episodes by a change from sandstone to shale dominance.

The recognition of a prominent marker bed in the lower part of the second sequence makes it possible to distinguish two sequences and to establish the thickness of the Kyrkås Quartzite to approximately 90 m. The Kyrkås Quartzite contains slump horizons up to 3 m thick probably reflecting tectonic activity affecting unstable slopes. An intraformational conglomerate and mud-cracks was observed in the Rannåsen quarry decades ago but have not subsequently been found there or at any other locality. Sedimentological evidence suggests that the Rannåsen succession was deposited in a more proximal setting than the Nifsåsen strata.

Fauna: The lowermost strata of the Kyrkås Quartzite (or the uppermost Kogsta Siltstone) has yielded the trilobite *Tretaspis*, suggesting an approximate age of latest Rawtheyan to earliest Hirnantian for these beds. In the lower part of the second sequence, below the marker bed (the RMB), a shelly fauna containing typical *Hirnantia* faunal elements have been recorded.The fauna is dominated by bivalves, which suggest an Ashgill age and comprise a shallow water shelf assemblage with primarily infaunal forms, and some epibyssate benthos. The fauna include the brachiopods *Eostropheodonta hirnantensis*, *Dalmanella testudinaria* ?*Kinnella kielanae*, *Orbiculoidea* cf. *radiata*, *Leptaenopoma trifidum*, and a species related to *Aegiromena,* together with the trilobites *Brongniartella platynota* and *Mucronaspis mucronata*. Additionally cephalopods and hyolithids can be found.

The fauna from the same level at the nearby Nifsåsen Quarry differs in composition, by not being dominated by bivalves. The dark siltstone at this locality contains many shell fragments, but complete specimens of *Leptaena* and a possible *Dysprosorthis* together with orthide and strophomenide shell exteriors occur as well, suggesting a Hirnantian age. The fauna includes also fragments of *Mucronaspis*.

From the faunas at Rannåsen and Nifsåsen it is concluded that Nifsåsen occupied a more distal position as compared to Rannåsen locality. Graptolites of the *P. persculptus* Biozone have been reported above the RMB at Rannåsen. No diagnostic fossils have been reported above these graptolite-bearing levels. The Kyrkås succession is interpreted as comprising most of the Hirnantian.

Depositional evolution: The depositional pattern is interpreted to reflect Late Ordovician glacio-eustatic changes, possibly influenced by regional and local tectonism. The two sequences of the Kyrkås Quartzite indicate repeated shoreline progradation. The presence of smaller scale sets indicating shoaling (parasequences?) points to episodic shallowing. The lower sequence of the Kyrkås Quartzite formed during a regression in the early Hirnantian (early *N. extraordinarius* graptolite Biozone), while the upper sequence was deposited during a second regressive cycle in the mid–late Hirnantian (*P. persculptus* graptolite Biozone). The timing of these regressive phases correlates well with two previously proposed glacio-eustatic regressions. Parasequences may reflect sea level changes of higher order cycles. The Kyrkås Quartzite is the youngest preserved strata in the Kyrkås area.

A study on detrital zircons from the upper sequence at Nifsåsen suggests that part of the material was derived from Proterozoic–Cambrian sedimentary rocks to the present west south-west and/or from the Southwest Scandinavian Domain.

Stop 9 Österulvsås, Kälom

Location: 7042740/1425617. In the eastern part of the village Kälom.

Age: Ordovician (Hirnantian) – Silurian (Aeronian)

Description and faunal association: The village of Kälom is situated on a series of hills, made up of large synclinal folds, folded and thrusted during the Caledonian orogeny (Fig. 19). The rock sequence covers the Upper Ordovician to the Lower Silurian and is composed of three major lithological units, i.e. Kogsta Siltstone, Ede Quartsite and Berge Limestone, and belongs to the Lower Allochton of the Caledonian orogeny. It is one of the more accessible localities in the area displaying the Ordovician–Silurian boundary. In contrast to

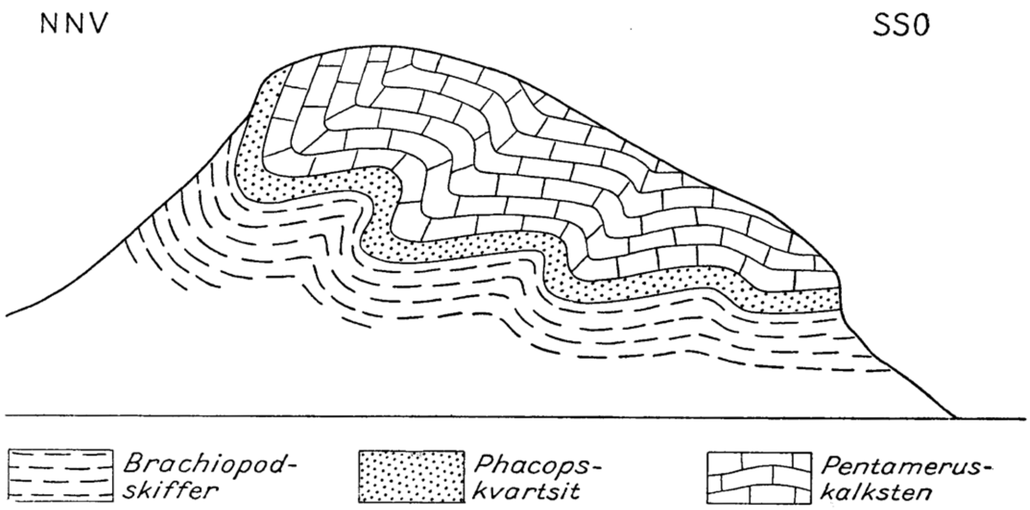

Fig. 19. Schematic profile of the hill in Kälom. From bottom to top; Kogsta Siltstone (Brachiopodskiffer), Ede Quartzite Formation (*Phacops*-kvartsit) and Berge Limestone (Pentameruskalksten). Length scale is approximately 1:5000. Height scale is half of the length scale. From Thorslund 1943, fig.3.

many other localities in Jämtland the geology at this locality has not been stratigraphically inverted, hence the oldest unit, the Upper Ordovician Kogsta Siltstone is also the lowermost unit. It is only the uppermost part of the Kogsta Siltstone that is exposed. External moulds of a shelly fauna (mainly brachiopods, trilobites and echinoderms) indicating a Hirnantian age (Dahlqvist et al. 2007) can be found approximately 1 meter below the unconformity. Like in most sections in Jämtland, minor (and major) internal faults makes it difficult to estimate the real thickness of the unit without detailed studies combining structural geology and stratigraphy.

Following Dahlqvist & Calner (2004), the Ordovician–Silurian boundary at Edefors is defined by an unconformity, underlying the favositid biostrome, representing the hiatus associated with the drop in sea-level owing to the Hirnantian glaciation and possibly also a peripheral bulge in the area. The favositid biostrome is also present at Kälom, however, it appears to lie closer to the underlying Kogsta Siltstone than at Edefors since the quartzite beds at Kälom are only approximately 10 cm thick. There is also a possibility that the lowermost part of the Ede quartzite or the upper part of the Kogsta Siltstone, may not be present at this locality, although no detailed study has been undertaken confirming this hypothesis. Available evidence indicates a Silurian age for most of the Ede quartzite present at this locality. The thickness of the unit is difficult to estimate since there are several internal faults causing repetition. The limestone on top is the Aeronian (early Silurian) Berge Limestone, which recently has been biostratigraphically dated using conodonts (Dahlqvist & Bergström 2005).

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Abstracts

Darriwilian high energy sedimentary facies in Baltoscandia – possible responses to meteorite shower?

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The findings of numerous fossil meteorites from the Middle Ordovician limestones at Kinnekulle, southern Sweden, allowed investigators to assume, that meteorite palaeoflux was at that time was enhanced by up to two orders of magnitude as compared to recent flux. Abundant extraterrestrial chromite grains have been found from coeval stratigraphic interval from different localities in Sweden (Schmitz et al. 2003). All this material, indicating distinctive L chondritic composition, is probably derived from a single asteroid disruption event in the Ordovician. Recent dating of shocked L chondrites by multiple ^{40}Ar–^{39}Ar isochrones has indicated the asteroid breakup event at 469±5.4 Ma. The beds of increased content of extraterrestrial material in Sweden occur in narrow stratigraphic interval of the lowermost part of the Kunda Stage (*Lenodus antivariabilis*, *L. variabilis* and *Yangtzeplacognathus crassus* conodont zones; Schmitz et al. 2003), which dates the L chondritic meteorite shower at 466–467 Ma (lower Darriwilian). One of the four biostratigraphically well-dated Baltoscandian meteorite craters – the Granby crater in southern Sweden – has the same, early Kunda age. In this study we analyse some of the sedimentation events indicating increased hydrodynamic energy that occurred in East Baltic area close to the time interval of meteorite shower.

The Middle Ordovician palaeobasin was a carbonate ramp in the East Baltic, with minor lithofacies changes between the middle ramp (northern Estonia) and outer ramp (southern Estonia, Latvia, Sweden) settings. Inner ramp area was probably represented by non-sedimentation during most of the time. Sea level change cycles are expressed as depositional sequences in the succession, bounded by sedimentary gaps in the updip areas. Sedimentary gap at the base of the Kunda Stage and missing of the lower substage in northern Estonia is interpreted as a sequence boundary.

The sedimentary succession of the Kunda Stage starts with the Pakri Formation in the shallow part of the ramp. This is a bed of sandy limestone and limy sandstone, up to 4 m thick, representing possibly the middle substage of the Kunda Stage. It rests on the limestones (Volkhov Stage) and sandstones (Lower Ordovician, Cambrian) of different age in the area from NW Estonia to the island of Gotska Sandön, Sweden. The Pakri Fm is a mixture of well-rounded quartz sand and bioclastic material, deposited in the wave action zone. This type of rock is unusual for the Middle Ordovician succession of Baltoscandia as carbonates of this age are particularly poor in the sand-sized siliciclastic material here.

The rocks of the Pakri Fm and underlying beds are brecciated and penetrated by limy sandstone injections in NW Estonia (the Osmussaar Breccia) found over an area of more than 5 000 km^2. The breccia blocks consist of fragmented and displaced rocks of the Billingen, Volkhov and Kunda stages. Sizes of the carbonate lithoclasts range from tens of centimetres to tens of metres. Fine-grained matrix filling dike- and vein-like space between blocks is composed of limy silt- and sand-sized material. The main siliciclastic component in the matrix is composed of unsorted, angular to well-rounded arenite sand. Both the breccia matrix and sandy limestone clasts of the Pakri Formation contain quartz grains with distinctive PF and PDF in the Osmussaar outcrops (Suuroja et al. 2003). The brecciation is considered as a single or multiple events of Kunda age. An earthquake or series of earthquakes has been suggested to have caused seabed fracturing and brecciation of rocks. As a possible place of origin of the PDF quartz the redepositon of ejecta material from the nearby Early Cambrian Neugrund Crater has been assumed (Suuroja et al. 2003).

Another distinct rock type of the Kunda age is the Jentzschi Conglomerate, found only as erratic boulders from Gotska Sandön, Gotland and northern Germany. The conglomerate is mainly composed of rounded clasts of phosphatic quartz sandstone in the limy sandstone matrix (Buchholz et al. 2006). The source bedrock of the Jentzschi Conglomerate is assumed to be situated in the bottom of Baltic Sea, in between Saaremaa and Gotland islands. The Kunda age is approved by the shelly fauna (brachiopods, ostracodes) and it has been considered as a shoreward facies (or basal conglomerate) of limy sands of the Pakri Fm.

A conspicuous Middle Ordovician sandstone layer, up to 1.5 m thick, is described from drillcores of Latvia. The sandstone bed in between argillaceous limestones, called the Volkhov Collector is supposed to be of late Volkhov age, but the Kunda age can not be excluded by existing micropalaeontological data. This bed is distributed in western Latvia as a 100 km long and 50 km wide belt, probably continuing westwards below the Baltic Sea. The Volkhov Collector was studied in the Vergale drillcore, where it was subdivided into four gradationally fining-upward beds, resembling well the Bouma divisions of turbidite succession. This turbidite bed, single and unique for the whole Palaeozoic carbonate succession in East Baltic, represents the turbidite flow that moved downslope from the inner-middle ramp in the north to the Jelgava Depression, a deep part of the Livonin Basin in the south. The quartz sand could be derived from the inner ramp or from some unknown uplifted structure in the middle-outer ramp.

The occurrence of high energy hydrodynamic environments of early Darriwilian age in the Baltoscandian inner-middle ramp area could be explained by sea level drop. Quartz sand might have been transported from the Cambrian-Lower Ordovician sandstones and mixed with bioclastic material in the coastal zone during increased erosion episode. The sea level drop might re-open the neighbouring Neugrund impact crater to the erosion and the shocked quartz may be derived from that structure. However, the origin of some unique and approximately coeval events, like brecciation of lithified sedimentary rocks in NW Estonia and turbidite flow in Latvia, remain still problematic. Therefore their direct or indirect relation to Darriwilian meteorite shower could not be excluded.

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Katian and Hirnantian (Upper Ordovician) $\delta^{13}C$ chemostratigraphy in North America and Baltoscandia: A trans-Atlantic comparison

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The conspicuous regional biogeographic differentiation of Ordovician shelly faunas, chitinozoans, and conodonts has in the past made detailed trans-Atlantic correlations of the cratonic carbonate successions difficult and uncertain. Extensive studies in recent years have shown that $\delta^{13}C$ chemostratigraphy is a very useful tool for both local and long-range correlation of Ordovician rocks. This is particularly the case in the Upper Ordovician Katian and Hirnantian stages, within which there are several distinctive positive $\delta^{13}C$ excursions that appear to be of global nature. The currently best known of these are the lowermost Katian Guttenberg excursion (GICE) and the uppermostst Ordovician Hirtnantian excursion (HICE). Most Ordovician chemostratigraphic work has been carried out in northern Europe (Baltoscandia, the British Isles, Poland, Russia) and North America (Nevada, the Midcontinent, Quebec, Yukon, Canadian Arctic Islands) but there are also some studies from China and Argentina.

Thus far, Sandbian (lower Upper Ordovician) chemostratigraphy has received less study in North America than that of the upper parts of the Upper Ordovician, the most detailed $\delta^{13}C$ curves having been recorded from Nevada, Iowa, Kentucky, and New York State. The few minor positive excursions recognized in uppermost Sandbian strata in the Upper Mississippi Valley appear to be of local, rather regional, nature and most $\delta^{13}C$ data from other areas differ little from baseline values.of ~0–1‰. The same seems to be the case in Baltoscandia, where $\delta^{13}C$ curves from Estonia and southern Sweden show no obvious positive excursions.

In the lowermost Katian Stage, the GICE is a prominent feature in the $\delta^{13}C$ curves from localities across North America and Baltoscandia. Recent, largely unpublished, studies show that this positive excursion is of major significance regionally and it is an excellent tool for trans-Atlantic correlations of the cratonic carbonate successions.

Among the chemostratigraphic investigations of the middle and upper Katian successions in the North American Midcontinent, a most important one has recently been carried out in the 300 m thick, stratigraphically unusually complete, richly fossiliferous Cincinnatian Series carbonate succession in Ohio and adjacent states, which is the type section of the North American Upper Ordovician. This research led to the discovery of four positive $\delta^{13}C$ excursions (1–2‰ shifts) above the GICE. Significantly, based on available conodont and graptolite data, these excursions, which are referred to as the Kope, Fairview, Waynesville, and Whitewater carbon isotope excursions, appear to correspond precisely to recognized excursions in the coeval stratigraphic intervals in Estonia, and as recently shown by Bergström et al. (Acta Geologica Sinica), these excursions provide a new tool for much improved trans-Atlantic correlations between North American and Baltoscandic regional stages. Hence, the base of the North American Edenian Stage corresponds to a level at, or near, the base of the Baltoscandic Rakvere Stage; the base of the Maysvillian Stage is at, or near, the base of the Nabala Stage; and the base of the Richmondian Stage appears coeval with a level in the middle Nabala Stage. Furthermore, based on the recent correlation of the base of the Ashgill Series into the Estonian succession using British chitinozoan data, it appears that the base of this British unit would correspond to a level somewhere in the middle of the North American Maysvillian Stage. It is expected that this new Cincinnatian $\delta^{13}C$ curve will be a global $\delta^{13}C$ standard for that stratigraphic interval.

The latest Ordovician Hirnantian Stage is not represented in the type Cincinnatian Series, nor in many other parts of the Midcontinent. However, recent studies have proved that the HICE, and hence Hirnantian strata, occur in several areas in the Upper Mississippi Valley (parts of Missouri, Illinois, and Iowa) as well as in southern Ontario. Excellent sequences with the HICE are previously known from central Nevada (Hanson Creek Formation, etc.), where it is well dated by graptolites, conodonts, and palynomorphs, Anticosti Island in Quebec, and the Canadian Arctic. In northern Europe, the HICE is particularly well documented in carbonate facies in the East Baltic region (especially Estonia) and Sweden (including the Osmundsberg Quarry in the Siljan area and Västergötland), but it has been recorded also from the Oslo region of Norway and the northern Urals in Russia.

Because the HICE ends within the *N. persculptus* Zone well below the Ordovician-Silurian boundary, as this is formally defined by graptolites (base of the *A. ascensus* Zone), the precise position of this boundary cannot currently be recognized by chemostratigraphy in stratigraphically complete carbonate successions lacking graptolites. In the case of conodonts, the replacement of Ordovician-type taxa with those of Silurian aspect also takes place well below the systemic boundary and the same may be the case in other fossil groups. Accordingly, the establishment of the precise level of this boundary in non-graptolitiferous successions remains a problem. Fortunately, this problem is alleviated by the fact that in many areas, such as in large parts of the North American Midcontinent and Baltoscandia, the boundary falls within a stratigraphic gap caused by a latest Ordovician-earliest Silurian glacio-eustatic regression.

We conclude that the new chemostratigraphic data open up interesting possibilities for novel and exciting studies in not only regional biostratigraphy and biogeography but also in other fields, such as eustatic sea level fluctuations and marine water temperature changes associated with glaciations.

Late Ordovician shelly faunas from Jämtland, central Sweden

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Late Ordovician shelly faunas occur at several localities in Jämtland (Sweden). In the eastern part of the region, the middle parts of the Kyrkås Quartzite contain elements of the widespread terminal Ordovician *Hirnantia* fauna, including *Kinnella kielanae*, *Eostropheodonta hirnantensis*, *Dalmanella testudinaria*, *Leptaenopoma trifidium* and *Orbiculoidea radiata* together with the trilobites *Mucronaspis mucronata* and *Brongniartella platynota*; in the western part, the uppermost Kogsta Siltstone contains *Hirnantia sagittifera*, *Cliftonia psitticina*, *Leptaena rugosa* and *Orbiculoidea concentrica*, together with the trilobites *Mucronaspis mucronata*, *Brongniartella platynota* and a species of *Tretaspis*. In both areas the faunas occur in a variety of shale and siltstone facies and were probably developed on the mid shelf. The faunas permit correlation between the eastern and western successions, which show major differences in facies development. The eastern area preserves two regressive events of similar magnitude, whereas the western area shows a more minor regression (within the Kogsta Siltstone) followed by a major regressive event (Ede Quartzite). The Hirnantian faunas occur, in both the eastern and western areas, a few meters below the second regressive event. The differences in depositional patterns and lateral facies changes in response to eustatic sea-level fluctuations, are probably related to a palaeoslope, which dipped from the eastern part, basinward towards the west. The migration of a peripheral bulge over the Ede area could be a possible cause for the uneven basin topography and the distribution of biofacies.

Middle and Upper Ordovician trilobites from Leningrad district (Russia)

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A key question to the geology of Baltoscandia is the correlation of Middle and Upper Ordovician macrofaunal complexes in Leningrad Region and neighboring areas. This study is aimed at documenting the trilobite record in the Leningrad Region. It is based on the results of biostratigraphical studies of several Middle and Upper Ordovician outcrops (Diatlicy, Alekseevka, Klyasino, Zimiticy, Kas`kovo, Slobodka and Gorki quarries and a coastal outcrop on Khrevitsa River). The material from these outcrops was investigated for biostratigraphic purposes. The material contains some taxa, previously not recorded in this area, which demonstrate some potential for correlation.

In the Middle–Upper Ordovician transition, the representatives of the trilobite Family Pterygometopidae are more diverse, although representatives of other families do occur as well. Eight investigated outcrops cover nearly 2/3 of the stratigraphic interval of Uhaku-lower Keila, but the boundary intervals of the stages are poorly represented in the outcrops. Three of the studied outcrops, Diatlicy, Slobodka and Gorki, lack previous macrofaunal record.

The Uhaku Stage is recognized in the type area as limestones and argillaceous limestones with the trilobites Xenasaphus devexus and Illaenus intermedius. The overlying Kukruse Stage, limestones and marls interbedded with kukersite, contains the trilobites *Paraceraurus aculeatus* and *Hoplolichas conicotuberculatus*. The Uhaku and Kukruse stages (the Mednikovo and Viivikonna formations) crop out in the Diatlicy and Alekseevka quarries. At these localities, the lower boundary of the Kukruse Stage is tied to the base of the lowermost thicker kukersite bed. The Uhaku and Kukruse stages are lithologically similar at Diatlicy and Alekseevka, differing only in thickness of the kukersite beds, which is restricted to 0.2 meters at Diatlicy but reaches 1.2 m at Alekseevka. The trilobites in the Diatlicy quarry are less diverse than in Alekseevka, being characterized by *Asaphus (Neoasaphus) lepidus, A. (N.) robergi, Pseudobasiliella* sp., *Illaenus crassicauda, Ill. kuckersiana, Ill. schmidti, Ill.* sp., *Paraceraurus* cf. *aculeatus, Sphaerocoryphe* sp., *Achatella (Vironiaspis) kuckersiana, Estoniops exilis, Chasmops* cf. *odini*, *Lonchodomas* sp. nov., *Homolichas* aff. *depressus*, *Remopleurides nanus elongatus, R.* sp. nov., *Illaenus schmidti* and *Lonchodomas* sp. nov. are widespread only in the uppermost part of the Uhaku Stage in both quarries. The Kukruse Stage contains *Asaphus (Neoasaphus)* sp. indet., *Leningradites longispinus, Pseudobasiliella kuckersiana, Illaenus crassicauda, Paraceraurus* cf. *aculeatus, Reraspis plautini, Atractopyge* sp., *Cybelella coronata, Achatella (Vironiaspis) kuckersiana, Estoniops exilis, Chasmops odini, Ch.* (cf.) *odini, Lonchodomas rostratus, Remopleruides nanus elongatus, Harpidella planifrons, Pharostoma nieszkowskii*. In the lower part of the Kukruse Stage several species make their first appearance in the area: *Leningradites longispinus, Pseudobasiliella kuckersiana, Cybelella coronata, Lonchodomas rostratus, Harpidella planifrons, Pharostoma nieszkowskii*. The Uhaku – Kukruse interval is generally similar in terms of trilobite assemblages, but some new trilobite genera and taxa, mainly represented by small-sized trilobites (*Harpidella planifrons, Pharostoma nieszkowskii*) do appear in the Kukruse Stage. Several appearing species and genera become more common in the upper part of the Kukruse Stage, obtaining also larger size. In general terms, the Uhaku and Kukruse stages may be called 'Chasmops odini beds' as this species is the commonest in this interval.

The Haljala Stage comprises the former Idavere and Jõhvi stages. The limestones of the Idavere Substage contain *Scopelochasmops wrangeli, Conolichas triconicus, Estoniops bekkeri*. Two formations are distinguished in this interval in the vicinity of St. Petersburg, the Gryazno and Shundorovo formations. These strata crop out in the Kliasino, Zimiticy and Kas`kovo quarries. The Klyasino quarry also exposes the transition from the uppermost Kukruse Stage to the lower Haljala Stage. The Kukruse Stage revealed rare trilobites characteristic of this stage – *Asaphus (Neoasaphus)* sp., *Estoniops exilis* and *Chasmops odini*. The stage boundary is marked by a hiatus, overlain by limestones, marls and calcareous clays of the Griaznovo Formation. The argillaceous unit is very rich of fossils, containing *Asaphus (Neoasaphus) itferensis, Atractopyge* sp., *Calyptaulax* sp., *Chasmops itferensis, Ch. marginatus, Ch.* sp. nov., *Conolichas peri, C. triconicus, Estoniops bekkeri, Illaenus sphaericus, Metopolichas squamulosus, Nieszkowskia cephaloceras, Panderia* sp., *Pharastoma* sp., *Scopelochasmops wrangeli, Sphaerocoryphe huebneri* and *Stenopareia avus*. The trilobites mainly occur as juveniles. These unit also comprises more deep water trilobite taxa common in Sweden, Norway and North America: *Calyptaulax, Pharastoma, Panderia*. All listed taxa are characteristic of the Idavere Substage, except for *Conolichas peri, Illaenus sphaericus, Nieszkowskia cephaloceras* and *Stenopareia avus* which make their appearance in the Kukruse Stage. This is interval can be called 'Scopelochasmops wrangeli beds', as this species is widespread both in the studied area and in north-east Estonia.

The upper part of the Idavere Substage, the Shundorovo Formation, was investigated in the Kas`kovo quarry. In the outcrop area, the Shundorovo Formation is characterized by occurrence of thin intercalations of kukersite, quartz (chalcedony) concretions and spicules of *Pyritonema* in limestones. The trilobites are represented by *Asaphus* sp., *Panderia* sp., *Atractopyge* sp., *Chasmops marginatus*. The latter species is also the most characteristic of the particular interval.

The Jõhvi Substage is recognised in the type area as the beds with Rollmops wenjukowi and *Toxochasmops (Schmidtops) proavus*. In the vicinity of St. Petersburg, the Jõhvi Substage is represented by the Khrevitsa Formation. The Khrevitsa Formation crops out on the banks of the Khrevitsa River and in quarries near the villages Slobodka and Gorki. These outcrops have similar trilobite record, containing *Asaphus (Postasaphus) jewensis, Illaenus* sp., *Platillaenus jewensis, Stenopareia glaber, Panderia parvulus, Rollmops wenjukowi, Toxochasmops (Schmidtops) proavus, Chasmops marginatus, Ch. tumidus, Ch.* sp., *Atractopyge dentata, Nieszkowskia ahtioides, Hemisphaerocoryphe rosenthali, Conolichas monticulosus, Otarozoum pahleni* and *Amphilichas* sp.

The section at Gorki consists of two parts. The first is represented by an intercalation of bluish-grey limestone and argillaceous limestone, with two distinct layers of clay (the Khrevitsa Formation). The second part is represented by an intercalation of yellowish-grey limestone and argillaceous limestone lying on a thick layer of illite clay (tentatively attributed to the Elizavetino Formation).

The three beds with trilobites distinguished in course of investigation – the Chasmops odini beds, the Scopelochasmops wrangeli beds and the Rollmops wenjukowi beds – have apparently some further potential in biostratigraphy of the Uhaku-Haljala stratigraphic interval.

Ordovician sedimentary environments and facies of northwestern Siberia: the Kulumbe river section

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The Ordovician succession of the northwestern Siberian platform (in present-day orientation) is most fully represented in exposures at the Kulumbe River banks (Igarka-Norilsk region). The succession is composed by five distinct sedimentological complexes (facial belts), which can be organized into nearshore-offshore facies profile. From the shallow-water nearshore facies to the relatively deep-water offshore ones the complexes are as follows (in terms of regional stages and formations):

Quartz sand beaches
These are the most nearshore shallow-water facies. They are represented by well washed pure fine- to medium-grained quartz sands locally with distinct cross-stratification. Ripple marks and mud cracks are the most frequent features visible on bedding planes. The color varies from white to light grey and pink. Vertical burrows of Psilonichnus?-type are abundant at some levels. No marine fauna has been reported from these facies. The quartz sandstones are best represented in the middle part of the Guragir Formation (Vikhorevian Regional Stage; Middle Ordovician).

Red beds lagoon
The rocks are dominated by red usually slightly dolomitized siltstones with caverns from leached gypsum nodules. At some levels red siltstones are intercalated with grey or violet siltstones containing locally glipto-morphoses after galite crystals. Intercalations with quartz sandstone beds are also common. Body or trace fossils have not been reported from these facies. The red facies constitute the lower and upper parts of the Guragir Formation (Vikhorevian and Mukteian Regional Stages) and Amarkan Formation (Kirensk-Kudrino Regional Stage; Middle Ordovician). Sedimentary environments are interpreted as shallow-water hypersaline lagoon.

III. Oolite barrier complex
The rocks are dominated by fine-grained oolithic grainstones with distinct ripple marks indicating extremely shallow-water environments. Stromatolites and flat-pebbled conglomerates are common at some levels. Abundant trace fossils indicate normal marine environments. Carbonates are pure with no traces of siliciclastic input. Typical examples of these facies are the Lower and basal Middle Ordovician deposits of the Il'tyk Formation (Njaian, Ugorian and Kimaian regional stages). The facies are interpreted as barrier bar complex separating the hypersaline red beds lagoon from the open sea.

IV. Middle shelf facies
The rocks are light to dark grey heavily bioturbated bioclastic waskestones. Thalassinoides ichnotexture are very common. Bioclasts occur mainly as broken shells of ostracods, trilobites, brachiopods and gastropods. Echinoderm ossicles are also common. At some levels black calcareous shales intercalate with bioclastic wackestones. A typical example of these facies is the Angir Formation of the Volgian Regional Stage (Upper Darriwilian). The facies are interpreted to be normal marine middle shelf.

V. Slope facies
The rocks are represented by flysh-like intercalation of grey and dark grey calcareous siltstones and bioclastic waskestones. Trilobites, brachiopods, echinoderms, bryozoans, and ostracods occur in abundance at some levels. Typical example of the facies is the Zagorninskaya Formation (Chertovskian and Baksanian Regional

Stages, Upper Ordovician). The facies are interpreted as relatively deep-water slope facies with predominantly event sedimentation.

The observed basinward and landward shifts of facies most likely reflect sea-level fluctuations.

The *Pygodus* evolutionary lineage and its significance for detailing the Ordovician conodont scale of the Southern Urals

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The Ordovician conodont scale of the Southern Urals was recently elaborated by S.V. Dubinina. This scale comprises twelve subdivisions based on the succession of conodont associations from Late Tremadoc to Ashgill times as well as on the changes of the evolutionary lineages of *Periodon, Protopanderodus, Ansella, Pygodus*. The latter lineage has a particular significance for establishing detailed Uppermost Llanvirn conodont subdivisions in the Southern Urals scale. The *P. serra* → *P. protoanserinus* → *P. anserinus* evolutionary succession is traced in the *Pygodus* lineage in which the middle member, i.e. *Pygodus protoanserinus* Zhang is essentially valuable. It means that two short-ranged subdivisions might be established in the Uppermost Llanvirn (i.e. in the uppermost part of the Middle Ordovician) in the conodont scale of the Southern Urals. Really, in the Uppermost Llanvirn, the subdivision comprising *P. protoanserinus* and *P. serra* is succeeded by the subdivision containing *P. protoanserinus* and *P. anserinus.* The first subdivision is equivalent to the uppermost part of the *Pygodus serra* Zone in the Baltoscandic Region. The second subdivision being characterized by *P. protoanserinus* and *P. anserinus* is an equivalent of the lowermost part of the *Pygodus anserinus* Zone in Balto-Scandia. Besides, in the Southern Urals sections we have found associations included *P. serra* (Hadding) and *P. anserinus* Lamont et Lindstrom. These associations have been related to the faunal characteristic of the second subdivision and, respectively, to the lowermost part of *Pygodus anserinus* Zone in Balto-Scandia. In the Southern Urals the Ordovician conodonts have been found in different types of sections (for example, in chert-basalt, tuff-chert and mixed composition volcanogenic types) related to various parts of an active margin of the Paleo-Urals Ocean. The conodont faunas from deep-water deposits of the Southern Urals are relatively low diversity faunas consisting of cosmopolitan and widespread species. Endemic species are rare. The Ordovician conodont scale of the Southern Urals is one of the few scales related to the Tropical Domain of the Open-Sea Realm (OSR). As to reconstruction of the evolutionary lineages such as *Pygodus* lineage, it seems it is very useful for establishing detailed subdivisions in the Ordovician conodont scale of the Southern Urals.

Mass concentration of nautiloids and associated fauna in the Late Ordovician at Osmundsberget, Siljan district, Dalarna, Sweden

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A unique concentration of oriented orthoconic nautiloids is exposed at the south entrance of Osmundsberget Quarry in the Siljan District, Dalarna. Here steeply dipping pelmicritic beds of the Glisstjärn Formation overly massive micrites of the Boda Limestone mud mound. The contact is an angular disconformity with the surface of the older unit being broadly undulating. Close to the boundary beds two distinct horizons with nautiloid cones are found within 10 cm of each other. On a well exposed surface measuring 3 × 2 m the direction of 167 cones has been plotted so far, giving a strong bipolar distribution. Two orthoconic nautiloid genera are present; *Dawsonoceras* sp. and a smooth unidentified form. A third rare, coiled nautiloid is represented by three specimens. Especially the smooth form has long and thin cones, measuring up to 110–120 cm. Smaller specimens are also present, but a size distribution of the specimens has not been made. Though some cones are truncated or obscured by weathering and/or general fragmentation, they appear to have been intact when buried. None of the investigated specimens show signs of encrustation.

Most cones are parallel to the substrate but their orientation show signs of being affected by each other, giving slightly oblique orientations in some specimens. The body chambers are generally filled with shell debris, while chambered shells show partial infilling of fine carbonate sediment in the bottom of the anterior most chambers only. In some investigated specimens these geopetals record different angles from one chamber to the next, suggesting differential infilling with slight movement of the cone in between, and hence rapid sequential deposition.

In the northern flank of the quarry, the depositional sequence from the cephalopod wall is repeated though here the concentration of cones has diminished significantly. There is also a different and thicker development of the Glisstjärn Formation here, reflecting again the underlying topography of the Boda Limestone. The angular unconformity can be measured to about 10 degree angle in this locality.

Very few other macro fossils are found *in situ* with the nautiloids, though pelmatozoan matrix is the prevalent lithology. Otherwise two species of trilobites are recognized with a few specimens each, a calymenid and a large *Stenopareia*, though none of these are complete. In addition a *Septatrypa* and an unidentified articulate brachiopod are represented with a few specimens. Small rynchonelliformean as well as phosphatic brachiopods have been identified in previous studies. The most abundant group beside the nautiloids are gastropods and paragastropods, and *Loxonema*, *Maclurites*, and *Angulospira* are identified. Specimens of the high spired gastropod *Loxonema* are most common. The two other taxa are known from one specimen each, but are interesting from a stratigraphic point of view because they strongly suggest an Ordovician age of the strata. Species of the sinistrally colied paragastropod *Angulospira* are endemic to the Ashgill Boda Limestone, and the specimen in the Glisstjärn Formation represents a new species. The gastropod *Maclurites* is a distinct Ordovician genus. The existing literature suggest that the Hirnantian through the earliest Aeronian is missing in Siljan, but the sequence from the uppermost part of the Boda Limestone to the base of the Kallholn Formation overlying the Glisstjärn Formation has hitherto been without biostratigraphic control.

The concentrations of nautiloids are interpreted as distinct events, possibly caused by storm and wave action. Deposition was in a very shallow environment around the margins of the pre-existing topographic height represented by the Boda Limestone, and burial was rapid. Associated fauna, especially among the gastropods and paragastropods, suggest an Ordovician age of this part of the Glisstjärn Formation. Detailed interpretation of the distribution and depositional history of the nautiloid event and its associated fauna will have implications toward understanding of the facies surrounding the Boda Limestone mound, as well as the stratigraphy at the Ordovician–Silurian transition in Siljan.

Gaps, grains & graptolites – ups and downs of Scandinavia in the Ordovician

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The Ordovician succession of Scandinavia is considered to have formed in an overall tranquil tectonic setting where predominantly carbonates and clays were deposited within an epicontinental sea. Although some tectonic influence was documented to influence sea level fluctuations during the Cambrian and into the Early

Ordovician in the Russian part of the basin, Sweden and Norway is thought to represent a stable intracratonic environment.

Gaps in the lithostratigraphic succession, however, reveal a somewhat different story. When comparing Scandinavian second-order eustatic trends of sea-level (tens of millions of years) with other continents, it becomes clear that only the Norwegian sections reflect worldwide base level fluctuations. The Tremadoc interval there represents an overall highstand of sea-level worldwide whereas in Västergötland, Öland and Scania the upper Cambrian to lower Tremadoc is marked by a considerable hiatus, in part with documented subaerial exposure. These regions therefore must have undergone tectonic uplift, probably induced by a major fault system that intersected Baltica and was active during the Lower Ordovician. This tectonic lineament or zone is likely also responsible for the facies distribution during the Ordovician known as Jaanusson's confacies belts: The extension of relatively deeper shelf sediments onto the Baltic plate forming the embayment of the Livonian tongue mirrors crustal movements resulting in varying subsidence rates during the deposition of the Ordovician succession. Slightly later, during the Middle Ordovician (Late Darriwilian) the western rim of the Baltica plate in Norway reflects synsedimentary tectonic activity, too. Uplift, subaerial exposure and subsequent denudation at the western basin margin is recorded in the onset of turbidite deposition in the basin center today exposed around Oslo. Based on the limited amount of sediment shed into the basin it seems likely that only a relatively small island consisting of basement rocks and surrounded by a carbonate beach was created by these movements. This island must have been situated quite a bit west of the study area, and today nothing is preserved of it but the carbonate and quartz grains forming the turbidites in the Norwegian part of the basin.

The Scandinavian Ordovician succession offers two intriguing possibilities to detect base level fluctuations – whether produced by tectonics or eustasy or a combination of the two – with the help of organisms and trace fossils. Within the Swedish succession, a short term subaerial exposure within an overall mud-rich carbonate succession can be recognized by using fossil beach structures produced by crab-like organisms in the Late Darriwilian (Llandeilian) of Västergötland. In the other extreme of the basin, the deep shelf, the graptolites mirror environmental changes within a monotonous shale succession. Pandemic and endemic faunal elements show an intriguingly interesting story of coming and going of graptolite communities in a deeper shelf setting at Mt. Hunneberg. They clearly outline the various deepening and shallowing events of this part of Palaeozoic Scandinavia. The integration of all aspects – gaps, grains and graptolites – help us to attain a more coherent story that much better explains the complex history of this seemingly quiet and tranquil Palaeozoic platform in the Ordovician.

A continuation of the Late Ordovician – Early Silurian ice-house period

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The origin of the prominent, positive, middle Palaeozoic carbon isotope excursions (CIE's) has been an intensely studied and debated topic during the last decade. Although the CIE's differ in magnitude, the strata they occur within have many features in common; e.g. faunal redistributions and extinctions as well as unconformities reflecting fluctuations in global sea-level. From these similarities, a common origin of the CIE's is likely, and a number hypothesis and models have been put forward. In common for the majority of these models are changes in primary production and/or organic burial potential following oceanographic-climatic changes. Since the Late Ordovician (Hirnantian) and the Early Silurian (latest Telychian-earliest Sheinwoodian) CIE's are correlated with tillites, a coupling to glacio-eustasy has previously been proposed. However, due to lack of younger Silurian tillites, the icehouse period starting in the Late Ordovician is generally regarded as being replaced by greenhouse conditions following the Early Silurian. Therefore, a general coupling between glaciations and the middle Palaeozoic CIE's is controversial. Here we present sedimentary data from the carbonate platforms on southern Gotland in the Baltic basin, and $\delta^{18}O$ data, measured on conodont apatite, from the Muslovka, Pozary and Kosov quarries in the Prague basin. The combined data form strong indications for a Late Silurian glaciation associated with the exceptionally prominent late Ludfordian CIE.

From facies analysis of outcrops and drillcores, three depositional sequences (sequences #1 – #3), including two periods of forced regressions (FSST:s #1 and #2, respectively), are identified within the late Ludfordian strata on southern Gotland (Fig. 1). The first forced regression (FSST #1) started within the uppermost Hemse Group, close below the last appearance datum of the conodont *Polygnathoides siluricus* and more or less contemporaneously with the onset of the CIE. The forced origin of the regression is evident by the occurrence of karstified peritidal deposits (Botvide Member and basal Eke Formation) on top of mudstone and wackestone deposited below storm wave-base. The ensuing transgression of sequence #2, starting within the Icriodontid conodont Zone, resulted in the development of a microbially dominated platform during highstand conditions (middle and upper Eke Formation). This platform developed within the slope settings of sequence #1, indicating that the transgression was minor. Sequence #2 ends with a renewed period of forced regression (FSST #2), starting close to the first appearance datum of the conodont *Ozarkodina snajdri*. This forced regression was associated with significant siliciclastic influx (Burgsvik Sandstone) and resulted in a seaward dislocation of the shoreline in the order of at least ca 20 km, reflecting a sea-level fall in the order of several 10's of metres. Associated with the ensuing major transgression of sequence #3, the CIE starts to decline.

Within the Prague basin, a $\delta^{18}O$ excursion exceeding 2‰ starts in the upper *P. siluricus* Zone and ends within the *O. snajdri* Zone. The $\delta^{18}O$ excursion shows indications for two separate peaks in accordance with the two separate periods of forced regressions within the Baltic basin. This close interrelationship is regarded as a strong indication for that the $\delta^{18}O$ excursion reflects climatic cooling and ice-sheet build up, and that the two regressions reflect the resulting glacio-eustasy. The temporary lower values between the two peaks of the $\delta^{18}O$ excursion, and the minor transgression between the two periods of forced regression, are interpreted to reflect interglacial conditions. A Late Silurian glaciation associated with the late Ludfordian CIE may have implications not only for our understanding of the middle Palaeozoic CIE's, but also for the duration of the ice-house conditions starting in the Late Ordovician.

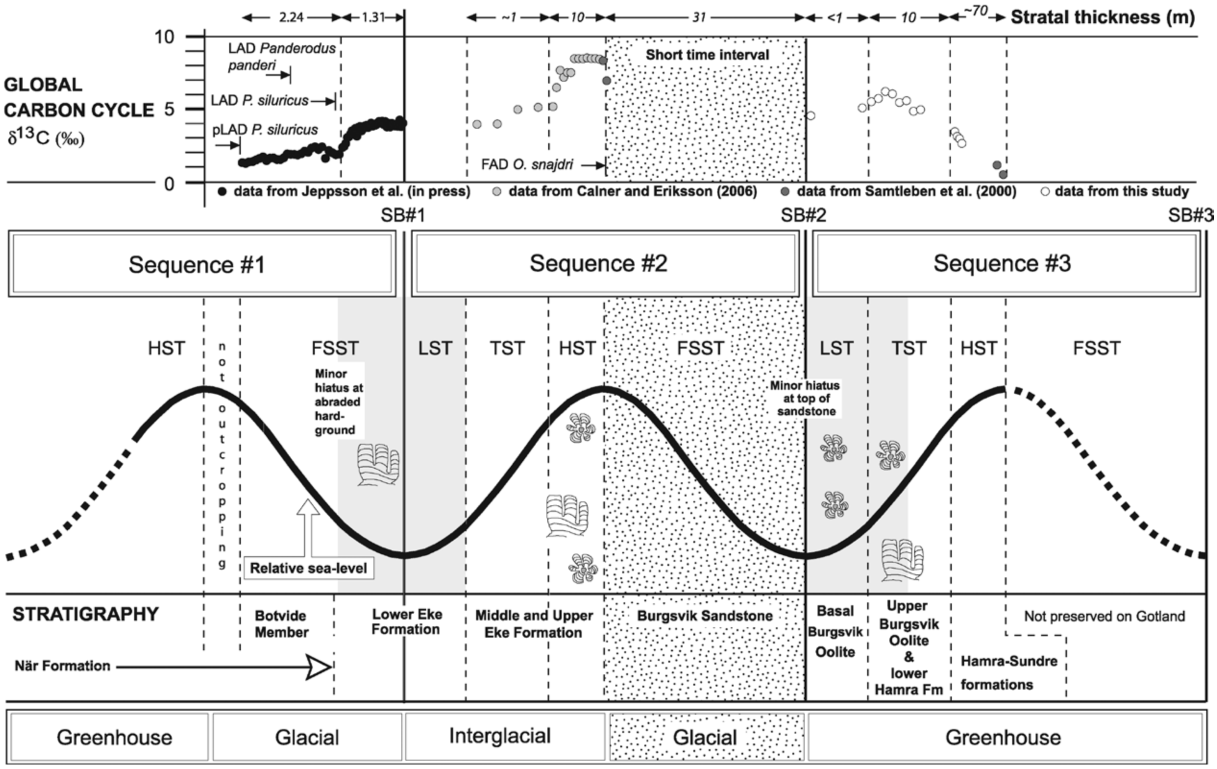

Figure 1. The relationship between the late Ludfordian CIE and depositional sequences on Gotland, and inferred climatic changes. Simplified from Eriksson and Calner (in prep.).

Paragastropoda, Tergomya and Gastropoda (Mollusca) from the Upper Ordovician Dalby Limestone, Sweden

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Exceptional carbonate deposits of the Dalby Limestone developed during the Upper Ordovician (Kukruse Stage to Idavare substage) in the area of Tvären and Lockne (Sweden) as a result of two nearly coeval bolide impacts into the marine environment. The deposits are characterized by thicknesses numerous times greater than common for the unit and with a wider range of facies. The type area for the Dalby Limestone in the Siljan District, Dalarna, (Sweden) is used together with the Kårgärde section in Siljan for comparison of gastropod diversity and distribution together with the Lockne and Tvären successions. A fauna of 12 species, comprising about 200 specimens, of paragastropods, tergomyans and gastropods is described presenting a higher diversity than previously documented from the limestone. Species recognized from Tvären include *Bucania erratica* Frisk & Ebbestad, 2007, *Holopea*? sp., *Eotomaria* cf. *E. notabilis* (Eichwald, 1840), *Lophospira* cf. *L. subulata* (Koken *in* Koken & Perner 1925), and *Pleurorima*? sp. These have been found in erratics originated from the shallower rim facies in the Tvären crater. The fauna from Lockne includes *Sinuites* cf. *S. corpulentus* Koken *in* Koken & Perner, 1925, *Deaechospira* cf. *D. elliptica* (Hisinger, 1831), and *Ectomaria* sp. In Dalarna (Fjäcka and Kårgärde) *Mimospira tenuistriata* Wängberg-Eriksson, 1979 has previously been recorded (Wängberg-Eriksson, 1979). Besides this species, an *in situ* specimen of *Eccyliopterus regularis* Remelé, 1888 and museum collections of *Laeogyra reinwaldti* (Öpik, 1930), *Sarkanella epelys* Frisk & Ebbestad, 2007 and *Deaechospira elliptica* (Hisinger, 1831) are recognised from the type locality, Kårgärde, and Furudal.

Significant biostratigraphical and biogeographical results from this study are 1) the presence of *Mimospira*, *Laeogyra*, *Sarkanella epelys* indicates a strong faunal connection with Bohemia, Czech Republic. 2) *Sarkanella* is reported from outside Bohemia for the first time. 3) *Bucania erratica* n. sp. represents one of the earliest records of the genus in Baltoscandia. A single case of shell repair from failed predation is recorded in this species. 4) Synonyms for *Eccyliopterus princeps* Remelé and *E. regularis* Remelé are proposed. 5) The significance of *Laeogyra*, *Eccyliopterus*, and *Deaechospira* for regional correlation within the Upper Ordovician of Baltoscandia is confirmed.

The relationships between sea-level changes and facies for Late Ordovician faunas, western Baltica: geochemical evidence of oxic and dysoxic bottom-water conditions

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The fauna, geochemistry and sedimentology of the Sandbian-Katian (Upper Ordovician) have been investigated in the Oslo Region, Norway. The aim was to study the relationships between sea-level changes, oxygen levels in the bottom water and faunal changes (especially for the brachiopods) in the region during this period.

The Arnestad Formation (upper Sandbian) is characterized by shaly deposits interbedded with calcareous mudstone layers and stratabound carbonate nodules. The overlying Frognerkilen Formation (basal part of the Katian) is dominated by nodular calcareous mudstones with interbedded siliciclastic mudstone. Some horizons in the Arnestad Formation contain scattered phosphorite nodules indicating, at least periodically,

low sedimentation rates. No phosphorite nodules were observed in the Frognerkilen Formation. K-bentonites occur throughout the Arnestad Formation. The deposits are thoroughly bioturbated, resulting in homogenization of the matrix and poorly preserved sedimentary structures. The trace fossil *Planolites* ichnosp. (often pyritized) is abundant while *Chondrites* ichnosp. is somewhat less common. *Thalassinoides* ichnosp. is common in the Frognerkilen Formation, but the specimens of this characteristic trace fossil are poorly preserved because they are overgrown by carbonate nodules. An ichnofauna dominated by *Chondrites* ichnosp. indicates relatively low oxygen levels in the bottom water during deposition.

The soft-bottom fauna shows an overall high biodiversity with fragments of brachiopods, bryozoans, conchostracids, conulata, echinoderms, graptolites, machaerids, molluscs, ostracods and trilobites. Brachiopods are the dominating macrofossils and four different assemblages have been recognized. These are, in ascending order, the *Grorudia-Septorthis*, *Chonetoidea*-lingulid, *Chonetoidea-Onniella*, and the *Cremnorthis*-lingulid assemblages. The *Chonetoidea*-lingulid and *Chonetoidea-Onniella* assemblages are known from deep and slightly shallower environments, respectively, in other parts of the world.

Trace element ratios such as the V/(V+Ni) ratio are valuable for distinguishing variations in the oxygen content of bottom waters. This analysis indicates that the lower and upper parts of the Arnestad Formation were mainly deposited in an environment transitional between oxic and dysoxic bottom-water conditions. A narrow stratigraphical interval, including the Kinnekulle K-bentonite, is characterized by lower dysoxic conditions. Prior to the deposition of the thick K-bentonite layer, the fauna became low-diverse with a dominance of sporadic, pelagic graptolites. The uppermost part of the Arnestad Formation shows a clear transition into oxic conditions. This trend continues into the lower part of the Frognerkilen Formation before dysoxic conditions gradually returned at the top of the Frognerkilen Formation and the overlying basal part of the Nakkholmen Formation (Katian Stage). The bryzoan, *Diplotrypa*, in the same part of the succession also shows a gradual change from smaller to large colonies in the oxygenic lower part of the Frognerkilen Formation followed by a return to smaller colonies with the return to dysoxic conditions. Among the brachiopods, a *Cremnorthis*-lingulid assemblage characterizes the interval with relatively high oxygen, which is preceded and succeeded by a diverse *Chonetoidea-Onniella* assemblage.

Our data are closely comparable with sea-level curves proposed for central Baltica. These show an overall trend from a lowstand to a transgressive phase in the basal part of the succession. In the upper part, there is evidence of a succession from a highstand at the Kinnekulle K-bentonite to an absolute lowstand in the lower part of the Frognerkilen Formation, followed by a major transgression. Dysoxic conditions prevailed during the highstand, whereas oxygenated bottom-water conditions prevailed during the lowstand, represented by the lower part of the Frognerkilen Formation.

Two major immigrations of brachiopods took place during the late Sandbian, after the cessation of the lower dysoxic conditions but prior to the major oxic and shallowing event. The sea-level changes also had a marked influence on the preservation of the brachiopods. There is a higher articulate to disarticulate ratio of brachiopod shells during highstand than lowstand conditions, and this difference is attributed to less post-mortem reworking of the skeletal material in the more tranquil sedimentary environment during highstand.

Depositional environment of the Middle Ordovician Elnes Formation, southern Norway

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During most of the Darriwilian (Middle Ordovician), the south Norwegian Oslo Region was characterized by wide-spread deposition of dark graptolitic mudstones, which are separated as the Elnes Formation. New investigations on this nearly 100 metres thick formation and its depositional environment support earlier views regarding the presence of a western land area, the Telemark Land, which supplied the Oslo Region with siliciclastic sediments. The presence of a northern source area as proposed in more recent years is not supported.

Discrepancies in lithofacies and inferred relative sea-level changes between the southern and northern Oslo Region are indicative of tectonical uplift to the south, suggesting a late Middle Ordovician continuation of the continent-island arc collision thought to have commenced just prior to the deposition of the Elnes Formation. The water depth was probably somewhat less than 100 metres through much of the period of deposition, and most likely never exceeded c. 200 metres.

The Impact of Ordovician Climate Change on the Carbonate Facies of the East Baltic (Estonia and northwest Russia)

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The northward movement of Baltica from sub-polar to tropical settings during the Ordovician is well documented from palaeomagnetic data and has been used to explain the relatively thin Ordovician section in the region. The carbonate facies transitions document the succession of depositional changes along this temporal environmental gradient.

Ordovician strata in Estonia and northwestern Russia occur along the northwestern (present day orientation) edge of the East European Platform between the Baltic Shield to the north and the Livonian Basin to the south. The Ordovician outcrop belt nearly parallels depositional strike and exposes section of shelf and shallow ramp facies. The shelf sections grade through a transitional zone into basinal facies (available in core sections) in southern Estonian, western Latvia and northwestern Lithuania.

The sedimentary facies, biostratigraphy and cyclicity of these strata have been studied by numerous workers for many decades. On a regional scale, the Ordovician facies succession can be divided into temperature-related phases (here noted in terms of Baltic regional stages) based on depositional constituents. They also illustrate a consistent association of increased sediment accumulation rates and progradational geometries during the shift from cool-water to tropical carbonates.

The depositional phases are:
Phase I: Siliciclastics. Pakerort to mid-Billingen Stages

- Phase I is marked by numerous unconformities, long hiatues, and thin and laterally discontinuous units. Siliciclastic-dominated units include both coarse and fine-grained facies. Carbonate deposits are absent and fauna sparse. The sediment accumulation rate is low (2.3 m/Ma) reflecting the numerous gaps in the section.

Phase II: Cool-Water Carbonates. Mid-Billingen to Volkhov Stages

- Hardground dominated subphase: The mid-Billingen to lower-Volkhov interval is dominated by chemical processes such as hardground formation, mineralization and corrosion that overprint very low background deposition of bioclastics and clay materials. The result is a very thin section that consists of chemical carbonate units that accumulated at a very low rate (1.1 m/Ma).
- Firmground dominated subphase: The Upper Volkhov strata are marked by a shift toward increased bioclastic carbonates with clays over chemical (hardground) horizons. Glauconite remains common, and some iron ooids occur. The accumulation rate of 6.9 m/Ma is similar to the lower part of the temperate carbonate phase, reflecting the transitional aspect of the upper Volkhov interval.

Phase III: Temperate Carbonates. Kunda to Haljala Stages

- In the Kunda to Aseri Stages, glauconite is rare and sandy carbonates occur in updip sections. Iron ooids are common in the Kunda Stage as lowstand deposits, and become abundant in the Aseri Stage. The accumulation rate of the lower part of the temperate carbonate phase (6.7 m/Ma) is considerably higher than the hardground-dominated subphase of the cool-water carbonates, but similar to the upper Volkhov interval.
- The upper part of the temperate carbonates (Lasnamägi to Haljala Stages) are slightly muddier and include kukersite beds (Uhaku and Kukruse Stage). The pronounced progradational strata geometries in the Kukruse Stage may reflect the increased sediment accumulation rates (11.1 m/Ma) associated with the Lasnamägi to Haljala interval.

Phase IV: Tropical Carbonates. Keila to Porkuni Stages.

- The full suite of tropical carbonate constituents is found in the Keila to Porkuni Stages including carbonate ooids, corals, and numerous small reef bodies (mud mounds). Progradational stratigraphic geometries occur at several levels associated with the upper parts of sequences (Keila) or prograding sets of sequences (Pirgu). The sediment accumulate rate (16.4 M/Ma) is the highest of all phases.

These phases record the transition of sub-polar to tropical settings associated with the northward drift of Baltica during the Ordovician. Phases I and II (Parkerort to early Volkhov) are cool-water deposits, and the shift toward temperate carbonates began in the late Volkhov. Temperate carbonate deposition was clearly in place by the Kunda and Aseri, with more muddy carbonates appearing in the later (warmer) part of this phase (Lasnamägi to Haljala). The Keila to Porkuni interval (Phase IV) has clear tropical carbonate features.

The carbonate facies document the shift in major constituents (ooids, lime mud etc.), degree of sea-floor diagenesis, and accumulation rates associated with the cool-water to warm-water transition. Less predictable findings are the predominance of hardground and corrosion surfaces in the cool-water facies, and the clear sequence in the changes of carbonate constituents. Well-developed progradational geometries in the Kukruse and later intervals are associated with higher sediment accumulation rates. Although present in earlier intervals, progradation is more localized.

These facies changes are superimposed upon a sequence stratigraphic framework of approximately nineteen identifiable sequences. These consist of the ten regional sequences recognized by Dronov and Holmer (1999) with additional subdivisions based on detailed sedimentological studies. The sequences can be correlated to similar sequences in Laurentia and can be identified within the four carbonate phases despite their different depositional styles.

The Vormsi Stage in the East Baltic: depositional sequence, facies and faunal differentiation

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The Ordovician carbonate sequence in the East Baltic comprises two stratigraphical intervals when the basinal black shales reach the Central East Baltic (western Latvia, southern Estonia and northwestern Lithuania): Mossen Formation during the Keila-Oandu time and Fjäcka Formation during the Vormsi time. The aim of this study is to clarify the facies patterns and faunal associations in the depositional sequence comprising deposits of Late Ordovician Vormsi age. Data on the Vormsi Stage in about 100 drill core sections in the East Baltic (Estonia, Latvia and Lithuania) are analysed, more than 10 cross sections aligned along the onshore-offshore (north–south) and latitudinal (east–west) profiles are compiled, and the boundaries and correlation of sections and thickness patterns are discussed. The facies patterns are analysed within temporal framework based on detailed chitinozoan biostratigraphy.

The main part of the Vormsi Stage consists of a shallowing-upward depositional sequence capped by shallow-to-deep ramp deposits. The Vormsi facies range from grain-supported bioclastic facies in the shallow shelf, to mixed bioclastic facies in the mid-shelf environments, to mud-supported and black shale facies in deep shelf and basinal environments.

An integrated study of deposits and different fossil groups revealed palaeontologically distinct strata in the middle part of the Vormsi Stage in Central Estonia. These beds are missing, or have very restricted thickness, in shallow shelf facies and contain taxa common with relatively deep-water faunas of other regions in Europe, particularly Scandinavia, United Kingdom and Belgium. The shallow shelf benthic faunas of large brachiopods, bryozoans, corals, molluscs and trilobites in association with calcareous algae are replaced by less diverse faunal associations of small-shelled brachiopods, bryozoans and pelmatozoans within a relatively short distance (tens of kilometers).

The facies changes on the base and top of the Vormsi Stage are sharp and coincide with those of the depositional sequence. The seismic data recorded in the westernmost Baltic Sea revealed the occurrence of channels, formed before Vormsi deposition. In shallow shelf facies (northern Estonia), a marked discontinuity surface was formed on the top of carbonate mudstones (Saunja Formation of the Nabala Stage), which are overlain by mixed shelf facies of the Vormsi time. The top of the Vormsi Stage is marked in slope environments in the East Baltic by the channel like structures and localized stratigraphic erosion.

Small-scale sea level changes may be responsible for the varying siliciclastic content of Vormsi shallow shelf carbonate facies, but become less clear in mud-supported deeper shelf and basinal sections. The co-occurrence of scolecodonts of both shallow- and deeper water associations may indicate transitional facies and/or small-scale sea level fluctuations in the mid-Vormsi time. The first and last appearance levels of zonal or other biostratigraphically significant chitinozoans allow the stage to be subdivided into four parts, the distribution and thickness of which indicates a complex stratal architecture. The Vormsi sequence may be divisible into four or more parasequences.

Biostratigraphic data also allows regional correlation of the Estonian sections. The mid-Vormsi brachiopod fauna of Central Estonia includes several taxa in common with the specific Hulterstad Fauna recovered in the erratics of Öland, including *Hulterstadia cor* (Wiman). Wide spatial distribution of subzonal chitinozoan *Acantochitina barbata* in the topmost part of the Vormsi Stage ties grain-supported shallow shelf carbonates of the East Baltic and black shales of basinal facies in Sweden.

Late Ordovician Sclerites in the Siljan District, Sweden

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Isolated and semi-articulated sclerites of machaeridians are common in the Upper Ordovician (lower Nabala Stage) Fjäcka Shale of the Siljan District in Sweden. The organic rich shale offers a high preservation potential, preserving a dysaerobic, quiet deepwater environment. In the succeeding carbonate mounds of the Boda Limestone (Nabala-Porkuni stage) machaeridians and other sclerite bearing animals have hitherto been unknown. Though still rare, the presence of various sclerites in environments such as the carbonate mud mounds is not surprising, as many of these taxa are widespread stratigraphically, geographically and environmentally.

Amongst the machaeridian sclerites perhaps the most striking find are a few minute sclerites from pockets in the Kallholn and Solberga quarries. These animals are associated with minute fauna of gastropods, ostracodes and complete trilobites, which may have belonged to a cryptofauna. However, the presence of such faunas in the fossil record is difficult to prove. The diversity of the machaeridian sclerites is high with different genera represented in different settings; it also seems to indicate a higher presence of machaeridians than what is shown at present.

Among the macro fauna, a single large sclerite of a plumulitid machaeridian has been identified in the Osmundberget quarry from a fossil pocket consisting largely of pygidia of the trilobite *Eobrontus laticauda*. It is inferred, by comparison with studies on trilobite ecology, that the machaeridian animal lived on the upper part of the mound. In Jutjärn quarry a single large sclerite of the polyplacophoran *Chelodes* was found in a pocket dominated by cephala of the trilobite *Stenopareia linnarssoni*. By analogy with the previous find, the polyplacophoran probably lived on the upper surface of the mound.

Life habits of Ordovician lingulids: first record of a lingulid brachiopod within a hard ground from the Uhaku Stage, Estonia

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A new occurrence of a lingulid brachiopod occurring in assumed vertical life position within deep depressions in a phosphatized hard ground are described from the Uhaku Stage, Estonia. Well-documented records of lingulid brachiopods preserved in life position have previously been described from Ordovician and younger deposits, but this is the first known *in situ* occurrence of a lingulid from within a hard ground. There is no evidence indicating that the lingulid was responsible for the excavated depression in the hard ground, but it most likely settled within an existing depression. If active burrowing was at all involved, it was most likely performed by burrowing with the pedicle oriented downward into the soft sediment filling the narrow pre-existing depressions. Some of the depressions in the hard ground are apparently of *Amphora*-type and may represent organic borings. Lingulids preserved inside organic borings have previously only been documented from Late Ordovician and Silurian tabulate corals and stromatoporoids.

The Lower Silurian (Llandovery) Osmundsberg K-bentonite

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The Lower Silurian (early Telychian) Osmundsberg K-bentonite is a widespread altered volcanic ash bed that occurs throughout Baltoscandia and other parts of northern Europe. The type section of this K-bentonite is in the abandoned Osmundsberg Quarry in the eastern part of the Siljan impact structure in the Province of Dalarna where the ash bed is located in the Kallholn Shale that unconformably overlies the Upper Ordovician Boda Limestone and Nittsjö Formation. The Osmundsberg bed is 115 cm thick at this locality and is accompanied in the approximately 10 m thick section of the Kallholn Shale by 8 additional K-bentonite beds that range between 1 and 32 cm in thickness. Graptolites of the *Spirograptus sedgwickii* Zone have long been recorded from the basalmost part of the Kallholn Shale, which is a few meters below the interval of the Osmundsberg K-bentonite. From higher portions of the Kallholn Shale, including the interval of the Osmundsberg K-bentonite, there have been reports of *Spirograptus turriculatus* and other graptolites of the *Spirograptus turriculatus* Zone. However, the level of the base of the latter graptolite zone remained undetermined until 2003 when Loydell & Maletz clarified the graptolite biostratigraphy in the section. Their data show that the interval from about 5 m to 9.5 m above the base of the Kallholn belongs in the *Spirograptus guerichi* Zone, and that *S. turriculatus* and other graptolites of that zone appear about 0.5 m below the base of the Osmundsberg K-bentonite. Loydell & Maletz also recorded the zonal index *S. turriculatus* about 0.5 m above the Osmundsberg K-bentonite, hence confirming the correctness of the original assignment of this prominent ash bed at its type locality to the *S. turriculatus* Zone. In terms of chitinozoan biostratigraphy, it occurs in the lower part of the *Angochitina longicollis* Zone.

The Osmundsberg and associated beds consist largely of clay minerals accompanied by a variety of primary volcanogenic crystals and secondary sulfides, sulfates, oxides, carbonates, and silicates. Although the clay mineral composition of lower Palaeozoic K-bentonites is generally distinctive compared with adjacent siliciclastic rocks, their volcanic origin can be confirmed through the recognition of fragmented or euhedral phenocrysts of volcanic origin.

The abundance and thickness of this succession together with the similarity of biostratigraphically coeval ash beds elsewhere constitutes the basis for a study of the geographic extent and the stratigraphic and palaeotectonic significance of these beds. K-bentonite samples from sections containing the Osmundsberg K-bentonite bed were investigated to determine whether the chemical composition of these beds might serve as a basis for high-resolution chemostratigraphic correlation on a regional scale. TiO_2, the High Field Strength (HFS) elements Zr, Nb, Hf, Ta, and the Rare Earth elements (REE) are commonly considered to be immobile under most conditions of diagenesis and low grade metamorphism, and are thus useful indicators of petrogenetic processes. The Nb/Y ratio is widely used as a measure of alkalinity and Zr/TiO_2 as an index of differentiation. Many explosively erupted volcanic ashes tend to have moderate to high Nb and Zr content reflective of their silicic and high volatile (H_2O) character. A plot of Zr/TiO_2 against Nb/Y shows that most Osmundsberg K-bentonites are subalkaline to alkaline in nature and derived from silicic magmas that were trachyandesite to dacite in composition. Bivariate plots of Eu-Th/Yb, Zr-Eu, Yb-Th, Eu-La/Lu, V-Hf, Zr/Tb-Th/Yb, Eu-Ta/Yb and Zr-Th/Yb show the separation of the groups when trace elements and elemental ratios are used as discriminators. The Osmundsberg samples plot away from the other three groups and show good clustering. Thirty-three samples were analyzed for 26 trace elements by Instrumental Neutron Activation Analysis (INAA) and the data subjected to multivariate statistical analysis. The results of the discriminant analysis of these models generally support the correlation of the Osmundsberg K-bentonite bed from Baltoscandia to the British Isles and northern Europe as suggested by Bergström et al. (1998) based on biostratigraphy, but with some minor corrections.

Radiometric analysis of zircons from the Osmundsberg K-bentonite at its type locality gave a $^{207}Pb/^{235}U$ age of 437.6±0.5 Ma. In the entire Llandovery there are only three published radiometric dates that have been considered sufficiently controlled by fossils to fulfill currently acceptable biostratigraphic requirements. Two of these are from the same upper Rhuddanian graptolite zone and one is from a graptolite zone in the middle Telychian. No accepted radiometric date is available from the Middle Llandovery Aeronian Stage or from a stratigraphic level right at any of the stage boundaries. Furthermore, the cited age of the base and the top of the Llandovery Series are based on extrapolations using values from levels several graptolite zones above and below these boundaries. In the case of the Ordovician/Silurian boundary, the youngest reliable Ordovician radiometric date (445.7±2.4) is from the *Paraorthograptus pacificus* Zone, which is the third graptolite zone below the systemic boundary, and the oldest Silurian date (438.7±2.1) has been regarded as representing the *Coronograptus cyphus* Zone, which is the fourth standard graptolite zone above this systemic boundary. The Llandovery time scale is still in a highly provisional state with most published isotopic dates of zones and stage boundaries based on extrapolation rather than on direct radiometric analysis. This new age will bring much-needed stability to this portion of the early Palaeozoic time scale.

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Linguliformean brachiopods from the Ordovician–Silurian boundary beds, Osmundsberget, Dalarna, Sweden

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Late Ordovician (Harju Regional Series) to Middle Llandovery (*sedgwickii* Zone) Linguliformean brachiopods from the top Boda Limestone, Glisstjärn Formation and lower Kallholn Shale are documented from the Osmundsberget quarry, Dalarna, Sweden. The Late Ordovician linguliform fauna includes a new species of the enigmatic lingulid *Litoperata* as well as the acrotretid *Scaphelasma*. The unconformably overlaying beds yielded a somewhat more diverse linguliformean fauna comprising the cosmopolitan acrotretids *Acrotretella* and *Opsiconidion*, the discinid *Acrosaccus* as well as a new species of the siphonotretid *Orbaspina*, which is otherwise only known from the Silurian of Australia and Bohemia. These finds should be considered in the light of new information strongly suggesting that the Glisstjärn Formation belongs to the Hirnatian (latest Ordovician) as compared to the lower Silurian.

Sounding the Ordovician sea by impact craters

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The interdependence of impact cratering and its environment facilitates the reconstruction of pre- and post-impact conditions in some ways hitherto impossible. For instance, the rim wall of a fresh impact crater on land rises about 0.035 crater diameter above the target surface. At water-covered targets the rim wall diminishes as the water gets deeper. This opens the crater to forceful resurge of water. In water a few hundred meters deep the rim wall of a medium-sized crater is no obstacle to the resurge. The depth of the sea also influences the volume and spread of rock ejecta in ways subject to mathematical modelling.

The early Late Ordovician Brent crater (Ont.; width 4 km) defines a coastal situation by having formed on land, later on to develop into a coastal lagoon. The late middle Ordovician Ames crater (Okla.; 16 km) formed on a shallow-water carbonate platform. The resurge was too weak to overthrow the mighty rim wall that stood up as a morphologic atoll and even developed karst hollows. The early Late Ordovician Kärdla crater (Est.; 4 km) formed at probably 50–75 m water depth near the coast. The rim wall was at least 100 m high in places. Much of it apparently collapsed into the crater, but there was no major resurge invasion. The late Middle Ordovician Granby (Swe.; 3 km) and Hummeln (Swe.; 1 km) craters formed when the Orthoceratite limestone sea was only at most 100 m deep where they formed, which was not enough for resurge to cross the wall. The early Late Ordovician Tvären crater (Swe.; 2 km) formed at a modelled water depth of 100–150 m. The sediment-loaded resurge entered the crater with full strength. However, the rim wall locally rose to near sea-level and provided clasts to the crater a long time after impact. The early Late Ordovician Lockne crater (Swe.; 7 km) formed in a sea at least 500 m deep. The rim wall was low, and the strong resurge formed thick deposits inside the crater. The diversity of environments on the cratered sea-bed influenced local sedimentation and biota in spectacular ways.

Ordovician sedimentation at Brent, Hummeln, and Tvären would have been unknown but for the craters.

Ordovician carbon isotope stratigraphy – some comments on the current state, mainly from the Baltic viewpoint

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Carbon isotopes applied as environmental and chronological proxies have gained an eminent position in palaeoenvironmental studies and stratigraphy. The Ordovician carbon isotope research has in the same lines shown remarkable progress during the last decade. The IGCP 503 and studies on Ordovician GSSPs have promoted many new projects in different regions of the world, which have provided a considerable amount of new data, including those from Europe, North America and China. Our main interest has been detailed investigations in Baltoscandia and compilation of a complete general trend for the whole Ordovician.

Recently our team published a summarising paper where the following seven main positive and one negative carbon isotope excursion were recognised: (1) the mid-Darriwilian excursion (peak $\delta^{13}C$ value 1.9‰) in the Kunda, Aseri and Lasnamägi stages; (2) a wide negative excursion (named the Kukruse low) at the Darriwilian/Caradoc transition with the most negative $\delta^{13}C$ values (–1.6‰) in the uppermost part of the Kukruse Stage; (3) the mid-Caradoc excursion (2.2‰) in the uppermost part of the Keila Stage; (4) the first late Caradoc excursion (2.3‰) in the lower part of the Rakvere Stage; (5) the second late Caradoc excursion (2.4‰) in the upper part of the Nabala Stage; (6) the early Ashgill excursion (2.5‰) in the lowermost part of the Pirgu Stage; (7) the mid-Ashgill excursion (2.0‰) in the upper part of the Pirgu Stage; (8) the widely known large Hirnantian excursion (in Estonia the peak value reaches 6.7‰) in the Porkuni Stage. According to the modern Ordovician terminology, the "low" of excursion 2 is located in the mid-Sandbian and excursions 3–7 are distributed rather evenly throughout the Katian.

The carbon isotope excursions of Baltoscandia, especially the Upper Ordovician ones, can be rather clearly correlated with those of North America (Nevada). It might be concluded that the $\delta^{13}C$ trends established on the Baltica and Laurentia continents are in general lines very similar, indicating synchroneity of main triggering processes and providing good prospects for global chemostratigraphical correlation.

However, some discrepancies have become evident from several recent publications discussing Hirnantian carbon isotope stratigraphy. Melchin et al. (2003) redefined the lower boundaries of the *Normalograptus extraordinarius* and *N. persculptus* biozones at the Dob's Linn section and correspondingly placed peak values of the Hirnantian $\delta^{13}C$ excursion into the latter biozone as well as the entire Porkuni Stage of the East Baltic. In this way the *Belonechitina gamachiana* chitinozoan Biozone (showing low $\delta^{13}C$ values) was correlated with the lower Hirnantian *N. extraordinarius* Biozone. Such correlations fully ignore the evidences presented by Finney a. o.. from the Nevada Monitor Range and Vinini sections, where the rising limb of the $\delta^{13}C$ excursion with peak values is reported from the *N. extraordinarius* Biozone.

Mainly on the basis of data from the Baltic and Nevada sections, Brenchley et al. (2003) suggested a model trend for the Hirnantian excursion with a rising limb in the *N. extraordinarius* Biozone, followed by a slightly lowering plateau and a rather steeply falling limb in the *N. persculptus* Biozone. Considering boundary corrections at the Dob's Linn, we place the peak values of this excursion into the lowermost part of the latter zone. Bergstöm et al. (2006) discussed recently isotope data from several localities of the North American Midcontinent, where they documented nearly the same plateau-like Hirnantian excursion as mentioned above. In the top of the excursion they fixed two gaps marking significant sea level drops, which were traced also in Nevada, Anticosti and Baltoscandia.

Depending on the geological and environmental conditions, two general types of the Hirnantian $\delta^{13}C$ trends have been presented: (1) A plateau-like trend, mostly in carbonate rocks with some amount of shale interbeds. The thickness of the Hirnantian rocks is usually more than 10 m. The occurrences are mentioned above. (2) A narrow peak-like trend as known from the Dob's Linn (shales, 4 m) and Wangjiawan Riverside sections, China (shales and a carbonate bed containing Hirnantia fauna, less than 1 m). The latter section is according to Chen a. o. data firmly correlated with the GSSP section for the base of the Hirnantian only 180 m away. The rising limb of the excursion within the *N. extraordinarius* Biozone is rather similar to that in Baltica and Laurentia, the peak is in the carbonate bed, correlated with the bottom of the *N. persculptus* Biozone, and followed by a very steep falling limb.

Both peak-like trends are connected with deep-water environments, therefore any gaps known from shallower seas are here little probable even if the steeply falling trend causes some doubt. Anyway, differences in the shape of the excursion and geology of the section, extreme condensation included, should be considered when applying carbon isotopes in stratigraphy.

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Filling in the last gap between "golden spikes": "Volkhovian" as a name for the third global stage of the Ordovician System

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In 1996 the International Subcommission on Ordovician Stratigraphy voted in favour of a subdivision of the Ordovician System into three series. The base of the Middle Ordovician was tentatively positioned near the lowest occurrence of *Protoprioniodus aranda* or *Baltoniodus? triangularis* and the base of the Upper Ordovician at the lowest occurrence of *Nemagraptus gracilis*. In 2006, ten years after the tripartite subdivision was agreed, selection of Global Stratotype Sections and Points (GSSPs) and primary correlation criteria for all seven global stages was completed. Today, six of seven stages of the Ordovician System are named in accordance with the generally accepted principles. However, the Third Global Stage, which also defines the base of the Middle Ordovician Series, still lacks a proper name.

The GSSP for the Third Stage was established in the Huanghuachang section, southern China, where the lower boundary of the stage and the Middle Ordovician Series coincides with the level of lowest occurrence of *Baltoniodus? triangularis.* The opportunity of naming the unit in parallel to the formal definition was not used in due time.

To complete the unified Ordovician timescale, it is now time to fill in the last nomenclatorial gap between the "golden spikes". In this situation, erection of a new unit could be an easy way; however, this approach has also some weaknesses. Such a unit would be defined according to the "gap" left in the succession of the Ordovician stages rather than serving as a truly "operational unit". Three Ordovician stages have been named on this basis: Floian, Sandbian and Katian. On the other hand, well-established regional stratigraphical units have been used for deriving names for global units: Tremadocian, Darriwilian and Hirnantian.

Looking for a well established unit, Webby (1998) tentatively proposed "Volkhovian" as the name for the third stage. The name itself was first introduced by Raymond (1916) based on classic studies by Schmidt

(1858, 1881) and Lamansky (1905) in particular. This selection was emphasizing a good fit of this unit in the pre-Darriwilian Middle Ordovician, even before a final definition of the exact boundary level and the index species. A relevant proposal to introduce the name “Volkhovian” for the third stage was published by Dronov and co-authors considerably later, in 2003.

Today, after the boundaries of the stratigraphic interval of the third stage are fixed, we can still consider the “Volkhovian” a nearly perfect fit for this “pre-defined” interval. Although the sections in eastern Baltic area are condensed, the conodont succession is complete in this stratigraphic interval. According to the data from the St. Petersburg area and northern Estonia, the appearance level of the index conodont species *Baltoniodus? triangularis* coincides with the base of the Volkhov Regional Stage. The base of the Darriwilian, which is defined by the lowest occurrence of *Undulograptus austrodentatus* and is nearly coeval with the base of *Baltoniodus norrlandicus* conodont zone, lies near the top of the Volkhov succession, probably in its upper part. This means that the Volkhov Regional Stage, as it is used today in regional stratigraphy, may slightly overlap with the global Darriwilian Stage.

In the former proposal by Dronov et al. (2003), several other important aspects were considered. The arguments like accessibility and continuously fossiliferous section are not relevant any more in today’s particular situation. For a name which is filling in the last gap in a continuous succession, the “best fit” and long-time use in stratigraphy seem to be the main arguments.

If the proposal of using the name “Volkhovian” for the third stage of the Ordovician System will be accepted, some changes may be required in the regional stratigraphic classification.

Distribution of cheirurid trilobites in Baltoscandia

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The trilobite suborder Cheirurina appeared in early Tremadocian and went extinct in the Taghanic-*Pharciceras* “Extinction Event” in the Middle Devonian. The most ancient families were Pliomeridae and Pilekiidae, then soon afterwards appeared Encrinuridae and Cheiruridae. Most of them were adopted to a benthic life in near shore areas, and mainly in so called illaenid-cheirurid associations. However, they were pelagic in their early stage of life during the protaspid period, so they could actually migrate in several ways. It is a well known fact that the benthic fauna of the Baltic shelf was rather isolated during the Early Ordovician and that several trilobite families were endemic to that terrane. One abundantly represented subfamily is Megistaspidinae. Still, my study on evolution (and systematics) of the suborder Cheirurina have brought out some interesting aspects on their distribution and migration.

In the Baltoscandian palaeobasin the earliest representatives of the suborder Cheirurina appeared nearly simultaneously with the beginning of the carbonate sedimentation in Hunneberg in the western part, or in late Hunneberg or early Billingen in the eastern part. In the latter case, the environment has been favourable for development of several new families including Cheiruridae. *Krattaspis* was part of the stem-group for the subfamily Cyrtometopinae (if not to the entire family Cheiruridae), displaying a mixture of characters found in several succeeding genera (*Cyrtometopus*, *Hemisphaerocoryphe*, *Reraspis*, etc.), resulting from different patterns of heterochrony in their evolutionary development.Cyrtometopinids are mostly distributed in different habitats around the Baltica from late Hunneberg to early Silurian, but also a few emigration events are traced. First, at the beginning of Darriwilian, *Sphaerocoryphe* appeared in Laurentia together with the earliest Cheirurinae – *Laneites*, also reaching South China. A second migration occurred during the Late Ordovician when *Sphaerocoryphe* spread widely in low latitudes, reaching Avalonia and equatorial Gondwana. *Actinopeltis*, a probable descendant of the Baltoscandian genus *Cyrtometopella* was the only cyrtometopine inhabiting high latitude Gondwana throughout the Upper Ordovician.

The largest change in distribution of Baltoscandian cheirurid trilobites took place at the Oandu/Rakvere boundary. The endemic cyrtometopine genera *Hemisphaerocoryphe* and *Reraspis* disappeared and the Laurentian cheirurine *Xylabion* appeared for a short period. The Boda Limestone and the contemporaneous Jonstorp Mudstone were favorable to *Hadromeros* and *Cheirurus*, both common in mud mounds of the latest Ordovician and early Silurian at the high latitudes.

An ordovician perspective to molluscan evolution

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While helcionelloid molluscs are abundant even in the Early Cambrian, it is first in the vicinity of the Cambrian–Ordovician boundary that familiar molluscan crown groups are prominent. The relationship between older Cambrian molluscs and these Ordovician and younger groups is speculative, but recent new finds and re-interpretations of previously described material from the Ordovician help clarify the early evolution of the Mollusca. Relevant taxa include *Pinnocaris*, *Janospira* and *Rhytiodentalium*.

The endogastrically coiled helcionelloids are now known from the Lower Ordovician and a clear morphological relationship is established between these, the rostroconchs and the extant scaphopods. While it is unlikely that the latter originated in the Ordovician, as has previously been proposed by some (and denied by others), a model is now available to explain the occurrence of scaphopod-like fossils in the Early Palaeozoic. Morphological evidence from shell-coiling supports recent rRNA evidence that the traditional close grouping between bivalves and scaphopods is convergent; the latter may lie in closer proximity to cephalopods which were also probably derived from the helcionelloid stock.

Ordovician Geschiebes in Lower Saxony – their potential for trilobite research

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Long before the theory of glaciation in the northern part of Germany became accepted, trilobites found within glacial erratic boulders known as geschiebes have been the attraction to both amateurs and scientists. Geschiebes located in the Neogene sediments in Lower Saxony (northern Germany) are mainly thought to be derived from Sweden, Bornholm, Estonia and the Baltic sea. The geschiebes could also represent strata that have completely eroded in the former provenance areas and therefore are a valuable archive for scientific research.

Although there has been a long history of intensive research, Ordovician geschiebes still offer interesting and challenging tasks for stratigraphers, palaeontologists and sedimentologists. Unfortunately research on geschiebes seems not to be en vogue anymore for German scientists. Today an increasing number of studies on geschiebes are carried out by amateurs or at least on material from amateur collectors.

Ordovician geschiebes found in the Neogene deposits of southern Lower Saxony mainly belong to two categories: 1) Silicified limestones of the «brick-limestone» ("Backstein-Kalk") type. The silification is thought to be derived from bentonites overlaying limestones. There are several horizons of different ages (belonging to Mid- to Upper Ordovician strata) that delivered this type of geschiebe. 2) Pure limestones, mainly of the "Orthoceratite-limestone" type with a dominating red and a less common grey type to appear in southern Lower Saxony. Other Ordovician geschiebes are rare.

Due to weathering the "brick-limestone" is mainly found as brown to yellowish white decalcified geschiebes with fossil remains as internal and external moulds sometimes with silicified hardparts. Trilobite remains in these geschiebes can be frequent but do not always offer a satisfying preservation for a proper determination. In its unweathered form the "brick-limestone" is a greenish blue, extremly hard and splintery rock. A fossil preparation in this type of rock is very time consuming and challenging work. The dissolution of unweathered "brick-limestones" with hydrofluoric acid led to micropalaeontologic, stratigraphic and palaeogeographic results but is a research method accessible only for scientists. Trilobites from the "brick-limestone" type were featured in publications throughout the 1970's; however since then very few references have been made. There is yet no work on trilobite remains from the unweathered "brick-limestone".

The geschiebes of the "Orthoceratite-limestone" type in southern Lower Saxony are typically weathered. The weathering process softens the rock and whitens the calcitic hardparts, therefore making it possible to find and prepare very small trilobite remains in several ontogenetic stages. These common fossils can be exposed using physical preparation techniques. The small trilobite *Stenoblepharum glaciviator* is an example of a new species that has been described from Ordovician geschiebes from Lower Saxony. Another trilobite that needs still further investigation is a species of *Cyamella* that was hitherto known only from younger strata but however was found in geschiebes of the "Orthoceratite-limestone" type. The weathered limestone geschiebes offer good opportunities for many disciplines (e.g. systematics, palaeobiology, palaeobiography, stratigraphy, sedimentology) to gain a better understanding of Baltoscandia during the Ordovician.

Permian remagnetization of Ordovician and Silurian carbonates from Estonia

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Palaeomagnetic studies on Early and Middle Ordovician carbonates from northern Estonia reveal three different remanent magnetization components. The first component has a steep southeasterly downward direction yielding a pole that plots onto the Ordovician apparent polar wander path (APWP) of Baltica. This component is interpreted as primary. The second component has a steep northeasterly downward direction, and it represents most likely a Permo-Triassic overprint. The third component has a steep northwesterly downward direction. The age of this component is unknown. A palaeomagnetic study on Early Silurian carbonates in central and western part of Estonia is still under work, but also here, different components from several outcrops have been revealed. The remanent magnetization components of the Ordovician and Silurian rocks were studied thoroughly, and one common direction was revealed – a secondary Permian magnetization. Identification of the mechanism for the remagnetization has been the main purpose of this study.

The Estonian Palaeozoic sequence is composed of Ediacaran to Devonian terrigeneous and carbonate sediments that overlay the southern slope of the Fennoscandian Shield. The studied sequence is composed of Ordovician (Arenig and Llanvirn age 485–464 Ma; Mäekalda, Narva, Pakri, Tõrvajõe) and Silurian (Llandovery and Wenlock 443–422 Ma; Rõstla, Analema) limestones and dolomites. To study the origin of the remanence components, alternating field (AF) demagnetization treatment was performed. After each step the intensity and direction of the natural remanent magnetization was measured with a superconducting SQUID magnetometer in the palaeomagnetic laboratory of the Geological Survey of Finland. Different components were revealed, but the most scheming was the component with an average mean direction of D=35.9°, I=41.9° (k=42 and α_{95}=7.1°). The corresponding pole position (59.1°N and 25.9°E) points to the Permian period. The component has dual polarity, but it is predominantly reversed. The component is clearly acquired after deposition, but the exact acquisition mechanism and source of this component is still poorly known. Magnetic mineral carriers in these rocks are mainly goethite and hematite according to XRD and electron microscopic studies.

In the course of finding reasons for the Permian remagnetization, we have found more than 100 documented indications of a late Palaeozoic secondary magnetization in different rock types (sedimentary and crystalline rocks) with different ages (Proterozoic up to Late Palaeozoic) all over the world. Events that have had a direct or oblique effect to the formation of a Permian remagnetization have usually been related to some local or regional processes, e.g. Alleghenian orogeny in North America and Africa, Hunter-Bowen orogeny in Australia, extensional faulting within the Caledonides or magmatic activity in Siberia and China. Effects that had an influence on these rocks instantly and after the tectonic processes are: fluid migration, temperature changes, sedimentary burial or sea level changes; all these have been reported as the causes of a worldwide Permian remagnetization.

The exact reason that caused the remagnetization of the Ordovician and Silurian carbonate rocks in Estonia during the Permian is still under research. One probable cause could be a chemical remanent magnetization due to migrating fluids when Baltica was affected by the post folding processes of Variscan orogeny on the southern margin of Baltica, but it could be also related to highly magmatic Oslo rifting in southern Norway at Permian time or the effect that followed collisonal Uralian orogeny at the eastern margin of Baltica. A remanent magnetization component with similar age has been also sporadically obtained all over the whole Fennoscandian Shield and it has been implied that it may be related to the late sedimentary processes after the Caledonian orogeny. In an expanded view, all these processes that have influenced the rocks that carry a Permian secondary magnetization may just be related to the formation of Pangea.

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Obolus Sandstone from the Baltic Klint area: a *Lagerstätte*?

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Exclusive preservation of baculate microstructure of linguloid brachiopods has been revealed in the samples from the Cambrian-Ordovician boundary beds of Estonia and northwestern Russia. Beds with mass accumulations of lingulate brachiopods preserved as coquinas are known as the *Obolus* Sandstone. Considering the exclusive preservation of microscopic features of linguloids, we believe that at least some localities of the Obolus Sandstone deserve to be called *Lagerstätte*.

The best results on details of microstructure were achieved by studies of unetched and uncoated valve surfaces by means of a low-pressure environmental SEM (ESEM). Broken surfaces of cross-sections and oblique sections of valves revealed structural details in three dimensions.

The phylogenetic significance of three main types of shell structure in lingulate brachiopods: baculate (e.g. Recent *Glottidia* and most linguloids), botryoidal (e.g. Recent *Lingula*) and columnar (e.g. acrotretoids) has been explained within the past 15 years by Alwyn Williams, Maggie Cusack, Lars Holmer, Leonid Popov and others.

Recent studies by Lars Holmer, Michael Streng, Christian Skovsted and others have revealed shell structures in some earliest stem-group lophotrochozoans from the Cambrian thought to be phylogenetically related to brachiopods.

Taphonomic factors have a crucial role in preserving ancient shell structures. However, very often the taphonomic overprint including the extent and type of re-mineralization can alter or obscure the original morphology. Alwyn Williams and co-authors have used well-preserved structures of *Obolus apollinis* Eichwald from the Obolus Sandstone to typify the baculate structure of Palaeozoic linguloids. Our studies of another species, *Obolus ruchini* from the Cambrian part of the Obolus Sandstone in NW Russia revealed fine microstructure preserved in a mineralized state owing to phosphatization. Some well-preserved parts of the microstructure show flexible strands composed of two fragile parallel fibres. We are inclined to interpret them as phosphatized compounds of organic matrix due to their similarity to some protein and β-chitin structures described in Recent lingulate shells, but this assumption needs further discussion.

In the same valve, it can be observed how these strands form larger elements of re-mineralized microstructure. As similar strand-like structures have been observed in the Devonian linguloid *Bicarinatina bicarinata*

Kutorga, these fine elements of microstructure may be characteristic of linguloids. Still, it appears that specific taphonomic conditions are needed for their preservation.

In most Ordovician linguloids from sandstones and limestones of Estonia, the shell structure appears to be re-mineralized to a larger extent. Thus, because of taphonomic overprint, observations of this kind of preservation appear to be quite rare. It is also likely that such fine structures may be destroyed during certain treatment, e.g., polishing a thin section or etching with weak acids.

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Was SW Alaska part of Baltica in the Late Ordovician?

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Research during the last three decades has suggested that most of Alaska was not a part of the Precambrian North American Craton. Instead it consisted of a number of terranes that were accreted to the craton throughout the Palaeozoic. Only a relatively small triangular area in east-central Alaska is thought to be an original part of the craton (Blodgett et al. 2002). Most terranes show biogeographical affinities with Siberia, but some also show close links to the Taimyr Peninsula. Whereas the southern and central part of this peninsula was an integral part of Siberia, the northern part is believed to belong to the Kara Block, an independent terrane that may have been located between Siberia and Baltica in the late Ordovician times (Cocks & Torsvik 2007).

An abundant and diverse, silicified brachiopod fauna, from the White Mountains area in southwestern Alaska, was located within the Farewell Terrane, itself consisting of three smaller subterranes, the Nixon Folk-, Dillinger- and Mystic subterranes. Whereas the latter two subterranes are regarded as representing a single stratigraphic succession of deep-water (Dillinger) to shallow water/nonmarine (Mystic) sequences of Cambrian – Triassic age, the Nixon Folk subterrane is predominantly a shallow-water carbonate succession of early to mid Palaeozoic age (Gilbert & Bundtzen 1984, Blodgett et al. 2002). In recent years, biogeographical studies have indicated that the Farewell terrane, during the Cambrian to Devonian, was either part of the Siberian continent, or, was derived from the northeastern margin of Baltica (i.e. the Urals) or the Kara Block (northern Taimyr, Blodgett et al. 2002).

Contrary to previous work, the current study, based on brachiopods, indicates a position for the Nixon Folk subterrane closer to Baltica and Taimyr, than to Siberia, during the Ashgill. At least 28 genera have been identified in a sample of over 1100 specimens; most are silicified and very well preserved. The high diversity is thought to be a result of mixing of an allochthonous shallow water fauna with an autochthonous deep water fauna by turbidity currents in slope settings. The autochthonous deep-water fauna dominates the material. The two most abundant genera, *Scaphorthis* and *Phragmorthis*, make up more than one-third of the material. These genera occur together with *Skenidioides*, *Anisopleurella*, *Anoptambonites*, *Eoplectodonta*, *Gunnarella*, *Leptellina*, *Oanduporella*, *Ptychoglyptus*, *Rugosowerbyella*, *Dolerorthis* and *Cyclospira orbus*, and probably lived within Benthic Assemblage Zones (BA) 4–5 during the Ashgill. The allochthonous fauna is probably derived from different areas of the shelf. The following taxa probably originated within: BA 2–3 are *Hesperorthis*, *Leptaena*, *S.* (*Sowerbyella*) and *Macrocoelia*?, whereas the nonarticulate *Acrosaccus* probably was derived from the intertidal BA1 zone. Some valves are encrusted by bryozoans. Biogeographically, these faunas indicate links with those of the Klamath Mountains, Kolyma, Taimyr Peninsula, Urals and Kazakhstan. Five genera are endemic for their respective regions. Of these *Sigmelasma* is from the Klamath Mountains, *Dulankarella*? from Kazakhstan, *Cyclospira orbus* is known from Kolyma, Taimyr and Baltica, and finally *Gunnarella* and *Oanduporella*, that are exclusively known from Baltica. The Farewell terrane was most likely positioned relatively close to Baltica in the Late Ordovician. Most of the other Alaskan terranes that accreted to the North American Craton in the Palaeozoic, show faunal links, especially with Siberia (Blodgett et al. 2002). Therefore, the Farewell terrane together with the other terranes, can be seen as forerunners to the 180° counterclockwise movement of the Siberian Plate to its present position east of Laurentia.

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Ordovician and Silurian sponges as erratics from Baltica

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Ordovician sponge faunas have been recorded from nearly all palaeocontinents. The oldest sponge assemblages described as early as in the 19th century have been collected in Europe. This Baltic sponge assemblage forms an exception, if compared with those from other continents, being the only one that is composed of erratic specimens, usually heavily silicified and without adhering remains of bedrock. This assemblage has been recorded from four main areas in northern and western Germany, The Netherlands and on Gotland (Sweden). Their provenance is yet unknown and attempts of localizing this area is still subject of research. In contrast with the assumptions in older literature, sponges being glacial erratics, they have been transported fluvially by the Eridanos river system. This system drained the Baltic shield during Miocene to Early Pleistocene times, and was subsequently destroyed by Pleistocene glaciers.

Nearly all erratic sponges are lithistid demosponges, representing four families, including 26 genera and c. 40 species. Representatives of Heteractinida and Calcarea have hitherto not been recorded. Hexactinellid sponges are extremely rare. Most of the sponge specimens are of Late Ordovician (Ashgill, Pirgu, F_{1c}) age. Some specimens are of Caradocian age.

Three distinct erratic sponge associations can be distinguished on account of associated fossils, different diagenetic processes and different stages of sedimentation: the Lausitz-Sylt association; the Gotland association and the Dutch-German association. Presumably, they originate from different source areas.

A striking problem is the contrast between the large number (c. 60 000) of collected erratic specimens in the areas mentioned before, and their sparse occurrence in areas around the Baltic Sea. Apart from some isolated specimens, Ordovician sponges have not been reported from Sweden or Finland, neither as erratics, nor autochtonous. Only a few numbers of Ordovician species were recorded from autochtonous strata in northern Estonia (Keila Stage, D2) and the Oslo region. The Ordovician assemblage went extinct or disappeared, probably, during Hirnantian time.

Recently, a new sponge assemblage with an endemic character has been recognized from pebble and cobble accumulations in two restricted areas along the west coast of Gotland. Associated pentamerid brachiopods, such as *Borealis borealis* and *Pentamerus* cf. P. oblongus, as well as tabulates and palynomorphs, document the assemblage to be of Aeronian or Telychian (Llandovery) age. The assemblage is composed of bodily preserved silicified lithistid demosponges, representing five families, including ten genera and, probably, twelve species, of which some are new taxa. Remains of hexactinellids and soft demosponges are attached to almost every lithistid sponge body, provided that the latter is not too heavily worn.

The varied assemblage has some conspicuous diagenetic features, and, generally, can be distinguished easily from intermixed Ordovician sponges. In addition, the most common genera in the Ordovician assemblage, such as *Aulocopium*, *Astylospongia* and *Caryospongia* do not occur in the Silurian assemblage. In contrast, most of the taxa in the Silurian assemblage are absent in the Ordovician assemblages, such as

Caryoconus Rhebergen & Van Kempen, 2002, as yet the only taxon in this assemblage described. Some taxa, such as the cosmopolitic *Hindia sphaeroidalis* Duncan, 1879, are represented both in Ordovician and Silurian assemblages.

Probably, the sponges originate from the "Red Layers", a formation underlying the Lower Visby Formation and thus not exposed on Gotland. Presumably, the sponges were transported ashore by Weichselian glaciers over a very short distance. In recent times, they are washed out from eroding pebble ridges, formed during post glacial periods of transgression (the Ancylus and Littorina Sea, respectively).

It is not clear from where the Silurian sponges immigrated. It is unlikely that they succeeded the Ordovician assemblage, considering the few taxa that the assemblages have in common. Contrarily, there are conspicuous similarities with Silurian sponge associations from Arctic Canada and the Mackenzie Mountains, Northwest Territories, Canada. These associations are younger (Wenlock–Ludlow), which may implicate a migration wave from Baltica towards Laurentia during the Silurian.

The disruption of the l chondrite parent body and the great ordovician biodiversification event

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Growing evidence suggests that the disruption of the L chondrite parent body ca. 470 Ma led to a two orders of magnitude increase in the flux of extraterrestrial material to Earth during c. 10–30 Ma. Frequent impacts of large L chondritic asteroids during this period may have spurred one of the most important species diversification events in the history of life.

The most compelling evidence for an enhanced flux of extraterrestrial material is the high abundance of fossil meteorites (1–20 cm in diameter) in mid-Ordovician marine limestone in southern Sweden. The meteorites are accompanied by abundant extraterrestrial chromite grains (>0.06 mm) dispersed throughout the limestone. The stratigraphic distribution of the chromite can be reproduced in sections over 350 km distance in Sweden, and tentatively also in sections from central China. Petrographic studies of the fossil meteorites and the chemistry of meteorite-enclosed and sediment-dispersed chromite grains indicate an L chondritic origin. Cosmogenic isotopes in the chromite support an origin of the meteorites from an asteroid break-up event.

Considering that meteorites struck the Earth at an enhanced rate it is likely that the same applies for large asteroids. Support from this comes from an overrepresentation in the geological record of impact craters with a mid-Ordovician age. For example, of 17 known craters on the Balto-scandian shield four have been dated with great confidence by chitinozoan stratigraphy to the middle or early late Ordovician. The recent discovery that the resurge deposits of the Lockne impact crater are extremely enriched in L chondritic chromite shows that at least one of the four mid-Ordovician craters may be related to the disruption event. This is consistent with model simulations that indicate an enhanced flux of objects to Earth during 2–30 million years after major disruption events in the asteroid belt.

The so called Great Biodiversification Event during the mid to late Ordovician is one of the most important events in the history of life. The biodiversity of invertebrates increased dramatically from a low in the Cambrian and early Ordovician to levels more similar to the present in the late Ordovician. Frequent bombardment of Earth by asteroids may have spurred these evolutionary changes. Repeated impacts created pressure on species to adapt to environmental perturbations. Previously, mid-Cenozoic faunal turnovers have been proposed to be related to a comet or asteroid shower, but although several craters of this age are known, there is no support from meteorite K-Ar gas retention ages for an asteroid shower of the same magnitude as in the mid-Ordovician. That impacts can have profound effects on life is obvious from the sequence of events at the Cretaceous–Palaeogene boundary.

Untangling *Asaphus raniceps*

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Several *Asaphus* (*Asaphus*) species concepts are in a state of flux. Recent investigations have made some progress in untangling the systematics of the type species *Asaphus expansus*, and the similar *A. fallax* and *A. raniceps*. Here we elucidate the morphological and stratigraphical relationships between *Asaphus raniceps* and *A. lamanskii*. It is shown that *Asaphus raniceps* and *A. 'raniceps'* of several authors include specimens of *A. raniceps*, *A. lamanskii*, *A. striatus*, *A. vicarius* and *A. fallax*. Angelin's *'A. acuminatus'* is interpreted as a distinct species. The dorsal pattern of terrace lines on the pygidium is shown to be a useful character for the discrimination of species of *Asaphus* (*Asaphus*).

Sea-level changes, glaciations and oxygen level during the Early Palaeozoic: Controlling factors for the Cambrian explosion and the Ordovician radiation?

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The Phanerozoic sea level curves reconstructed by the Exxon Group and A. Hallam deviate considerably with regard to the Early Palaeozoic segment. Hallam inferred that the sea level on a 1st order scale rose all through the Cambro-Ordovician interval and reached a maximum in the Late Ordovician. This highstand, in his interpretation, represents the highest sea level attained during the entire Phanerozoic. The Exxon Group infers a much lower general sea level for the Early Palaeozoic and in their reconstruction the sea level reached a maximum already during the Early Ordovician, at which stage the sea level stand was comparable to the well-known and widely accepted Late Cretaceous highstand. In Hallam's interpretation this sea level was reached by the mid Early Cambrian.

Analyses of Cambro-Ordovician sea level changes have been carried out based on condensed sections in Scandinavia and the East Baltic area. It is concluded that the sea level rose stepwise from the earliest Cambrian to the Late Ordovician and reached a peak during the *P. linearis* graptolite Zone. The sea level curve reconstructed for this stable craton thus corroborates Hallam's interpretation. Judging from Scandinavian conditions the sea level was already 50–100 m higher in the late Early Cambrian than during the Late Cretaceous and likely additionally 100 m higher or even more during the Late Ordovician. Hence, if the sea level was some 250 m higher during the Late Cretaceous (Campanian) than today it may have been about 400 m above the present sea level during the Late Ordovician.

The motif of the Cambro-Ordovician 3rd order sea level oscillations indicates a likely glacioeustatic control in the Early Cambrian and during most of the Late Ordovician from the mid-Caradoc onwards. The Early Ordovician Ceratopyge Regressive Event (CRE) is also a very likely candidate for a glacial event, whereas it is less obvious whether the early Mid Ordovician 2nd order sea level lowstand represents a glacial interval. However, this may well be so.

Unrelated to the rising sea level the sedimentary successions of Scandinavia record a very significant expansion of the oxygen minimum zone during the Mid and late Cambrian, causing a gradual spreading and intensification of the dys- to anoxic Alum Shale facies. The low oxygen conditions culminated during the late Cambrian (Furongian) at which stage dysoxic conditions even prevailed on the inner shelf in Scandinavia, i.e. probably from a few tens of metres of depth (?30–50 m). The general level of oxygenation seems to have improved gradually from the latest Cambrian and through the Tremadocian and the Alum Shale facies disappeared shortly prior to the late Tremadocian Ceratopyge Regressive Event.

The Cambrian 'explosion' seems to have occurred during a time interval with strongly rising sea level and relatively well-oxygenated conditions in the sea. It is regarded likely that the inferred disappearance of major glaciers around the Early/Mid Cambrian boundary may have been associated with more sluggish global circulation, causing a gradual expansion of the oxygen minimum layer which culminated during the Furongian. Glaciations in the earliest Ordovician may have been associated with renewed more vigorous global circulation and general improvement in overall oxygen conditions in the oceans and maybe this factor in concert with the high sea level, creating widespread epicontinental seas, played an important role for or even triggered the Ordovician radiation.

Ordovician ostracods from the Gullhögen quarry, Sweden

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The Gullhögen quarry, situated on the south-eastern slope of Mount Billingen in Västergötland, is one of the largest limestone quarries in Sweden. The almost 70 meters thick exposed section ranges from the Upper Cambrian to the lower part of Upper Ordovician.

The limestone samples, processed by standard methods yielded rich and abundant microfossil faunas with ostracods and gastropods as prevailing groups, especially from the Gullhögen and Ryd formations. Besides those, phosphatic inarticulate brachiopods and juveniles of rhynchonelliformean brachiopods were found in large numbers; less abundant were agnostid trilobites, trilobite protaspids and fragments of juvenile specimens.

The samples from the Gullhögen section yielded nearly 17 500 ostracod specimens, representing about 80 ostracod species from 21 families and six suborders.

The Gullhögen ostracod faunas can be divided into three major groups, which show substantial differences in their taxonomic composition: 1. Lanna-Holen ostracod assemblage; 2. Gullhögen, Ryd and Dalby assemblage; 3. Skagen, Slandrom, Bestorp and Jonstorp assemblage.

The lowermost 20 meters of the Gullhögen section, the Lanna and Holen limestones, comprise mostly red bedded wackestones. They are divided by a grey-coloured packstone layer, locally known as Täljsten. The Lanna-Holen ostracod assemblage can be characterised by rising diversity in the lower part and rather stable and high diversity in the upper part of the sequence. The first species entering the sequence is an eridostracan *C. socialis*, that is followed by palaeocopes *T. primaria*, *R. mitis* and *O. bocki* and kloedenellocope *U. punctosulcata*. Most species in the sequence appear one by one and continue up to the end of the Holen Limestone. A notable diversification, marked by the appearance of 9 new taxa, takes place in the Täljsten layer. Some of these taxa enter the sequence for a short period only (*Easchmidtella* sp., *Sigmobolbina* sp., *Drepanella* sp.), but others range up to the end of the Holen lmst. (*E. sigma*, *L. estonula*, *P. procerus*, *A. acuta*). The top of the Holen Lmst. shows abrupt disappearance of all previous taxa.

The discontinuity surface at the top of the Holen Limestone is overlain by the thin layer of the Våmb Limestone of late Aseri age, composed of brownish-red calcarenitic limestone and chamosite ooids. The following Skövde beds (of Lasnamägi age), lying between two distinct discontinuity surfaces, are characterized by grey mudstones with fine-grained limestone nodules. The Gullhögen Formation (of early Uhaku age) is mostly composed of dark grey mudstones with calcilutitic nodules, but it also includes beds with calcilutitic limestone. The Ryd Limestone (late Uhaku/early Kukruse age) is dominated by grey, thick-bedded calcilutites, with some finely nodular intercalations. The lower boundary is clearly defined lithologically, whereas the upper boundary is mostly drawn on faunal evidence. The Dalby Limestone (Kukruse and Haljala age) is composed of grey calcilutitic limestone in the lower, and calcarenitic limestone in the upper part. The upper part of the Dalby Limestone yields some beds with stromatolites. The upper boundary of the member is marked by a Kinnekulle K-bentonite bed.

Faunistically, Gullhögen, Ryd and Dalby limestones (together with the thin layers of Våmb and Skövde limestones) can be regarded as one complex. Although the lithological differences between them are noticeable, the ostracod fauna does not show any major changes. This complex is characterized by medium to high diversity faunas with the prevalence of metacopes (*L. parrectis* and *R. romboformis*), leiocopes (*Baltonotella* sp.) and palaeocopes (*E. locknensis*, *S. sigmoidea*, *Laccochilina* sp.).

The Skagen, Slandrom, Bestorp and Jonstorp limestones consist of different gray-coloured or red calcilutites and mudstones. This part of the sequence is tentatively regarded as only one complex. Although the Skagen, Slandrom, Bestorp and Jonstorp formations share some taxa, faunal differences in them are considerable. However, the majority of ostracodes in these formations belong to the palaeocopes or metacopes. Faunal diversity is low to medium, being highest in the Skagen Lmst. and lowest in the Slandrom Lmst.

Fossil fauna from the sediment intrusions at the Osmussaar Island

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Osmussaar Island, situated near the North-West coast of Estonia, is a relict island of the Baltic Klint, where the exposed carbonate section at the northern part of the island ranges from the Hunneberg to the Uhaku Stage. The most intriguing part of the Osmussaar section is related to the Volkhov and Kunda stages, where the limestones are split into blocks and penetrated by veins and bodies of breccia-like sandstone, the so-called sediment-intrusions. The sediment intrusions consist of yellow to grey-coloured (and the mixture of these both) calcareous quartz sandstone. The thickness of the intruded section is ~1–1.5 m.

For the pilot study, three samples from different intrusion rock types were disintegrated with hyposulphite. All samples yielded rich fossil fauna, but the yellow-coloured rock type showed the greatest number of ostracod fossils. The smallest number of fossils was found in the grey rock type. As this rock is also rich in pyrite, it can be presumed, that most fossils were destroyed in the course of pyritization.

Apart from some new, undescribed species, most ostracods have previously been described from the Kunda Stage. While some of the species, like *Glossomorphites grandispinosus*, *Ogmoopsis bocki* and *Aulacopsis simplex* have been documented from a wide range of facies from the Baltoscandian Palaeobasin, certain species, like *O. alata*, *O. variabilis* and *Aahithis vanspronsenae* have been described from a certain rock type only. Sarv (1959) described specific ostracod fauna from the erratics of Pakri sandstone from Estonia, and Schallreuter (1989, 1993) described ostracod fauna from the erratics of the so-called Rogö-Sandstein. Both rocks probably represent the Pakri Formation of the Kunda Stage.

Both, the unusual rock type for the area and the ostracod fauna refer to the Kunda age of the Osmusaar sediment intrusions. It is also noteworthy, that the ostracod fossils show excellent preservation, thus referring to short transportation from some nearby area.

Middle and Upper Ordovician conodonts from drill cores of the Kaliningrad Region

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The Ordovician deposits of the Kaliningrad Region are subsurface and can be studied in several cores that were drilled more than 35 years ago and stored in the Hydrogeological Expedition in small town Gusev. Average depth to the Ordovician is 1 500 m whereas it thickness ranges from 150 m in the most western part of the area to less them 50 m in it north-eastern part. Two drill cores, Severo-Gusevskaya 1 and Nemanskaya 1 located in the central part of the Kaliningrad Region, were available for conodont studies. The core at Nemanskaya 1 was sampled at approximately 1.5 m intervals spanning the Ukhaku to Idavere regional stages. Eight samples were obtained from sixteen meters of limestones with layers of calcareous shales and mudstones in the upper part of the core. The sampled interval from the Severo-Gusevskaya 1 drill core of more than 30 m thick ranges from Idavere to Porkuni regional stages. As a whole the samples yielded a collection of over 5 000 conodont elements. Limited sampling precludes the estimation of stratigraphic distribution of important conodont taxa, however the taxonomic composition of conodont assemblages shows the presence of the complete succession of conodont zones described in East Baltic. Generally the conodont fauna has a strong dominance of *Baltoniodus*, *Amorphognathus* and *Drepanoistodus* genera that are typical for relatively shallow water Baltoscandian facies.

Conodonts in the Lower–Middle Ordovician boundary interval of Estonia

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The Huanghuachang section in China was recently selected as the Global Stratotype Section and Point (GSSP) for the base of the Middle Ordovician Series. The first appearance of the conodont species *Baltoniodus*? *triangularis* marks the lower boundary of the Middle Ordovician. The distribution of conodonts in the Estonian Lower–Middle Ordovician boundary interval shows remarkable similarity with the Huanghuachang conodonts. The Chinese section comprises two conodont biozones, the *Oepikodus evae* Biozone in the uppermost Lower Ordovician and the *Baltoniodus*? *triangularis–Microzarkodina flabellum* Biozone in the lowermost Middle Ordovician (Wang et al. 2005). These zones are known also in the outcrops and borehole sections of Estonia – the former in the Billingen Stage and the latter at the very base of the Volkhov Stage.

In China the *O. evae* Biozone ranges from the first appearance of *O. evae* to the first appearance of *Baltoniodus*? *triangularis*. In this biozone the species *Oistodus lanceolatus*, *Stolodus stola*, *Drepanoistodus forceps* and *Tripodus* cf. *laevis* are common both in China and Estonia. In China the index species is missing in the upper part of the *O. evae* Biozone. This fact was long ago established in the Baltic region and in Estonia all outcrop sections and at least 8 borehole sections have the two-part *O. evae* Biozone. In Estonia the upper part of this biozone is characterized by *Periodon flabellum*, which is also known in the Huanghuachang section in the middle–upper part of the same biozone. In the Estonian sections *Baltoniodus triangularis* has been identified in the Jägala, Varangu and Narva outcrops and in the Ohesaare and Kaagvere boreholes, mainly in the lowermost Volkhov Stage. Some specimens, unfortunately often broken, similar to *Baltoniodus triangularis* have been found together with *Periodon flabellum* in the Päite Member of the Billingen Stage. In Huanghuachang section in the upper part of the *O. evae* Biozone *Baltoniodus*? cf. *B.*? *triangularis* is found, which was earlier identified as *Baltoniodus triangularis* by some Chinese conodont specialists. Wang et al. (2005) suppose that *B.*? cf. *B.*? *triangularis* is similar to typical *B.? triangularis* (Lindström) from the Baltic region, with only minor differences between the two taxa. They also suggest that *B.*? cf. *B.*? *triangularis* from the upper part of the *O. evae* Biozone is an intermediary form in a phylogenetic lineage from *Trapezognathus diprion* to typical *B.*? *triangularis.* In China the latter is the index species of the *B.*? *triangularis – M. flabellum* Biozone. In our opinion, the species *B.*? *triangularis* needs more detailed taxonomic and morphologic study and is therefore not a good index species for the lower boundary of the Middle Ordovician.

In the Huanghuachang section the *Baltoniodus? triangularis–Microzarkodina flabellum* Biozone defines the base of the Middle Ordovician, whereas the latter species makes its appearance 0.2 m above the base of the biozone. In Estonia *M. flabellum* is common in the lowermost Volkhov Stage and is present in almost all studied sections. Moreover, this species is taxonomically distinct and easily to identify. Therefore it is reasonable to define the base of the Middle Ordovician by the conodont *Microzarkodina flabellum* in Estonia.

The oxygen isotopic ($\delta^{18}O$) composition of the Silurian early vertebrate biogenic apatite

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Phosphatic fossils of early vertebrate exoskeleton appear to be indicators of palaeotemperature, if being well-preserved, and not strongly altered by diagenetic processes. The oxygen isotope ratios of conodont apatite have already been translated into realistic palaeotemperatures, thus successive $\delta^{18}O_{apatite}$ calculations for early vertebrate micro remains has been performed using a corresponding method (Joachimski et al. 2004, Joachimski & Buggisch 2002).

Biogenic apatite of early vertebrates from central Asia as well as from Lithuania (Baltic Basin) has been used for oxygen isotope ratio calculations. Conodont samples from the adequate facies of the Upper Silurian of the Baltic Basin have been processed to make a relative control of the early vertebrate $\delta^{18}O_{apatite}$ measurements.

Early vertebrate micro fossils (thelodonts, acanthodians, chondrichthyans, hetrerostracans, and mongolepids) from the Lower Silurian (Llandovery and Wenlock) of the northwestern Mongolia and south Siberia (Ilimia and Balturino districts), and from the entire Silurian sections (Llandovery to Pridoli) of central Tuva have been processed to establish the $\delta^{18}O_{apatite}$ values. Both early vertebrates (thelodonts, heterostracans, acanthodians) and conodonts from the same Upper Silurian (Pridoli) samples of Lithuania (Karatajūtė-Talimaa & Brazauskas 1994) have been examined separately for the oxygen isotope ($\delta^{18}O_{apatite}$) composition.

Early vertebrate biogenic apatite $\delta^{18}O$ values from the Silurian of central Asia and south Siberia have appeared to be too low for appropriate palaeotemperature reconstructions (Joachimski et al. 2004). Thus the possibilities of a strong freshwater influx as well as diagenetic alterations have been suggested.

The $\delta^{18}O$ analysis of the early vertebrate biogenic apatite from the Upper Silurian of Lithuania has yielded more reasonable values, and finally the control $\delta^{18}O$ analysis of the conodont apatite has given proper data for palaeotemperature calculations, pointing to low alterations of the Silurian strata of the Baltic Basin. Therefore palaeotemperatures for the late Silurian basin have been estimated.

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