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The Ordovician of Västergötland and Dalarna, Sweden

FIELD GUIDE FOR THE ISOS 14 POST-CONFERENCE EXCURSION

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Cover photograph: Hällekis quarry, view towards the southeast. The dominant, mainly reddish strata comprise the 'Lanna limestone' below the thin grey band (the 'Täljsten' level) slightly above the base of the 'Holen limestone', the latter of which is disconformably overlain by the grey Gullhögen formation. The Gullhögen formation is in turn overlain by the 'Ryd limestone' (not in picture).
Photo: A. Lindskog.

Layout: Björn Stake

A digital version of this excursion guide is available at:
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Introduction

Jan Ove R. Ebbestad

The Ordovician of Sweden has been studied for more than two centuries. Already Tilas (1740) gave an early account of the geology in the Osmundsberget area of Dalarna. This 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). Understanding of the Ordovician of Sweden developed further in various phases with important early contributions in the early to mid 1800s by William Hisinger, Johan Wilhelm Dalman, Nils Peter Angelin and others. The establishment of a national geological survey in 1858 also ensured that systematic mapping of the bedrock and stratigraphical studies were conducted (Posse & Kim-Andersson 2008).

In 1910 Sweden hosted the 11th International Geological Congress in Stockholm which was hugely important and became a great success (Sundquist & Nordlund 2004). The excursion guides and booklets alone totalled about 1700 pages, and all the major areas with Ordovician deposits were visited. In 1960 Sweden co-organized the 21st International Geological Congress, and once more new data on the Ordovician succession was presented. A greatly influential worker at that time was Valdar Jaanusson, who in a series of papers developed a completely new stratigraphical standard for the Swedish Ordovician (i.e. Jaanusson 1951, 1952, 1960, 1963a, b, 1964, 1973, 1976, 1982a, b).

A number of revisions and studies of the succession and the fossils have subsequently been developed based on Jaanusson's contributions. Seminal works on conodonts by e.g. Lindström (1954, 1971b), Löfgren (1993, 2003, 2004) and Bergström (1973, 2007), as well as by many others on a variety of fossil groups allowed precise correlation across most of Sweden and Baltoscandia (see references in Nielsen et al. 2023). Some of Jaanusson's units have later been modified (for instance Bergström & Bergström 1996) but the greatest change came with a completely revised regional Scandinavian stage classification introduced by Nielsen et al. (2023). An additional avenue that has been explored since the 1990s is the development of a coupled biostratigraphic and chemostratigraphic framework (for instance Lindskog et al. 2023 and references therein).

Much work remains, however, especially in revision of the so-called topostratigraphical nomenclature. This was a practical but unique approach developed by Jaanusson (1960, 1976). Topostratigraphical units were defined based on lithological and palaeontological traits, wherein one boundary of a unit was placed at a level of a recognizable faunal shift, and the other boundary was defined based on lithological features. The use of topoformations should be abandoned and has in fact been formally deemed obsolete (Kumpulainen 2017). However, the deeply rooted use of these names is likely to prevail, but they should also be considered as informal. In this guide the topstratigraphical names are cited in quotation marks. Since 2019, there is a Swedish national stratigraphic committee "The Swedish Committee for Geological Nomenclature", that approves or rejects proposals for new names, formalizations of existing names and revised names of geological units and other geological features in Sweden. The work is based on suggestions submitted by the geological community. More information and a list of names that has been formalized or made obsolete by the committee can be found at: https://www.sgu.se/om-geologi/geologiska-namn-i-sverige/.

The Swedish Ordovician succession has two ratified Global Stratotype Sections and Points (GSSPs), one for the Floian Stage of the Lower Ordovician Series at Diabasbrottet, Västergötland (Bergström et al. 2004; Stop 1 in our excursion) and the second for the base of the Sandbian Stage and the Upper Ordovician Series situated in the Fågelsång area of south-central Skåne (Bergström et al. 2000).

The 14th International Symposium on the Ordovician System (ISOS 14), held July 15–26, 2023 in Estonia and Sweden gives us a welcome opportunity to present a new and updated field guide to the classical areas of Västergötland and Dalarna (Fig. 1). The first two days will cover the Ordovician succession in Västergötland and the last two days the succession in Dalarna.

Figure 1. Present-day distribution of Ordovician strata in Baltoscandia and location of provinces and districts. Modified from Nielsen et al. (2023, fig. 1).

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Disclaimer

This excursion guide to the Ordovician of Västergötland and Dalarna is a modified and updated version of the guides by Calner et al. (2013) for Västergötland and Ebbestad et al. (2007) for Dalarna. Parts of the texts and figures are re-used by permission from the Geological Survey of Sweden. The guide is made possible through a collaboration between colleagues in Uppsala, Lund and Copenhagen.

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Introduction to the Ordovician of Scandinavia

Arne Thorshøj Nielsen & Per Ahlberg

Ordovician sedimentary rocks deposited in an extensive epeiric sea are widely distributed in Scandinavia. They are preserved in two distinct tectonic settings: as thick and largely siliciclastic successions of the allochthonous Caledonides, and as much thinner autochthonous platform successions south and south-east of the Caledonides, dominated by carbonates, mudstones and shales. The Ordovician of Scandinavia was recently reviewed in some detail by Nielsen et al. (2023), and the text below is with minor modifications adopted from that paper. The names of the Scandinavian districts with preserved Ordovician strata are shown in Figure 1.

The Ordovician sediments originally covered all of Scandinavia and adjacent countries, but are today preserved only in scattered outliers and impact craters in Sweden and Finland, as well as in the subsurface of the Bothnian Sea and Baltic Sea (Fig. 1). The Ordovician strata deposited along the western margin of Baltica were telescoped into the Caledonian Mountain chain during the Caledonian Orogeny in the Silurian and Devonian (e.g. Gee et al. 2008, Gee 2015). These successions are strongly overprinted by tectonism and associated metamorphism, but the original sedimentary sequence can usually be reconstructed, at least for the parautochthonous foreland deposits of the Oslo Region, Norway, as well as for the Lower Allochthon in southern Norway and western Sweden (e.g. Owen et al. 1990, Karis 1998). A more continuous package of Ordovician strata that are relatively undisturbed by tectonism is preserved in the Baltic Sea area, dipping southeastwards from the Swedish islands of Öland–Gotland and below Lithuania–Latvia–southern Estonia and Poland (Fig. 1). Exposures are restricted to Öland and Estonia–western Russia. Deeply buried Ordovician strata are also preserved in the Danish area and below the Baltic Sea north of Germany but they have been encountered only in a few deep wells (e.g. Michelsen & Nielsen 1991, Schovsbo et al. 2016). Exposures in that area are limited to Skåne–Bornholm.

The Ordovician platform strata east and southeast of the Caledonides are highly condensed (Lindström 1971a), with a maximum thickness of little more than 200 m, recorded in NW Skåne (Fig. 1; see Jaanusson 1973, 1982a, Nielsen 1995, fig. 41 and references therein). In the gently folded foreland basin of the Oslo Region, the thickness is close to 500 m in the Oslo–Asker district (Owen et al. 1990). Further westwards, the thickness increases but is difficult to reconstruct due to overprinting by the Caledonian tectonics; a magnitude of 1 km was indicated by Bruton et al. (2010). The western and southern parts of Scandinavia are dominated by graptolitic shales, deposited on the outer shelf, whereas stratigraphically condensed carbonate successions, deposited in shallower water, characterize most of mainland Sweden. It has, however, remained a long-standing issue how deep 'shallower water' is. One school infers deposition in quite shallow water (e.g. Hadding 1958, Jaanusson 1960, 1973, Nordlund 1986, 1989, Lindskog 2014, Lindskog & Eriksson 2017, Lindskog et al. 2018), whereas another school led by the late Professor Maurits Lindström argued for much greater depths of deposition even approaching kilometre-scale (e.g. Lindström 1963, 1979, 1984, Chen & Lindström 1991, Lindström et al. 1996, 2005, Shuvalov et al. 2005). Part of the controversy reflects the fact that these authors studied different sites on the platform and/or different parts of the stratigraphic column. It is evident that depth of deposition overall increased westwards across Sweden, but it also varied significantly during the Ordovician in association with sea-level changes (cf. Nielsen 2004, Lindskog 2017). The lithofacies distribution across Baltoscandia has traditionally been described in terms of 'confacies belts' as also the fossil faunas differ between the facies belts (Fig. 2; see Jaanusson 1976, 1995). For this reason, precise correlation between the facies is commonly difficult, at least based on macrofossils. The zonation of the Ordovician of Scandinavia is based on conodonts, graptolites, trilobites and chitinozoans (Fig. 3).

There is broad agreement that Baltica was positioned at high southerly latitudes during the early part of the Ordovician, moving into mid-latitudes in the Mid Ordovician and finally entering subtropical latitudes in the Late Ordovician (e.g. Torsvik & Cocks 2017 and references therein). Foreland deposition relating to the ongoing Caledonian collision developed in Norway and parts of western Sweden early in the Mid Ordovician. From then on clastic supply to the Scandinavian epicontinental sea was predominantly from the incipient Caledonides to the west with only minor influx from cratonic Baltica itself (e.g. Jaanusson 1973); the latter supply dominated in the East Baltic area. Reef and carbonate mound build-ups occurred from the Late Ordovician (Kröger et al. 2016a, b).

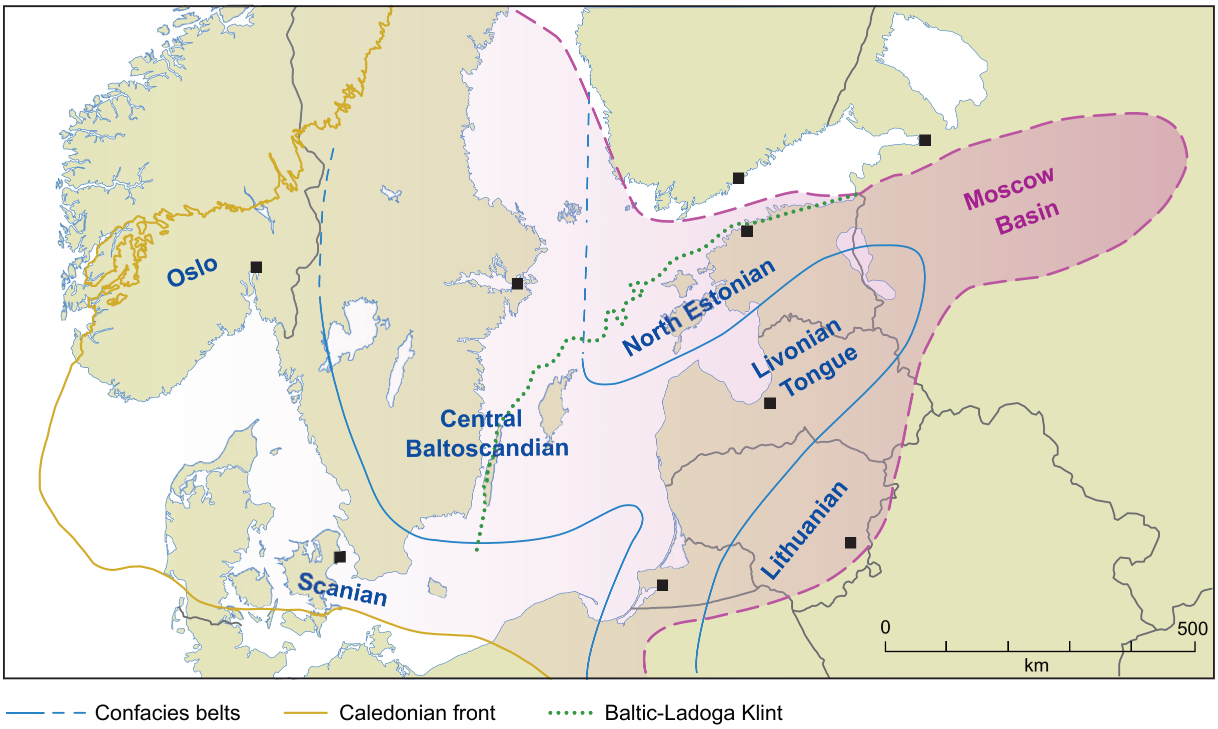


Figure 2. Ordovician 'confacies belts' sensu Jaanusson (1995) in Baltoscandia. Modified from Nielsen et al. (2023, fig. 2).

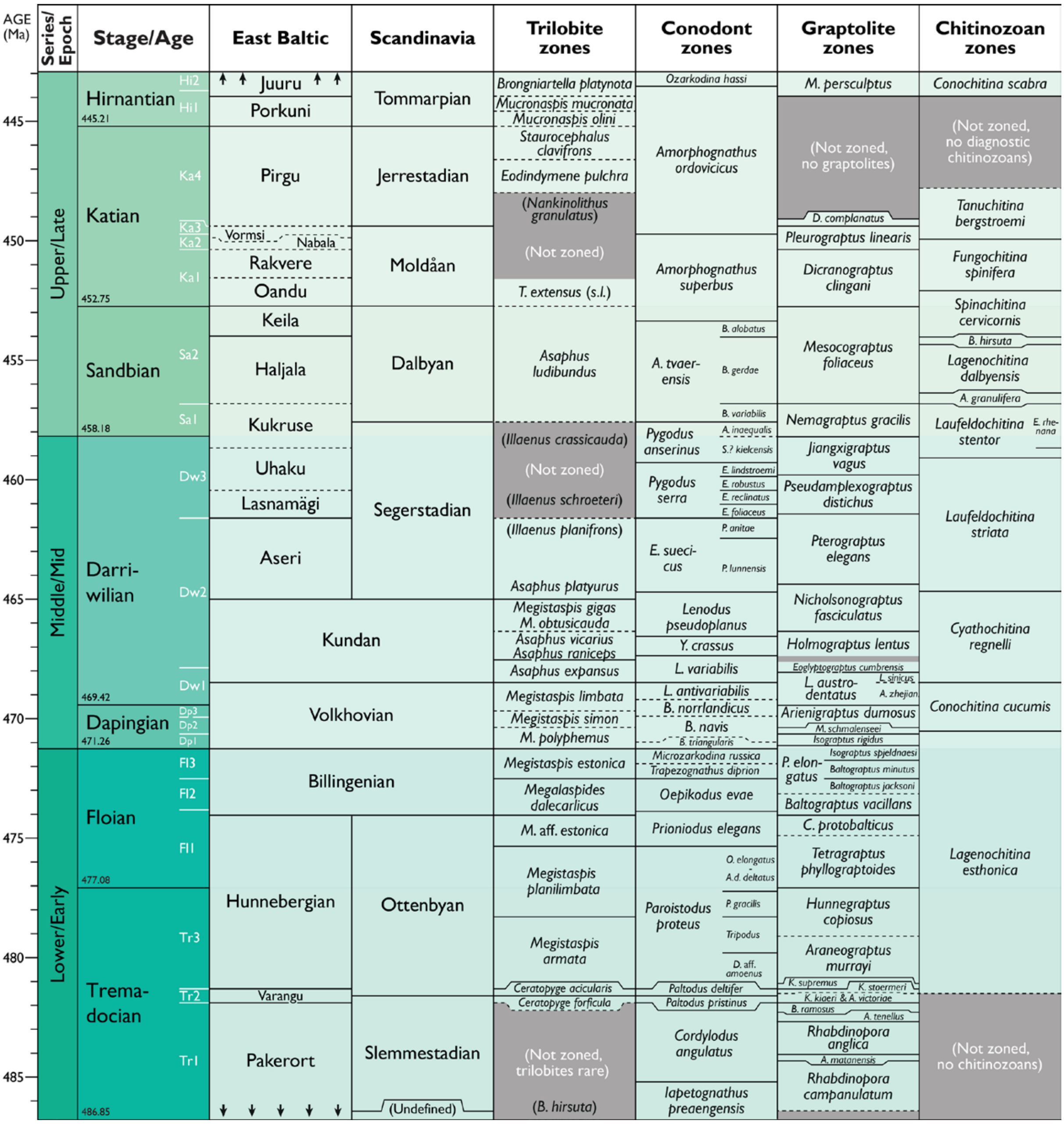


Figure 3. Correlation of the regional stages introduced by Nielsen et al. (2023) for the Ordovician of Scandinavia, and trilobite, conodont, graptolite and chitinozoan zonal schemes. The stage slices defined by Bergström et al. (2009) are also shown (left-hand column). From Nielsen et al. (2023, fig. 3).

Regional geology of Västergötland Province, Sweden

Per Ahlberg, Mikael Calner, Oliver Lehnert, Linda Wickström & Anders Lindskog

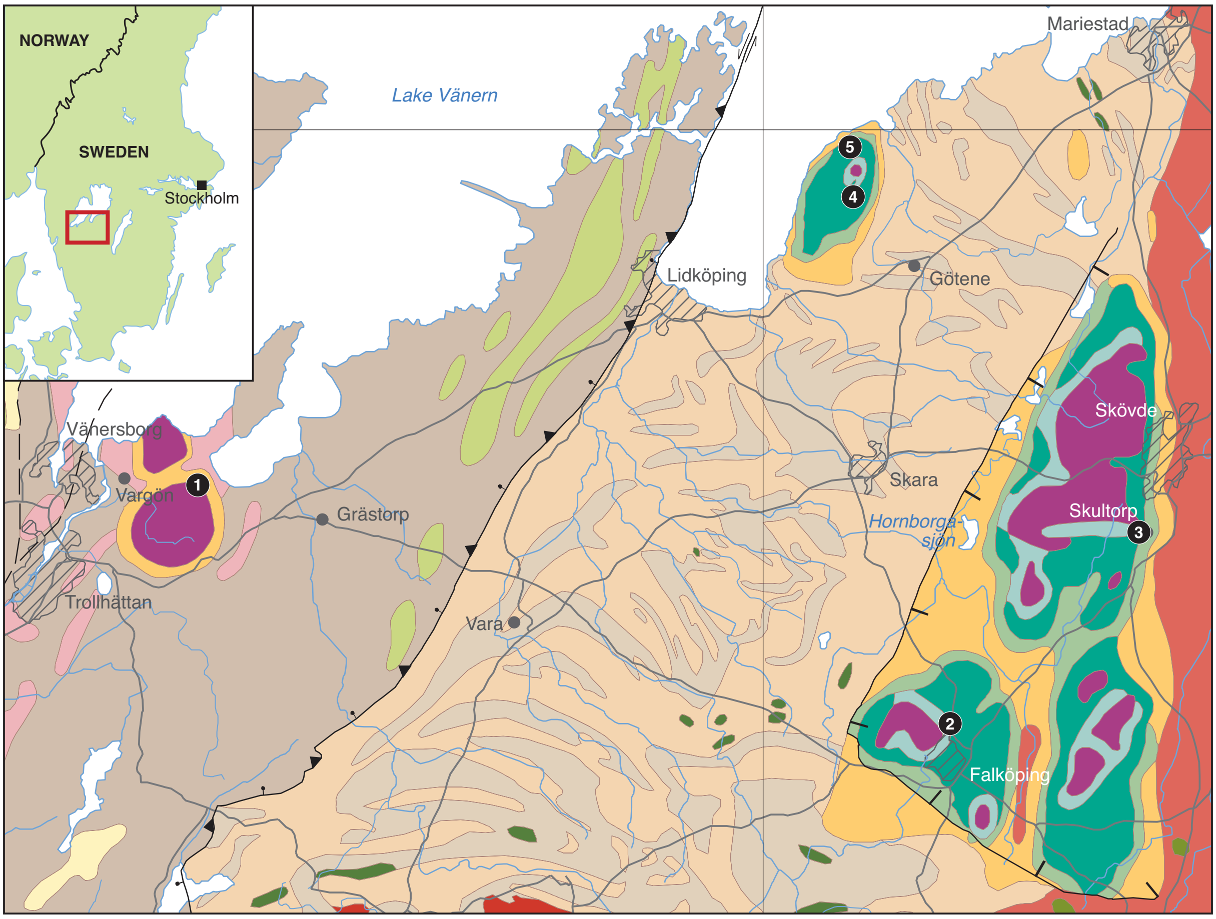
The Province of Västergötland is located between the two largest lakes of Sweden, Vänern and Vättern. The history of geological research in this area started in the early 18th century and Carl von Linné described the stratigraphic succession of the now classical table mountains during his famous excursion to Kinnekulle, Billingen and the Falbygden areas in 1747. After the initial studies, Angelin (1852, 1854) was the first geologist to describe and subdivide the succession based on fossils. Later, Linnarsson (1869) presented a paper in which he described the stratigraphy of the Lower Palaeozoic in Västergötland and made correlations to equivalent strata in other parts of Sweden, Russia (including the Baltic states), Bohemia, North America, Norway (which at the time was a part of Sweden), Ireland and the British Isles. Mapping of the Falbygden, Billingen and Kinnekulle areas by the Geological Survey of Sweden started in the late 19th century (Holm 1901, Munthe 1905, 1906, Munthe et al. 1928, Lundqvist et al. 1931, Johansson et al. 1943). Tjernvik (1956) presented an extensive study on the Early Ordovician of Sweden, including strata in Västergötland, and Jaanusson (1963a, 1964) reviewed and revised the upper Middle and Upper Ordovician of the province.

Prominent features in central Västergötland are the dolerite-capped table mountains that rise to elevations of more than 200 metres above the peneplain and that are visible over long distances. The peneplanisation over a long period of time is the result of deep weathering and erosion during the late Neoproterozoic. The crystalline basement rocks are locally soft due to kaolinitization, for example at Lugnås where the rocks for long times have been quarried to produce millstones. Before the first major early Cambrian transgression, the peneplain covered large parts of the Fennoscandian shield with only scattered monadnocks rising above the regionally flat surface. Due to tectonic processes, especially the uplift of the 'south-Swedish dome', the peneplain has later been modified by renewed deep weathering affecting the Palaeozoic sedimentary cover as well as the crystalline basement. The peneplain is well preserved in Västergötland due to a long period of protection (probably until the Neogene) underneath a Palaeozoic sedimentary cover.

The table mountains occur in three main districts: (1) Billingen-Falbygden, which comprises Mount Billingen in the north and Falbygden with its smaller mountains in the south; (2) Kinnekulle at Lake Vänern northwest of Billlingen; (3) Halleberg and Hunneberg at the southwestern end of Lake Vänern (Fig. 4). These outliers are relicts of the Palaeozoic cover, preserved due to their thick sheeted dolerite caps, which were intruded as sills at different levels into the sedimentary succession. Radiometric dating (K-Ar) of the dolerite gives an age of 282±5 Ma suggesting intrusion in the early Permian (Artinskian Stage, Cisuralian Series; Priem et al. 1968). Lugnåsberget north of Billingen is an outlier without a dolerite cap. In 2022 the Platåbergens UNESCO Global Geopark in Västergötland was recognized as a geological heritage of international significance – the first one in Sweden. It covers an area of 3,690 km² and includes the unique landscape with the 15 table mountains (Platåbergen in Swedish), after which the site is named.

The Lower Palaeozoic successions are flat-lying, or nearly so, and most complete on Kinnekulle and in the Billingen-Falbygden district, where they range up into the Cyrtograptus shale of the lower Silurian (upper Llandovery). The total thickness of the sedimentary succession is approximately 215 m at Kinnekulle and 150–160 m in the Billingen-Falbygden area. In the Halleberg and Hunneberg outliers, the dolerite intrusion cuts gently upwards from the north (Halleberg), where it rests on Cambrian strata, to the south (Hunneberg) where it rests on Lower Ordovician shales and limestones.

The Ordovician of Västergötland predominantly consists of limestones and mudstones, with a few graptolitiferous shale units (Fig. 5). For a long time, the upper Lower through Middle Ordovician bedded limestones of Sweden have been collectively referred to as 'orthoceratite limestone' (Kinnekulle was designated as the type area for this rock suite; Jaanusson 1982c, Lindskog & Eriksson 2017). This



Fault or ductile deformation zone with dip-slip movement, tag points to downthrown block

Fault or ductile deformation zone, kinematics unspecified

Fault or ductile deformation zone with combined thrusting and normal dip-slip movement

Fault or ductile deformation zone with combined reverse and strike-slip movement, sinistral

NEOPROTEROZOIC AND PHANEROZOIC PLATFORMAL COVER AND IGNEOUS ROCKS

- Dolerite (Permian to Carboniferous)
- Limestone, shale, sandstone (Silurian)
- Limestone, shale (Ordovician)
- Bituminous shale (alum shale) and subordinate limestone (Cambrian Stage 5 to Tremadocian)
- Sandstone, conglomerate, siltstone, shale (Cambrian Stage 4)

SVECONORWEGIAN OROGEN

Idefjorden terrane

- Granite, syenitoid and metamorphic equivalents (c. 1.36–1.27 Ga)
- Gabbro, diorite, ultrabasic rock, dolerite (1.6–1.3 Ga), metamorphic
- Granitoid, metamorphic (1.6–1.5 Ga)
- Rhyolite, dacite, andesite, sedimentary rock (c. 1.66 and c. 1.61 Ga), metamorphic

Eastern Segment, middle and upper units

- Granite, granodiorite, syenitoid, quartz monzodiorite and metamorphic equivalents (1.7 Ga)
- Gabbro, dioritoid, dolerite, ultrabasic rock and metamorphic equivalents (1.7 Ga)

Eastern Segment, lower unit

- Granite, syenitoid and metamorphic equivalents (1.2 Ga)
- Amphibolite, garnet amphibolite, mafic granulite, eclogite (1.7–0.9 Ga)
- Granitic migmatitic gneiss, granite (1.7–1.0 Ga)
- Granitoid to syenitoid migmatitic gneiss (1.7 Ga)

1 Diabasbrottet
2 Tomten quarry
3 Skultorp quarry
4 Högkullen
5 Hällekis

Figure 4. Map of Västergötland (part) showing the main geological features and excursion stops. Modified from Calner et al. (2013, fig. 36).

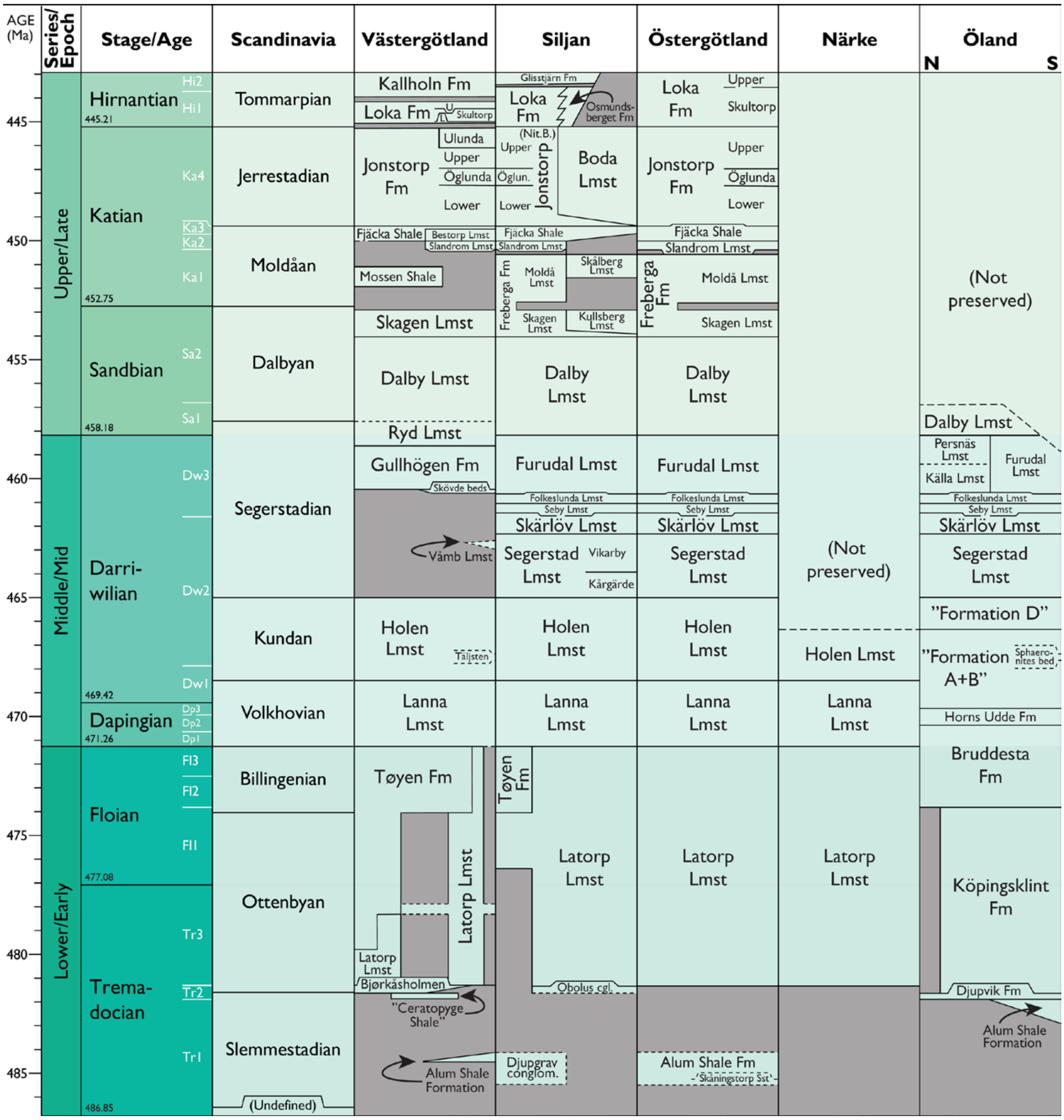


Figure 5. Correlation chart of Ordovician strata in the various districts of Scandinavia, including Västergötland and Dalarna. From Nielsen et al. (2023, fig. 5).

is a cool- to temperate-water limestone devoid of reef structures and with comparably low-diversity skeletal grain associations, and it is the most widely spread and well-exposed unit of the Ordovician succession throughout Västergötland (e.g. Lindström 1971a, Lindskog & Eriksson 2017). The total thickness of the Ordovician succession is 104 m at Kinnekulle and 84 m in the eastern Billingen area (Jaanusson 1982c). The Silurian succession is dominated by graptolitic shales (Kallholn and Cyrtograptus shales) and attains a maximum thickness of 56 m at Kinnekulle, where it is truncated upward by dolerite.

The last three decades have witnessed major efforts to increase the knowledge of the stratigraphy, sedimentology, palaeontology, and geochemistry of the Ordovician in Västergötland. This extensive research has, for instance, resulted in the establishment of a GSSP for the upper stage (Floian Stage) of the Lower Ordovician Series at Hunneberg in

Västergötland (Bergström et al. 2004), and in the identification of several Ordovician and Silurian K-bentonites with considerable event-stratigraphic and tectonomagmatic significance (e.g. Huff et al. 1992, 1996, Bergström et al. 1992, 1995, 1998). Furthermore, the Ordovician of Kinnekulle is famous because of its abundance of fossil meteorites, with more than one hundred macroscopic specimens found during quarrying of 'orthoceratite limestone' of Kundan age at Österplana, Kinnekulle (Lenaz et al. 2022). The 'orthoceratite limestone' of Västergötland (particularly Kinnekulle) has been the target of several focussed studies (e.g. Zhang 1998a, b, Tinn & Meidla 2001, Tinn et al. 2007, Bergström & Löfgren 2009, Schmitz et al. 2010, Kröger & Rasmussen 2014, Lindskog & Eriksson 2017, Lindskog et al. 2019, Bábek et al. 2021, and references therein) and is now among the most thoroughly documented intervals of the regional Ordovician succession overall.

Excursion Stops

Stop 1. Diabasbrottet

Per Ahlberg, Mikael Calner, Oliver Lehnert, Jörg Maletz & Anders Lindskog

Overview. Abandoned dolerite quarry near the northeastern end of Mount Hunneberg (58.358944, 12.502389) with a fairly thick and well-exposed succession of Lower Ordovician graptolitic shales and siliciclastic mudstones with several thin interbeds of dark, fossiliferous limestone. The ratified Global Stratotype Section and Point (GSSP) for the upper stage (the Floian Stage; Bergström et al. 2004) of the Lower Ordovician Series is at the top surface of a laterally persistent limestone (the E Bed) in the lower Tøyen Shale Formation (Fig. 6).

Description. Hunneberg is one of the famous table mountains ('platåberg') in Västergötland, capped by a thick sheet of Permian dolerite. The Cambrian–Lower Ordovician succession beneath the dolerite cover is highly condensed, essentially flat-lying and tectonically undisturbed. This sedimentary succession crops out at numerous localities along the slopes of Mount Hunneberg, particularly in old and abandoned quarries (e.g. Westergård 1922, Tjernvik 1956, Maletz et al. 1996). The best localities are in the northeastern corner of Mount Hunneberg, between Diabasbrottet quarry in the north and the village of Floklev in the south.

A long and continuous Lower Ordovician exposure is located along a quarry wall that extends for more than 1 km from Diabasbrottet to southward of Mossebo (e.g. Tjernvik 1956, Tjernvik & Johansson 1980, Maletz et al. 1996). The GSSP for the upper stage of the Lower Ordovician Series (Floian Stage) is at Diabasbrottet (Bergström et al. 2004, 2006a). The Floian Stage was ratified by the IUGS in 2002 and is named after the village of Flo located 5 km south-east of the GSSP in Diabasbrottet quarry.

Furongian strata are exposed at Floklev and Mossebo. The succession consists of black siliciclastic mudstones (Alum Shale Formation) with concretions and beds of dark grey, frequently fossiliferous limestone. Trilobites recovered from near the top of the Alum Shale Formation at Mossebo, about 1 km southeast of Diabasbrottet, are indicative of the *Peltura acutidens–Ctenopyge tumida* Zone (Westergård 1922, p. 75). Thus, latest Furongian strata are not represented (Tjernvik 1956) and according to the recent zonation of the Furongian in Baltoscandia by Nielsen et al. (2020), six polymerid trilobite zones are missing beneath the contact with the Ordovician. The hiatus records subaerial exposure by the presence of mudcracks in bedding surfaces (Egenhoff & Maletz 2012). At some sections around Mount Hunneberg, but not at Diasbasbrottet, the Furongian shales and limestones are overlain by a less than 1 m thick, black, and very hard shale that forms the top of the Alum Shale Formation. It has yielded basal Ordovician (early Tremadocian) graptolites, such as *Rhabdinopora flabelliformis* and *Adelograptus tenellus* (Maletz et al. 1996).

The lithologically variable succession overlying the Cambrian–Ordovician unconformity consists of a thin (<1 m) unit of mostly dark limestone, which can be subdivided into the Bjørkåsholmen Formation ('Ceratopyge limestone') and the 'Latorp limestone'. These units are of late Tremadocian age. The 'Latorp limestone' is overlain by the Tøyen Shale Formation. This formation is more than 10 m thick and composed of dark grey, siliciclastic mudstones with graptolites intercalated by several thin

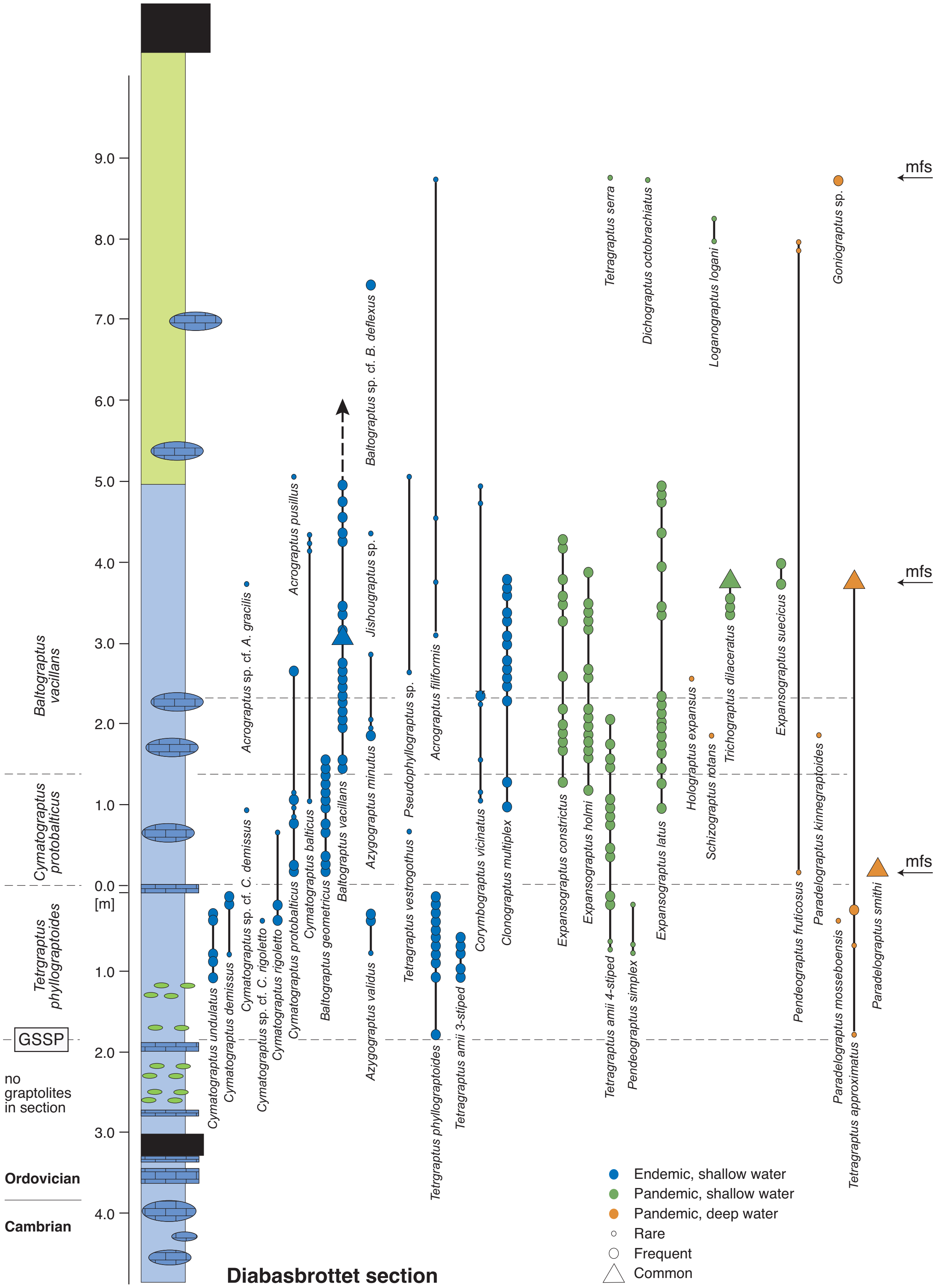


Figure 6. Lithologic succession and graptolite zonation in the Diabasbrottet section (modified from Egenhoff & Maletz 2007, fig. 3). The GSSP for the Floian Stage is located within the lower Tøyen Shale Formation and well exposed in the quarry wall. mfs = maximum flooding surface.

layers of dark, fossiliferous carbonate storm beds (Lindholm 1991a, b, Maletz et al. 1996, Egenhoff & Maletz 2012). Throughout deposition of the Tøyen Shale Formation, there was an increase in the amount of siliciclastic mudstone, probably due to an overall deepening of the environment (Egenhoff & Maletz 2012). The Permian dolerite cover on top of the Tøyen Shale Formation has a thickness of 60–70 m.

For the limestone units, a biostratigraphy based on trilobites (Tjernvik 1956, Tjernvik & Johansson 1980) and conodonts (Lindström 1971b, Löfgren 1993) has been established. The graptolites from the overlying Tøyen Shale Formation have been investigated in great detail by several authors (e.g. Tjernvik 1956, Lindholm 1991a, b, Maletz et al. 1996, Egenhoff & Maletz 2007).

The GSSP with its 'golden spike' is well-exposed in the quarry wall just adjacent to the southernmost underground mine in the Alum Shale Formation (Bergström et al. 2004). The GSSP is located 2.1 m above the top of the Alum Shale Formation and within the lower Tøyen Shale Formation (Fig. 6), just at the top of the laterally persistent limestone 'bed E' (Bergström et al. 2004). The GSSP is marked by the first appearance of *Tetragraptus approximatus*, a distinctive graptolite with a pandemic distribution. The stage boundary interval was deposited under offshore conditions. A highly diverse graptolite fauna and biostratigraphically significant conodont and trilobite species are present (Lindholm 1991a, b, Löfgren 1993, Maletz et al. 1996, Bergström et al. 2004, Egenhoff & Maletz 2012). In terms of conodont biostratigraphy, the GSSP is inferred to approximate the base of the *Oelandodus elongatus–Acodus deltatus* Subzone of the *Paroistodus proteus* Zone (Bergström et al. 2020, Nielsen et al. 2023). $\partial^{13}C_{org}$ data obtained from a series of closely spaced samples collected from the boundary interval show an absence of conspicuous isotopic excursions (Bergström et al. 2020).

Stop 2. Tomten quarry

Anders Lindskog, Michael Streng, Emma H.M. Arvestål & Lars E. Holmer

Overview. Abandoned quarry at Torbjörntorp on northeastern Mösseberg, north of Falköping, with Guzhangian–Darriwilian shale, stinkstone, and cool–temperate-water carbonates (58.224333, 13.608816). The succession spans the upper Alum Shale Formation through the 'Latorp', 'Lanna' and lower 'Holen' limestones ('orthoceratite limestone'). A significant hiatus separates the Cambrian and Ordovician strata.

Description. Tomten quarry was active for most of the 1900s, mainly supplying lime for burning and agriculture- and forestry-related purposes. The exposed succession begins in the Cambrian Alum Shale Formation, in strata belonging to the uppermost Guzhangian of the Miaolingian (Fig. 7A; Westergård 1922, Lehnert et al. 2013a). Furongian strata follow above, although this Series has several stratigraphic gaps and its upper part is missing (Ahlberg et al. 2016). The Cambrian interval was documented in detail by Ahlberg et al. (2016) based on a drill core (Tomten-1) retrieved from the quarry.

Ordovician strata follow above a distinct discontinuity surface with abundant karst-like features (Fig. 7B; e.g. Lehnert et al. 2013a, figs 59, 60). As compared to Hunneberg and Kinnekulle, the strata corresponding to the Tøyen Shale Formation are mainly developed as limestone ('orthoceratite limestone'; e.g. Jaanusson 1982c, Nielsen et al. 2023). Beginning with a conglomeratic, glauconite-rich limestone, this c. 0.25–0.5 m thick interval is referred to the 'Latorp limestone' (Floian, Ottenbyan–Billingenian Regional stages; Thorslund 1937, Tjernvik 1956, Olgun 1987, cf. Lehnert et al. 2013a). The overlying 'Lanna limestone' (c. 7 m thick, Dapingian–lowermost Darriwilian, Volkhovian Regional Stage) mainly comprises light grey limestone (locally beige–pinkish) with characteristic rhythmic bedding that alternates between limestone and marly/nodular intercalations (Fig. 8). Some beds are relatively rich in cephalopod conchs, and large megistaspid trilobite pygidia. Upward, the transition from the 'Lanna limestone' to the 'Holen limestone' (Darriwilian, Kundan Regional Stage) is marked by thicker bedding, a change into dominantly reddish strata, and a general coarsening of carbonate textures and grain sizes. Several mineralized hardgrounds occur in the transitional interval (cf. Kinnekulle, Stop 5). The 'Holen limestone' is commonly more fossiliferous than underlying strata, and echinoderm debris is relatively abundant.

Figure 7. Tomten quarry. **A.** Cambrian shale and limestone overlain by Ordovician limestones. **B.** Cambrian–Ordovician transition. The two systems are separated by a significant stratigraphic gap, marked by a discontinuity surface (marked by white arrow). Photos: A. Lindskog.

A greyish interval, colloquially referred to as the 'Blåsten' ('Bluestone'; Munthe et al. 1928, Lindskog & Eriksson 2017), occurs in the uppermost part of the quarry. This unit locally abounds with *Sphaeronites* cystoids and obviously corresponds to the 'Täljsten' at Kinnekulle (Stop 5). The Ordovician conodont biostratigraphy at Tomten quarry was documented by Olgun (1987), but taxonomic details need revision. The local succession ends in the

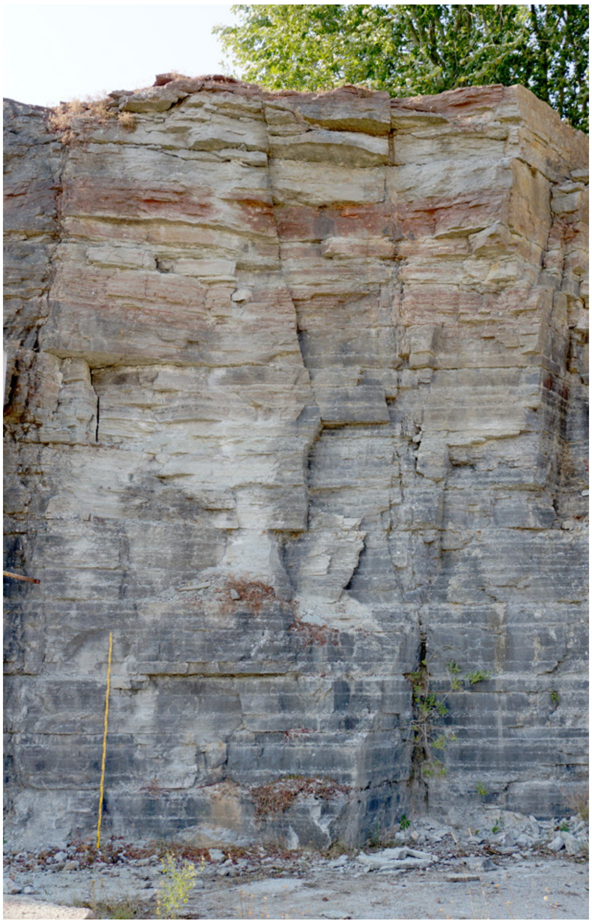


Figure 8. Middle Ordovician 'orthoceratite limestone', Tomten quarry. Photo: A. Lindskog.

mid-Kundan, i.e. the earliest middle Darriwilian, with red-coloured, cephalopod-rich limestones.

Stop 3. Skultorp quarry

Per Ahlberg, Mikael Calner, Oliver Lehnert & Anders Lindskog

Overview. Abandoned quarry exposing Upper Ordovician (Katian–Hirnantian) mud- and limestones about 900 m northwest of Norra Kyrketorp Church on the eastern slope of Mount Billingen (58.348450, 13.817206). The succession includes the late Katian Ulunda formation, the Hirnantian Loka formation, and the uppermost Ordovician–basal Silurian Kallholn formation (Fig. 9).

Description. In the Billingen-Falbygden area there are several well exposed Ordovician–Silurian boundary sections. One of the best outcrops across this interval is the abandoned quarry at Skultorp. The lower part of the exposed succession consists of

Figure 9. The western wall of Skultorp quarry exposing the Ulunda formation (main part of the section). The boundary to the overlying Loka formation is close to the thin, but distinct light bed where the trees begin. The softer shales of the Kallholn formation form the slope above the section. Photo: M. Calner (from Calner et al. 2013, fig. 53).

dark grey siliciclastic mudstones with a few limestone and siltstone interbeds. This part is referred to the Ulunda formation (Jaanusson 1963a), which has its type locality near Ulunda on the western slope of Billingen. This formation is of late Katian age and is poor in macrofossils. However, a diverse trilobite fauna, comprising at least 20 species, has been recorded from a siltstone bed 2.7–3.0 m below the top of the formation (Bergström 1973, Kielan-Jaworowska et al. 1991). It is a typical *Tretaspis* fauna dominated by trinucleid, raphiophorid, encrinurid and cheirurid trilobites (Fig. 10). The Ulunda formation is overlain by the Hirnantian Loka formation (Bergström & Bergström 1996, Bergström et al. 2011). This is an up to 1.5-m-thick light grey limestone unit with ooids in the upper part (Stridsberg 1980). The lower contact of the Loka formation is sharp and represents a regional discontinuity surface (HA unconformity of Bergström et al. 2006b). In the Kinnekulle area there is a conglomerate associated with the contact (Wærn 1948) and on Ålleberg table mountain the boundary is a distinct discontinuity surface (Bergström 1968). This break in sedimentation was discussed by Stridsberg (1980).

The prominent discontinuity surface forming the top of the Loka formation probably represents a stratigraphical gap corresponding to the HB Lowstand of Bergström et al. (2006b, 2011) and Schmitz & Bergström (2007). This surface has recently been documented also in the Siljan area and is known from several palaeocontinents (Bergström et al. 2012). Several metres of the late Hirnantian–early Llandovery Kallholn formation rest on top of this discontinuity surface.

At the type locality on the nearby Ålleberg, the Loka formation is divided in three subunits (Stridsberg 1980). The lower and upper members of the Loka formation are composed of mudstones and they are poorly developed or missing in the Skultorp quarry. The middle member is a limestone unit, which at least partly consists of an oolitic, cross-bedded grainstone that contains relatively abundant corals (Stridsberg 1980). This represents the first tropical carbonate elements in the Lower Palaeozoic of Baltoscandia and is evidence for deposition in warm and shallow water, possibly during an interglacial between the two major Hirnantian glaciations (e.g. Bergström et al. 2006b, 2014, Schmitz & Bergström 2007). Based on its distinctive lithology and wide geographical distribution, Bergström et al. (2011) proposed the designation Skultorp member for this calcareous middle member of the Loka formation. It consists of a micritic limestone rich in peloids in its lower part and is characterized by ooids in its upper part (Stridsberg 1980, Bergström et al. 2011). Bergström et al. (2011,

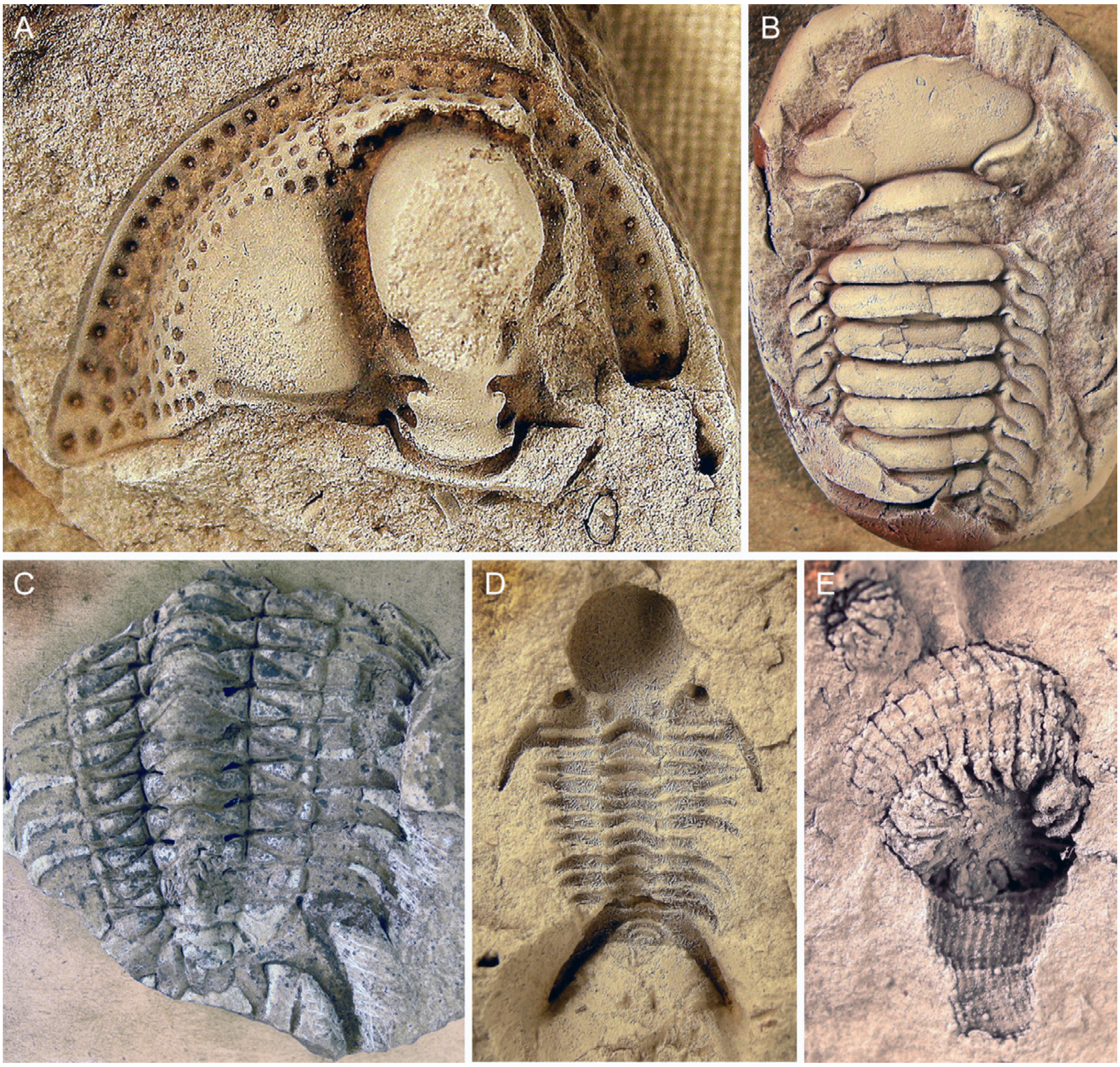


Figure 10. Upper Ordovician fossils from Skultorp quarry (A–D from the Ulunda formation, E from the Loka formation). **A.** *Tretaspis latilimba*, ×5.2. **B.** *Remopleurides* sp., ×2.6. **C.** *Hadromeros subulatus*, ×1.1. **D.** *Sphaerocoryphe dentata*, ×3.1. **E.** Solitary coral, ×3.2. Photos: P. Ahlberg (from Calner et al. 2013, fig. 54).

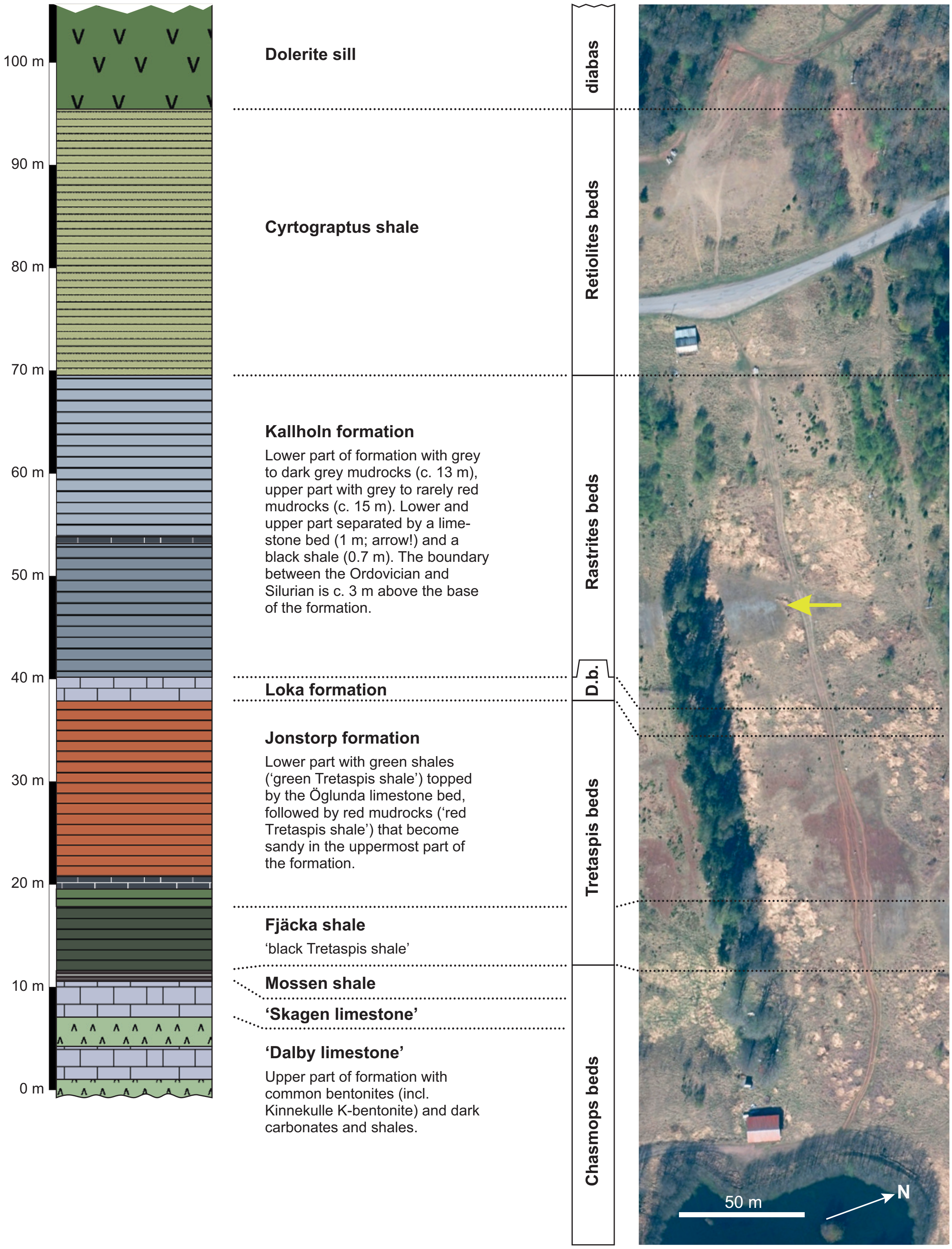


Figure 11. Simplified Upper Ordovician and lower Silurian lithostratigraphy on Kinnekulle (left) and traditional lithostratigraphic intervals (centre right) tentatively correlated with exposures on the ski slope at the Högkullen locality (right). Note the distinct intervals of dark mudrocks corresponding to the Mossen and Fjäcka shales and the red interval of the Jonstorp formation. (*D.*b. = *Dalmanitina* beds; aerial photograph from www.lantmateriet.se).

2012) provided an intercontinental correlation of the Loka formation.

Stop 4. Högkullen, Kinnekulle

Michael Streng, Anders Lindskog & Emma H.M. Arvestål

Overview. Ski slope at Högkullen (Kinnekullebacken) on the south-eastern side of Kinnekulle (c. 58.598333, 13.416667), with poor but only accessible exposures of Kinnekulle's Upper Ordovician lithostratigraphic units (Sandbian–Hirnantian). These units constitute the lower half of the slope whereas the upper half belongs to the lower Silurian (Llandovery). The Upper Ordovician succession largely consists of shales and mudrocks with intercalated limestone beds, starting with the 'Dalby' and 'Skagen' limestones, overlain by the Mossen and Fjäcka shales, followed by the Jonstorp, Loka and Kallholn formations. The Ordovician–Silurian boundary is in the basal part of the Kallholn formation.

As exposures of the units are poor, drill cores are the main source of information regarding thickness and lithology (see Wærn et al. 1948). The following description of the ski slope section is a combination of field observations and drill core data.

Description. The ski slope, Kinnekullebacken, just southwest of the restaurant Kinnekullegården (lunch stop), is the only locality on Kinnekulle where any significant interval of the Upper Ordovician succession is exposed and can be accessed relatively easily (however, large parts are overgrown). The c. 35 m thick succession starts at the little lake at the foot of the hill with the upper beds of the 'Dalby limestone' including the Kinnekulle K-bentonite (e.g. Bergström et al. 2016), followed by the 3.3 m thick 'Skagen limestone' also including bentonites in its lower part (Thorslund 1948). Individual limestone rocks found in the talus at this level might belong to this latter unit. The bentonites are not exposed at the ski slope but can be accessed at a locality about 400 m to the SSW. Above the 'Skagen limestone' follow the fine siliciclastic rocks of first the Mossen shale (c. 1–1.6 m) and then the Fjäcka shale (c. 6.5 m). The boundary between the 'Skagen limestone' and Mossen shale represents a discontinuity surface (paraconformity) which is characterized by a lithological change from dark-grey limestones to black bituminous shales coinciding with the Sandbian–Katian boundary (= boundary between the Dalbyan and Moldåan Regional stages; e.g. Nielsen et al.

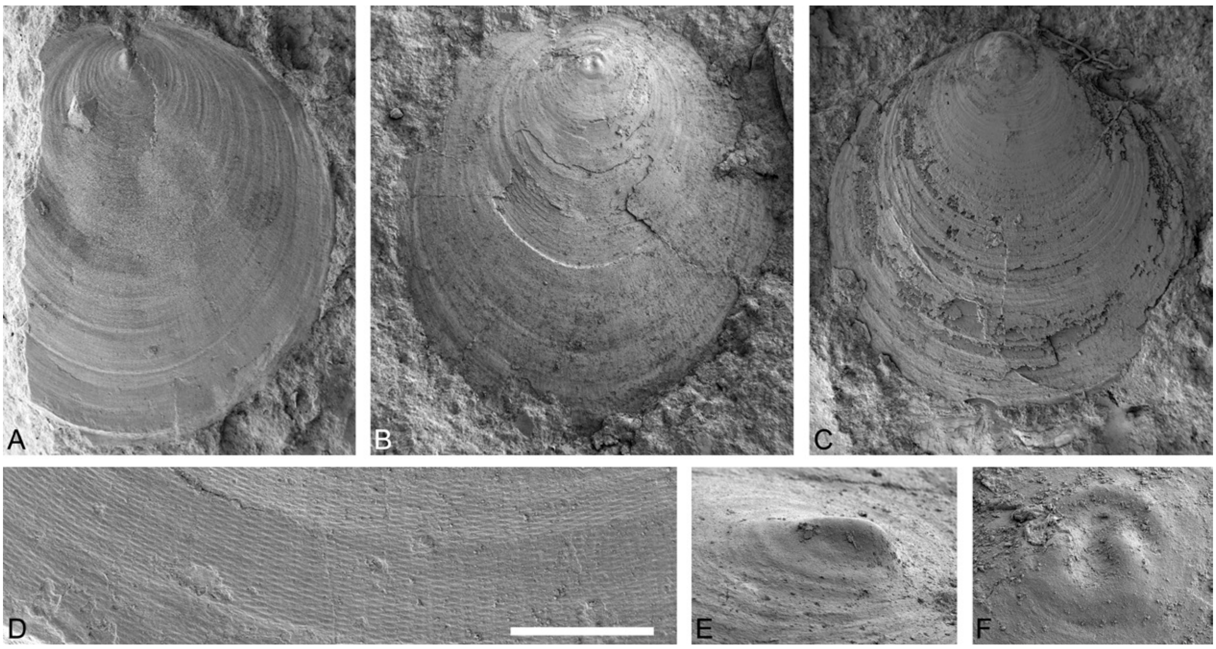


Figure 12. Fossils of the Fjäcka shale at Högkullen. A, B, D–F, *Paterula* sp., a cosmopolitan linguloid brachiopod. **A.** Ventral valve. **B.** Dorsal valve. **D.** Close-up of outer shell surface with characteristic ornamentation. **E.** Ventral larval shell. **F.** Dorsal larval shell. **C.** Dorsal valve of *Hisingerella* sp., an acrotretid brachiopod first described in 1837 from the same unit in Dalarna. Scale bar equals 500 µm (A–C) and 100 µm (D–F). Photos: M. Streng.

2023). The black and dark-grey mudrocks of the Mossen and Fjäcka shales form a distinct zone of talus on the slope (Fig. 11) and shales found in this interval can be rich in articulate and inarticulate brachiopods. Especially the lingulate taxa *Paterula* sp. and *Hisingerella* sp. are relatively common in small slabs belonging to the Fjäcka shale (Fig. 12; Henningsmoen 1948). Above the Fjäcka shale, the c. 21 m thick Jonstorp formation forms another distinct level in the slope due to the unit's dominating lithology of red shales (Fig. 11). Within the respective talus material remains of the trilobite *Tretaspis* spp. are common. The remaining Ordovician units (Loka formation, basal Kallholn formation) of the Upper Ordovician strata are not exposed. According to Bergström et al. (2014), the Loka formation is here a c. 3 m thick unit with a sandy base and top, and a middle part that is dominated by carbonates (mudstones) which contain the trilobite *Mucronaspis mucronata* (Brongniart). This middle part is also known as Skultorp limestone or Skultorp member (compare Stop 3, Skultorp, where the sandy base and top are not developed). The lower and upper boundaries of the Loka formation are marked by unconformities, of which the lower one represents the transition from the Katian to the Hirnantian (Jerrestadian–Tommarpian Regional stage boundary; Bergström et al. 2016) whereas the upper one was traditionally associated with the Ordovician–Silurian boundary. However, Bergström et al. (2014) placed the Ordovician–Silurian boundary c. 3 m above the base of the formation in accordance with observations in Skåne, southern Sweden. This suggests that on Kinnekulle, as well as in Skåne, sedimentation across the boundary was continuous, contrasting conditions at many other Swedish localities (including Dalarna) where the boundary is associated with a hiatus potentially related to an epeirogenic uplift in relation to the onset of the Caledonian Orogeny (Nielsen et al. 2023).

Stop 5. Hällekis quarry

Michael Streng, Anders Lindskog, Emma H.M. Arvestål & Lars E. Holmer

Overview. Large abandoned quarry on the north-western slope of Kinnekulle, with Floian–Darriwilian (Billingenian–Segerstadian Regional stages) cool-water–temperate carbonates and (calcareous) mudstones (58.610706, 13.393344). The succession spans the uppermost Tøyen Shale Formation, the 'Lanna' and 'Holen' limestones, and the Gullhögen formation and basal 'Ryd limestone' (Fig. 13).

Description. Hällekis quarry, which served the cement industry 1892–1979, hosts a c. 40 m thick succession of latest Floian through latest Darriwilian (Lower–Middle Ordovician) sedimentary strata, corresponding to the uppermost Billingenian through upper Segerstadian Regional stages (Nielsen et al. 2023; Figs 3, 5, 13). The locality provides an easily accessible and relatively expand-

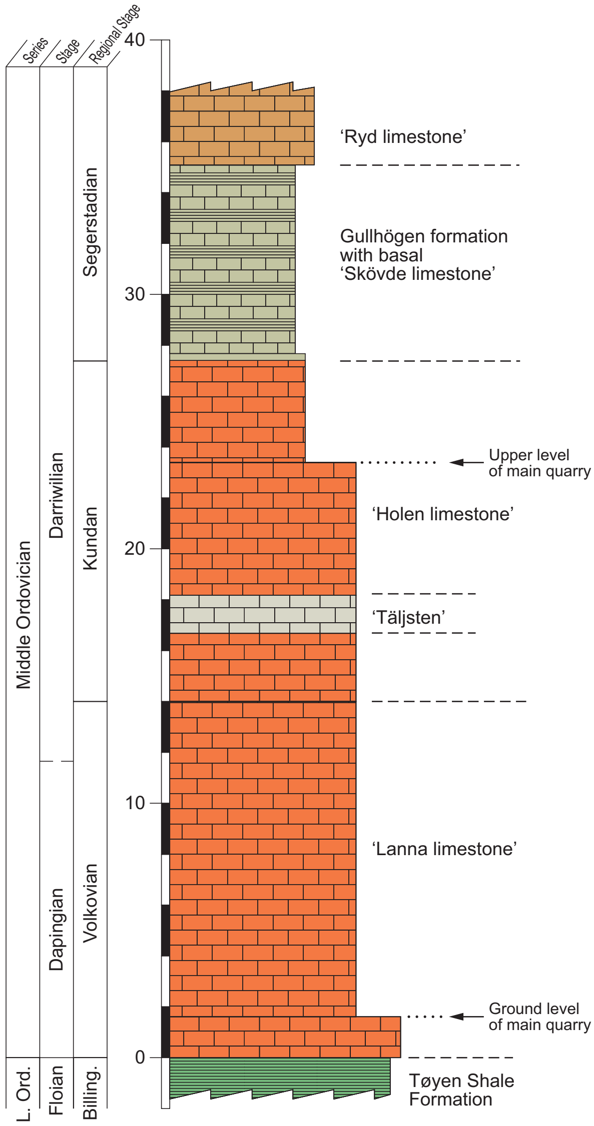


Figure 13. Simplified succession of stratigraphic units observed in Hällekis quarry (largely after Lindskog & Eriksson, 2017). L. Ord. = Lower Ordovician, Billing. = Billingenian.

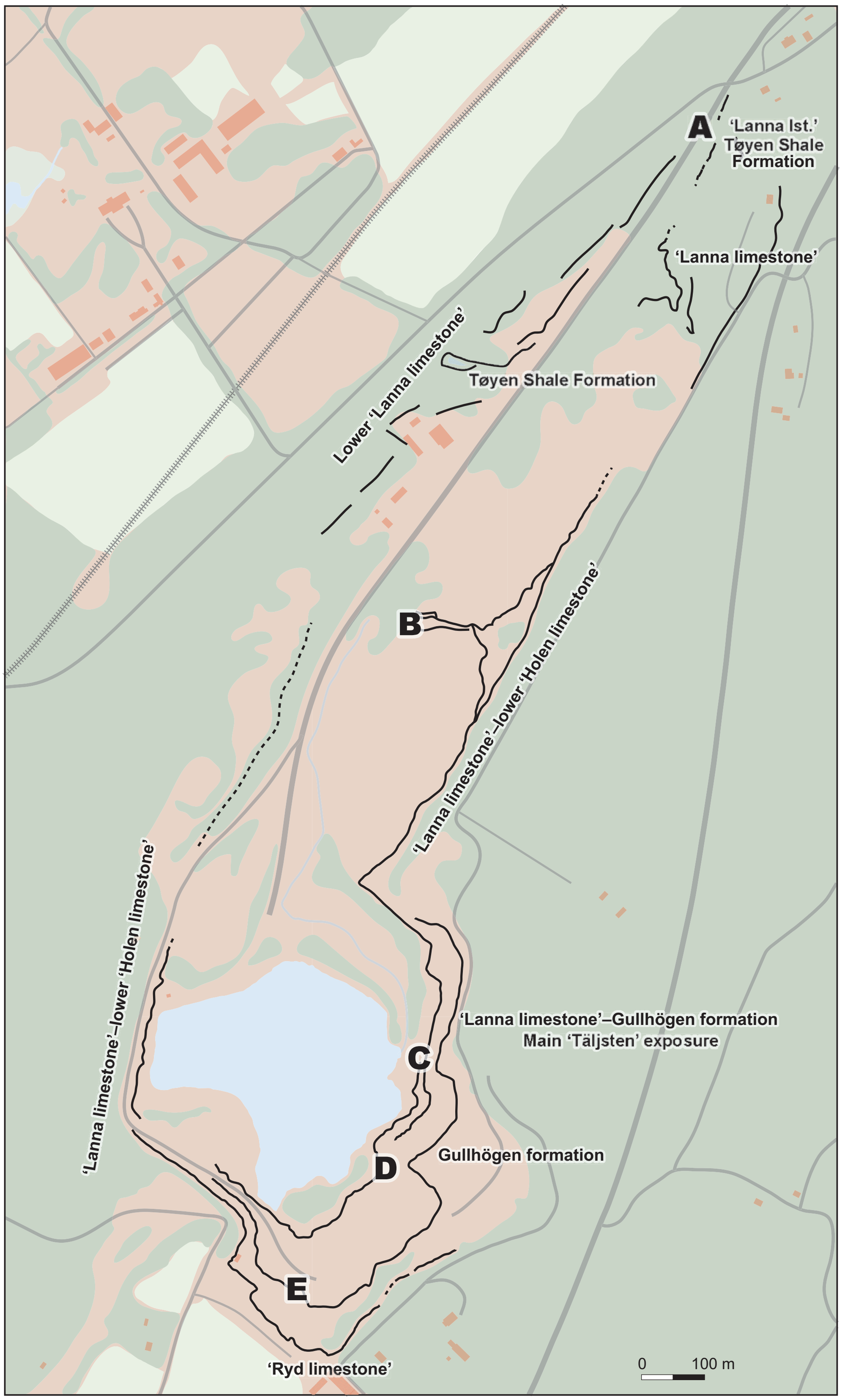


Figure 14. Sketch map of Hällekis quarry with points of interest mentioned in the text (modified after Lindskog & Eriksson, 2017, fig. 4). Heavy black lines indicate accessible rock outcrops. A and B. Contact between Tøyen Shale Formation and 'Lanna limestone'. C. Contact between 'Lanna' and 'Holen' limestones. D. Contact between 'Holen limestone', Skövde bed and Gullhögen formation. E. Contact between Gullhögen formation and 'Ryd limestone'.

ed succession for this part of the Ordovician stratigraphy. Near the entrance to the quarry area, in its northernmost part, the Tøyen Shale Formation (Billingenian) and its boundary to the overlying 'Lanna limestone' (Volkhovian Regional Stage) can be accessed along the east side of the road (A in Fig. 14; Lindskog & Eriksson 2017). Another possibility to see the boundary is in the more central part of the quarry where a fault exposes the contact (B in Fig. 14). The greenish grey mudstones and shales of the upper Tøyen Shale Formation are poor in macrofossils apart from ichnofossils (see Lindskog & Eriksson 2017 for summary), but Tjernvik (1956) documented the *Didymograptus hirundo* graptolite Zone in the uppermost beds. The base of the 'Lanna limestone' coincides closely with the base of the Dapingian, and thus with the Middle Ordovician (Bergström & Löfgren 2009), and also with the base of the Volkhovian (Lindskog & Eriksson 2017, Nielsen et al. 2023).

The 'Lanna limestone', which is c. 14.5 m thick, comprises brownish–reddish, relatively fine-grained and -textured 'orthoceratite limestones' with distinctly rhythmic bedding in the middle part of the unit (decimetre thick mudstone-marl and wackestone-marl couplets). Bedding becomes thicker towards the top of the unit and carbonate textures become coarser. Close to the boundary to the overlying 'Holen limestone', iron-stained (limonite and hematite) hardgrounds are common. Macrofossils are relatively rare in the 'Lanna limestone', and mainly comprise orthocone cephalopods and trilobite pygidia (typically *Megistaspis* spp.). Some beds in the upper part of the unit contain relatively abundant nileid trilobites, which may be found articulated (commonly enrolled).

The boundary between the 'Lanna' and the 'Holen' limestones is placed atop a prominently bioeroded limestone which is followed by red marly nodular limestone beds of the lower 'Holen limestone' (Fig. 15B). This lithological boundary coincides with the biostratigraphically defined Volkovian–Kundan boundary as indicated by the first appearance of Kundan trilobites in the basal marly layers of the c. 14 m thick 'Holen limestone' (Lindskog et al. 2014, Nielsen et al. 2023). The marly beds are followed upward after c. 2.75 m by a conspicuous, c. 1.5 m thick interval of grey wacke- and packstones referred to as the 'Täljsten' ('carving stone'). This limestone interval, easily recognisable also from great distance (Fig. 15A), represents a regional marker bed (compare 'Blåsten', Stop 2, Tomten quarry) which is associated with a facies change caused by a prominent sea level drop (Eriksson et al. 2012 and references therein). The observed facies change can be followed throughout most of the Baltoscandian basin and is best exposed in southern-central Sweden. In Hällekis quarry, the lower 'Täljsten' is rich in glauconite and microscopic fossil debris and centimetre-sized oncoids are common (see Lindskog 2014). Alternating centimetre-thick layers of darker grey fine-siliciclastics and nodular limestones are characteristic for the middle part, whereas in the uppermost part limonitic grains are frequent (Lindskog & Eriksson 2017). Several phosphate-coated hard- and firmgrounds occur throughout the unit. Most characteristic for the 'Täljsten' are, however, fossil-rich layers entirely dominated by *in situ* preserved specimens of the cystoid echinoderm *Sphaeronites* (Fig. 15D). Regionally, the beds that enclose the 'Täljsten' and equivalent strata are commonly very rich in cephalopods and other mollusc fossils (Kröger & Rasmussen 2014, Lindskog et al. 2015). The remaining c. 10 m of the 'Holen limestone' are again red in colour, of which the first 3.5 m are texturally similar to the 'Täljsten' and constitute (together with the 'Täljsten') the biologically and hydrodynamically most active environments of the 'Holen limestone' (Lindskog & Eriksson 2017). The uppermost beds of the unit are, like the basal ones, more marly in composition and macrofossils become rare whereas trace fossils in the form of *Planolites* and *Thalassinoides* are common and diagenetically highlighted as their burrows have a greenish colour contrasting the surrounding red matrix. Many beds in the 'Holen limestone' (at Hällekis and elsewhere) contain relatively abundant chromite grains with chemical compositions that indicate a meteoritic origin. Together with a remarkable occurrence of 'fossil' meteorites in the 'Täljsten' interval, this has been linked to an asteroid disruption event in space (e.g. Schmitz & Häggström 2006, and references therein).

The 'Holen limestone' terminates in a flat discontinuity surface with *Trypanites*-type borings and a coating of a 15 to 20 mm thick phosphorite layer containing phosphatic and chamositic ooids (Holmer 1983, Sturesson 1989). The discontinuity surface marks a significant stratigraphic gap in the

Figure 15. A. View of the north-eastern corner of the southern main area of Hällekis quarry showing exposures of 'Lanna limestone', 'Holen limestone' with 'Täljsten' and Gullhögen formation. **B.** Transition from 'Lanna' into 'Holen limestone' at Hällekis quarry at point B in Figure 14. The boundary between the two units is recognized in the field by a limonite stained hardground marking the top of the 'Lanna limestone' and a marl-rich, easily weathered interval characteristic for the lowermost 'Holen limestone'. The tip of the hammer's handle marks the boundary. Note another limonite stained hardground c. 1.3 m above the boundary (arrow). **C.** Limonite stained hard ground (same as arrow in B) and distinct planar discontinuity surface c. 15 cm below. **D.** Layer of *Sphaeronites* within the 'Täljsten'. Note that incomplete fillings of the spherical calyxes are geopetal structures. Hammer tip for scale in C and D. Photos: M. Streng.

Darriwilian succession on Kinnekulle spanning c. 4–5 million years, equivalent to the lower half of the Segerstadian (Nielsen et al. 2023). Above the discontinuity surface, overlying the aforementioned phosphorite layer, a decimetre-thick grey wackestone occurs. This limestone bed is equivalent to the so called Skövde beds or 'Skövde limestone' (Jaanusson 1982c) originally described from Billingen (c. 34 km SE of Kinnekulle) where the beds reach a thickness of up to 45 cm (Holmer 1989) and contain illaenid trilobites and inarticulate brachiopods (Jaanusson 1964, 1982c, Holmer 1989). On Kinnekulle, hash of inarticulate brachiopods has been described from the basal layer (Holmer 1983) and silicification of primary phosphatic and calcareous shells (brachiopods and gastropods) has been observed (Sturesson 1989).

Above the Skövde beds follow the greenish grey beds of the c. 7.5 m thick Gullhögen formation, which is characterized by a succession of thin beds (< 10 cm) of wacke- and mudstones alternating with equisized beds of marl and calcareous shales. In the basal part of the formation, trilobite debris is common and layers of chamositic ooids occur (Lindskog & Eriksson 2017). Trilobite taxa such as the asaphids *Pseudomegalaspis* Jaanusson and *Ogygiocaris* Angelin, the nileid *Nileus* Dalman and the trinucleid *Botrioides* Stetson are characteristic for the Gullhögen formation, alongside the ostracod *Actinochilina* Jaanusson and a few graptolite taxa (Jaanusson 1964, Owen 1987). An overall increase in the relative abundance of organic-walled fossils (notably, graptolites and acritarchs) in the lower part of the formation was mentioned by Lindskog & Eriksson (2017). Articulated, commonly enrolled, nileid trilobites are abundant in some beds. The Gullhögen formation differs significantly from the 'typical' rocks of mainland Sweden and can be considered a wedge of the Norwegian Elnes Formation, which spans most of the Segerstadian (e.g. Nielsen et al. 2023).

The Gullhögen formation is overlain by thick-bedded limestones belonging to the c. 9 m thick 'Ryd limestone', of which the lower c. 6 m are exposed in Hällekis quarry (Fig. 16). The 'Ryd limestone' is relatively poor in macrofossils besides cephalopods, and rare illaenid, nileid and trinucleid trilobites (Jaanusson 1964), whereas ostracods are common throughout the section; Holmer (1989) reported inarticulate brachiopods from the unit on Billingen. The Middle–Upper Ordovician (Darriwilian–Sandbian) boundary is probably located within the 'Ryd limestone', whereas the Segerstadian–Dalbyan boundary lies higher (probably within the basal beds of the overlying 'Dalby limestone'; Nielsen et al. 2023). Apart from the Floian–Dapingian boundary (see above), precise correlation of the regional and global stages (as well as locating the boundaries in-between global stages) in the successions of Västergötland is hampered by the lack of graptolites within the carbonates of mainland Sweden and the incomplete knowledge of the trilobites of this time interval (Nielsen et al. 2023).

Figure 16. A. Contact between the alternating limestone and shale beds of the Gullhögen formation and the thick-bedded limestones of the 'Ryd limestone' as exposed in Hällekis quarry. **B.** Detail of A; hammer marks the boundary. Point E in Figure 14. Photos: M. Streng.

The Ordovician of Dalarna

Jan Ove R. Ebbestad, Linda Wickström, Nastaran Ahanin & Sebastian Willman

The Siljan ring in Dalarna, central Sweden, appears as a nearly perfectly circular structure manifested by a sedimentary halo of Palaeozoic rocks in an otherwise Proterozoic basement (Fig. 17). It is the largest-known impact structure in Europe and was formed in the mid Devonian, at the Frasnian–Famennian boundary. The most conservative estimate gives an age of 380.9 ± 4.6 Ma (Reimold et al. 2005, Jourdan et al. 2012). Since 2019 the Siljan ring area is a Swedish national Geopark.

The size of the crater is difficult to estimate as the present structure is a denudated remain of a once larger structure. Four estimates exist based on different parameters: 1) a final crater measuring 52 km and pre-erosion transient crater measuring 26 km; 2) a 42 km transient crater and a final size of 65 km; 3) a final crater of at least 75 km, with the inner ring showing the estimated peak ring; 4) a transient crater with a pre-erosion mean diameter of 35 km and a final size of 90 km (see Juhlin et al. 2012

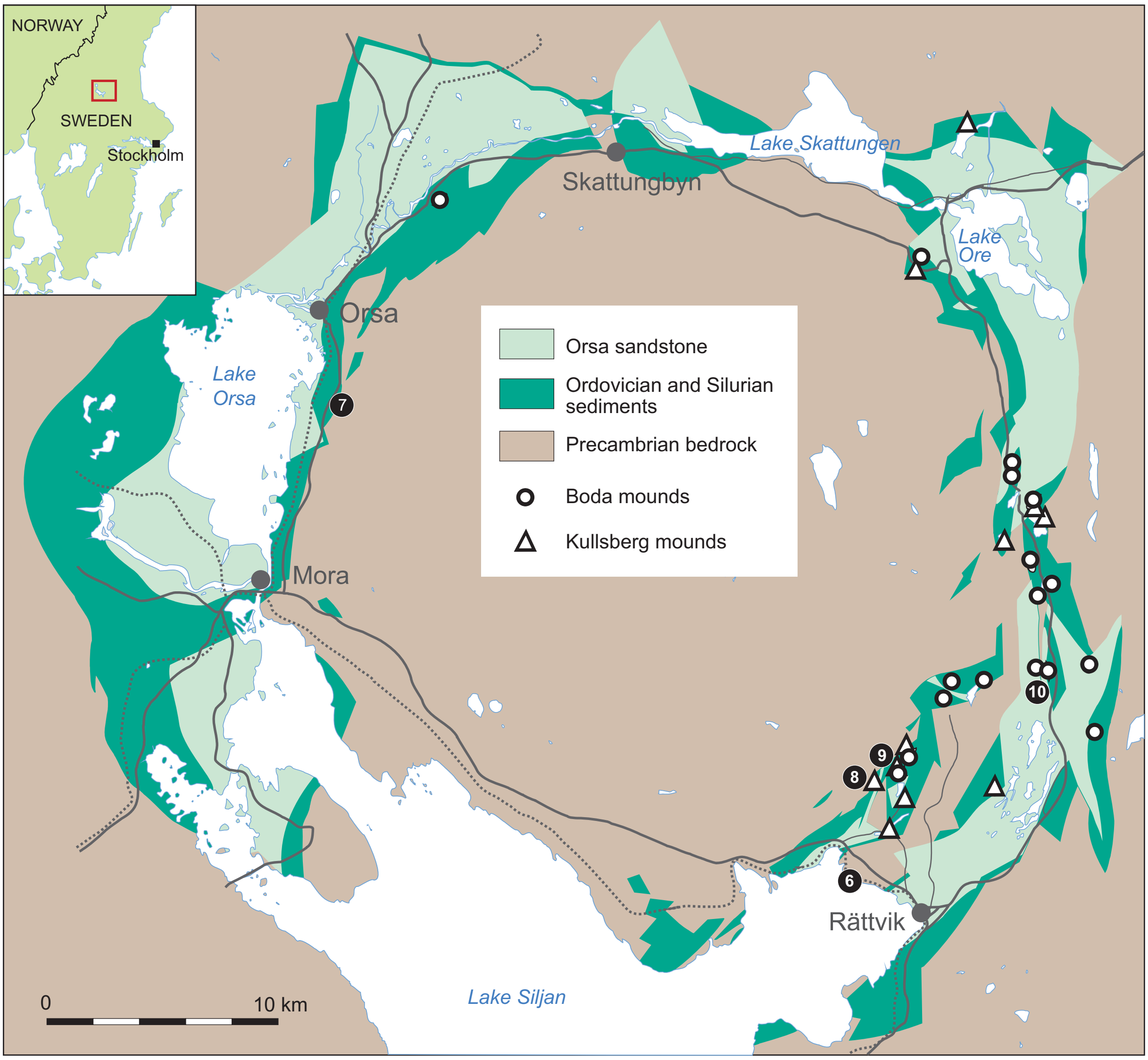


Figure 17. Map showing the Siljan ring with main lithologies, the Kullsberg and Boda limestone mounds and localities 6–10. Modified from Ebbestad & Högström (2007, fig. 1).

and references therein). Best fit model estimates after numerical modelling reveals a crater size of 65 km (Holm-Alwmark et al. 2017). Structurally, the Siljan ring is an annular ring graben with a mega-block zone preserving the Palaeozoic succession (Henkel & Aaro 2005). At the impact no sediments were present within the transient crater and what today is preserved in the graben represent radial inflow of the collapsed rim of the transient crater in concert with mass flow from the central area (Kenkmann & Dalwigk 2000, Henkel & Aaro 2005, Muhamad et al. 2017). The various blocks show different signs of impact related deformation that may reflect different distances away from the crater (Muhamad et al. 2017).

Despite the impact, the Ordovician succession in the Siljan district is remarkably complete and unaltered (Fig. 5). Conodont Colour Alteration Index values show that the rocks have not been heated above 90°C, even though they are tectonically disturbed (Bergström 1980). The entire Ordovician succession is no more than 100 m thick in the so called intermound facies (Jaanusson 1982a).

A palaeomagnetic study in the Siljan district has provided important new results. Samples have been analysed for palaeomagnetism, and rock magnetism and preliminary results suggest that during the deposition of the 'Lanna' and 'Holen' limestones, Baltica was situated in the southern hemisphere at a latitude of 55°S. Subsequently, Baltica began moving northward, and during the deposition of the 'Furudal' and 'Dalby' limestones, it had reached a latitude of 33°S (Ahanin & Gilder 2022, Ahanin et al. in prep.).

Cambrian strata are missing in the area, but erratic boulders with upper Cambrian (Furongian) phosphatic brachiopods are known (Holmer & Popov 1990). The first Ordovician sediments appear as the 'Obolus bed', which is a conglomerate deposited on top of the crystalline bedrock. In the railroad section at Sjurberg (now inaccessible) the 'Obolus bed' contains reworked Cambrian lingulids, but the lingulid fauna as a whole shows a range of ages from the late Cambrian (Furongian) to the Early Ordovician Ottenbyan Stage (*Megistaspis armata* trilobite Zone, lowermost *Paroistodus proteus* conodont Zone; Tjernvik 1956, Puura & Holmer 1993, Löfgren 1994). At other localities, the 'Obolus bed' is absent and Tremadocian (Ottenbyan) strata ('Latorp limestone') lie on the Precambrian basement (Fig. 5).

The classic 'orthoceratite limestone' encompasses the 'Latorp', 'Lanna', 'Holen', 'Segerstad', 'Skärlöv', 'Seby' and 'Folkeslunda' limestones and these units are no more than 20–30 m thick altogether in the Siljan district (Ebbestad & Högström 2007, Lehnert et al. 2014). The 'orthoceratite limestone' outcrops sparingly, and classic successions such as that in Vikarbyn (Jaanusson & Mutvei 1953) are no longer accessible. However, these beds can be studied in several drill cores (Lehnert et al. 2012, 2013b).

A tongue of the Floian (Billingenian) Tøyen Shale Formation, otherwise found in the deeper facies to the west in Västergötland and the Oslo Region in Norway, occurs in some parts of the Siljan ring (Ebbestad & Högström 2007, Lehnert et al. 2013b). The onset of the Middle Darriwilian $\partial^{13}C$ excursion (MDICE) is recorded in the 'Holen limestone' and a tripartite subdivision is recognized in its peak interval from the 'Holen' to 'Segerstad' limestones (Lehnert et al. 2014). The MDICE is a key isotopic excursion internationally and within Baltoscandia.

The undifferentiated thickness of the 'Furudal' and 'Dalby' topoformations is between 30 and 55 m (Ebbestad & Högström 2007, Lehnert et al. 2014). The upper boundary of the 'Dalby limestone' is at the top of the thickest K-bentonite bed (the Kinnekulle K-bentonite) the last in a complex of seven K-bentonite beds (Jaanusson 1960, 1982b, Holmer 1989). Both units are quite fossiliferous (Ebbestad & Högström 2007), but as with many units in Dalarna very few exposures are available today. The start of the major Guttenberg Isotope Carbon Excursion (GICE) is putatively recorded in the uppermost 'Dalby limestone', below the K-bentonites, and ends in the 'Freberga formation' (Lehnert et al. 2014). This is contemporaneous with the Kullsberg limestone which grew during the rising limb of the GICE and is truncated shortly after the peak of the GICE (Calner et al. 2010a). The smaller Kope $\partial^{13}C$ excursion has been recorded in drill cores and at Amtjärn quarry (Calner et al. 2010a, Lehnert et al. 2014). In the normal facies it occurs at the transition from the 'Freberga' to the 'Slandrom limestone' and in the uppermost Skålberg limestone in the mound facies.

The upper part of the 'Slandrom limestone' records a major palaeokarst horizon a few metres thick, which can be traced eastwards to Estonia and Latvia (Calner et al. 2010b). This is near the boundary between the *Amorphognathus superbus* and *A. ordovicicus* conodont zones (Bergström 2007) and marks a regional regression with basin wide cessation in carbonate production (see also Stop 8, Amtjärn quarry).

The following Fjäcka shale is one of the most conspicuous units in Baltoscandia (developed as the Vennstøp Formation in the Oslo Region, Norway). Sediments were formed under euxinic bottom conditions (Lu et al. 2017) which gave an extraordinarily organic-rich and highly fossiliferous shale (see Ebbestad & Högström 2007).

Seismic data and drill cores have in recent years given us a more nuanced picture of the depositional settings for this part of Sweden. To the east a carbonate platform succession developed during the Middle–Late Ordovician, whereas to the west the traditional beds above the 'Holen limestone' were seemingly eroded and replaced by deeper water Silurian sediments including debris flows (Lehnert et al. 2012, 2013b). This was interpreted as a result of uplift and erosion when a backbulge basin was formed to the west, shaped by the closing of the Iapetus Ocean (Lehnert et al. 2012, 2013b). However, the Ordovician sequence seems to be of constant thickness (Muhamad et al. 2018) and the observed disturbances may instead be a result of impact related tectonics (Maletz 2021).

In the Late Ordovician an extensive mound belt developed from the Oslo Region, into the Siljan area and Gotland (subsurface), and further into the Eastern Baltic area (Levendal et al. 2019). This belt represents stable environments that persisted for millions of years (Kröger et al. 2016a). In the Siljan area, the Boda limestone mounds, together with the Kullsberg mounds, grew distally and in deeper shelf settings than the shallower epicontinental mounds and reefs to the east (Kröger et al. 2016a). The Boda mounds are large structures, with a width of up to 800 m and a thickness of 140 m (Jaanusson 1982a). They are 'textbook' examples of stromatactis mud-mounds. Typically, mound growth started with carbonate formation on large patches of *Palaeoporella* algae colonies and shelly debris, giving small mounds with a significant relief (Kröger et al. 2015). These facilitated further algal and sponge growth in a taphonomic and diagenetic feedback cycle. Instead of forming a dome, the mounds are flat-topped with corals in the upper part, suggesting that they were levelled off by the sea level in the latest Katian. The late Katian *Holorhynchus* beds seen at the top of the mounds (see Stop 10, Solberga) represent the first covering of the mounds by marly sediments, which paused the algal and sponge induced mound growth and it finally stopped. The youngest carbonate deposits form the Osmundsberget formation, recording the Hirnantian Carbon Isotope Excursion (HICE; Ebbestad et al. 2015).

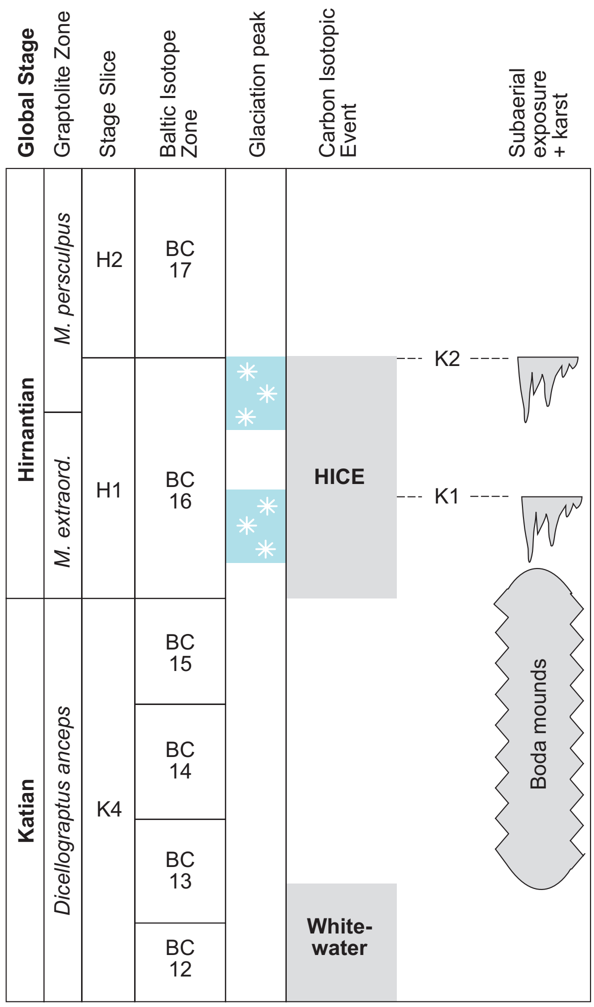


Figure 18. Diagram showing the timing of the Hirnantian subaerial exposure and karst development of the Boda limestone and Osmundsberget formation. K1 and K2 refer to two distinctive Hirnantian karst intervals. *M.* = *Metabolograptus*. Modified from Kröger et al. (2015, fig. 8).

Kröger et al. (2016a) pointed out that the so-called Boda Event of Fortey & Cocks (2005), a period of global warming and high sea level, represents a long period of more than 3 million years and spans two glacial cycles and pronounced palaeoecological changes.

The Boda mounds are typically deeply fractured by fissures radially dispersed around the mound core (Kröger et al. 2016a). Fossils, mainly monospecific accumulations of a few different types of trilobites, fill these fissures (Suzuki & Bergström 1999), but typically they have been reactivated and have different generations of infill (Ebbestad & Högström 2007). The biodiversity of the mounds is astonishing but many fossil groups remain poorly documented (Ebbestad & Högström 2007). In the last phase of deposition, some fissures record microbially meditated subaerial speleothems and infilling of siltstone (Kröger et al. 2015; Fig. 18, see also Stop 10, Solberga). These, together with meteoric solution cavities penetrate depths as much as 30 m into the mounds. The speleothems and the karst surfaces record an estimated sea-level fall in the range of 80–130 m during the HICE (Kröger et al. 2015).

Excursion Stops

Stop 6. Sjurberg beach section

Overview. Beach section at Lake Siljan, about 4 km northwest of Rättvik (60.905556, 15.046583), with gently dipping beds of the classic ’orthoceratite limestone’. The exposure spans the early Middle Ordovician ‘Lanna’ and ‘Holen’ topoformations with a well-developed lithological contact in-between.

Description. The lower part of the succession belongs to the ‘Lanna limestone’ (Fig. 19). It was originally named the Limbata limestone after the abundant trilobite remains of *Megistaspis* spp. and the Lower Red Orthoceratite limestone. This is a topoformation and its lower boundary is lithologically similar to the underlying ‘Latorp limestone’ (formerly the Planilimbata limestone), which is not exposed here. The ‘Lanna’ interval is poorly investigated biostratigraphically in the Siljan district, whereas it is considerably better known in other parts of Sweden (Tjernvik 1956, Tjernvik & Johansson 1980, Löfgren 1994). The boundary between the ‘Lanna’ and ‘Holen’ limestones is marked by a discontinuity surface lined by limonitic mineralisation (Fig. 20A, B; Jaanusson 1982b). Above the discontinuity surface is 1.2 m of grey oolitic limestone containing chamositic and limonitic ooids (Jaanusson 1982b, Sturesson

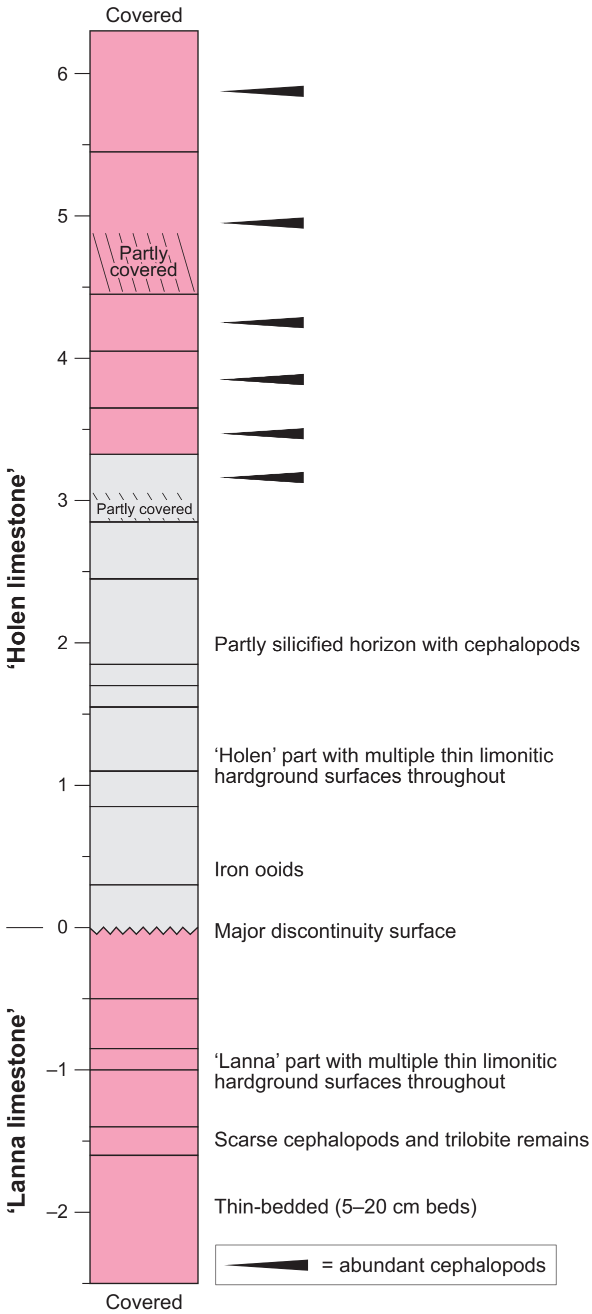


Figure 19. Simplified succession of stratigraphic units exposed at the Sjurberg beach section.

Figure 20. A. Overview of the beach section at Sjurberg, viewed towards the north. **B.** The contact between the 'Lanna' and 'Holen' limestones. The boundary represents a stratigraphic gap, marked by a discontinuity surface. **C.** Orthoconic nautiloid cephalopods on a bedding plane of the 'Holen limestone'.
Photos: J.O.R. Ebbestad (A, C) & M. Streng (B).

1988). Most of the 'Holen limestone' is exposed at this beach locality; the unit is 7.1 m thick at the type locality Kårgärde (Stop 7). It formerly encompassed the 'Lower Grey Orthoceratite limestone' (*pars*) and the 'Upper Red Orthoceratite limestone' (*pars*). This is a topoformation as well and the upper beds are indistinguishable lithologically from the overlying 'Segerstad limestone'. These units are separated biostratigraphically based on the presence of *Megistaspis (Megistaspidella) gigas* in the upper 'Holen limestone' and *Asaphus (Neoasaphus) platyurus* in the lowermost 'Segerstad limestone'. Previously the red and grey-green colours of the 'orthoceratite limestone', were used for correlation between various regions. The grey/green colouration stems from glauconite and oxidized iron-containg minerals and red from hematite, but the distribution of red and green colours can change from one locality to the next (Lindskog et al. 2014, 2018) and is therefore unreliable for correlation purposes.

Recently the section was sampled for palaeomagnetism. Calculations of the virtual geomagnetic poles make it possible to locate the palaeomagnetic pole and interpret the palaeogeography of Baltica during the deposition time of the 'Lanna' and 'Holen' limestones. Preliminary results place Baltica at a high latitude position at 55 °S during the early Middle Ordovician. It remained at this latitude for about 6 million years – during the entire deposition time of the 'Lanna' and 'Holen' limestones – then it started drifting northwards (Ahanin & Gilder 2022, Ahanin et al. in prep.).

A varied fauna of trilobites and nautiloids dominate the fossil contents of the units (see Ebbestad & Högström 2007) but the endocerid *Proterovaginoceras incognitum* is the most abundant species in the 'orthoceratite limestone' (Fig. 20C; Kröger & Rasmussen 2014). The *Lenodus variabilis–Yangtzeplacognathus crassus* conodont zones at the base of the 'Holen limestone' were studied by Löfgren (2003). The contact between the 'Lanna' and 'Holen' limestones also marks the boundary between the Volkhovian and Kundan regional stages (Nielsen et al. 2023).

Stop 7. Kårgärde section

Overview. The Kårgärde section is situated in the hillside above Holen village, about 3.5 km south of Orsa (61.083861, 14.630306). It is an excavated trench, and the profile preserves a nearly vertically dipping sequence from the 'Latorp limestone' to the 'Dalby limestone'. The excavation was initiated in 1947 and developed further in 1976. The section is a nature preserve which means that no hammering is allowed. All units are marked with signs on the outcrop.

Description. The oldest beds are the 'Latorp limestone' that rests, with a polymictic conglomerate at its base, on Mesoproterozoic age porphyry (older than 1.7 Ga). It's upper part is faulted at the contact with the overlying 'Lanna limestone' (Fig. 21A, B). In the Sjurberg railroad section (now inaccessible) the unit is about 3.7 m thick (Tjernvik 1956, fig. 23). The 'Latorp limestone' is developed as grey and red argillaceous calcilutitic limestones, which are glauconitic in the lower part of the unit. The unit spans the *Megistaspis armata* to the *Megistaspis estonica* trilobite zones (Tjernvik 1956, Tjernvik & Johansson 1980) and the *Paroistodus proteus* to the *Oepikodus evae* conodont zones (Löfgren 1993, 1994, 1995, Tolmacheva & Löfgren 2000). Both the 'Lanna' and 'Holen' limestones show a similar development in this section to that at Sjurberg beach section (Stop 6). As mentioned, Kårgärde is the type section for the 'Holen limestone' (Jaanusson 1982b, pp. 18, 40) and the unit is here 7.1 m thick. The upper part of the 'Holen limestone' was defined by Jaanusson (1982b) by the presence of *Megistaspis (Megistaspidella) gigas*.

The 'Segerstad limestone' is a topoformation (see the Sjurberg beach section). It was subdivided into the 'Kårgärde' and 'Vikarbyn' limestones (Jaanusson & Mutvei 1951, 1953; subsequently named by Jaanusson 1963b, p. 2). The type section for the thick-bedded to finely nodular 'Kårgärde limestone' is the Kårgärde section, where the unit is 2.4 m thick. A 6 cm thick stromatolite-like bed occurs at the base of this unit (Jaanusson 1982b pp. 20, 41; Holmer 1989), although these features may have a diagenetic origin (see discussion in Holmer 1989, p. 13). Similar structures have been found in the 'Holen limestone' in Jämtland (Lars-

Figure 21. A. Simplified succession of stratigraphic units observed in the Kårgärde section (modified from Holmer 1989, fig. 5B). **B.** Photo of the trench in May 2021. The stratigraphically older beds are exposed in the upper part in the photo and correspond to the lower beds in the section illustrated in A. Photo: L. Wickström.

son 1973) and Västergötland (Lindskog 2014). 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 & Mutvei 1951, 1953, Jaanusson 1963b), a section no longer accessible. Stromatolite-like structures occur also at this locality (Holmer 1989). The boundary between the two subdivisions of the 'Segerstad limestone' (the 'Kårgärde' and 'Vikarbyn' limestones) is marked in the Vikarbyn section (not seen on this trip) by a horizon of mud cracks which is overlain by a thin conglomeratic bed. This is not present in the Kårgärde section where the transition is marked by a change from a fauna dominated by the stratigraphically important nautiloid *Angelinoceras latum* to a fauna dominated by the trilobite *Illaenus* aff. *sulcifrons* (Jaanusson & Mutvei 1953, Jaanusson 1982b). Other macrofossils are rare (Ebbestad & Högström 2007). The upper boundary of the 'Segerstad limestone' is clearly marked lithologically by the change to the nodular limestones of the 'Skärlöv limestone'.

The 'Skärlöv limestone' is a reddish brown, finely nodular limestone unit with argillaceous intercalations (Jaanusson 1982b, Holmer 1989). The unit is bounded by massive, bedded limestone. Except for trilobites (Jaanusson 1953a) few macrofossils are known (Jaanusson 1982b, p. 21), but a rich microfauna of phosphatic brachiopods (Holmer 1989) and conodonts (Bergström 1971, 2007) 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, 2007). The Kårgärde section is the reference section for both of these conodont zones (Bergström 1971, p. 91).

The 'Seby limestone' is a thin but distinctive unit that occurs from Jämtland in the north to Gotland in the south (Jaanusson 1982b, Nõlvak & Grahn 1993). Holmer (1989) reported three levels with hematite-rich, laminated stromatolite-like domes in the Kårgärde section. Biostratigraphically the 'Seby limestone' falls within the *Pygodus serra* conodont Zone and the *Eoplacognathus foliaceus* Subzone (Bergström 1971, 2007), and the *Cyathochitina sebyensis* chitinozoan Subzone of the *Laufeldochitina striata* chitinozoan Zone (Nõlvak & Grahn 1993).

The overlying 'Folkeslunda limestone' is the uppermost unit in the traditional 'orthoceratite limestone' of Sweden. The lower boundary is at the base of a 15 cm thick grey calcarenitic limestone bed, which is overlain by thin-bedded calcarenitic and calcilutitic limestones. The upper half of the formation consists of thick-bedded calcarenitic limestones (Jaanusson 1963b, 1982b, Holmer 1989), but the upper boundary is placed "where the lithological change is most obvious" (Jaanusson 1960, p. 215). Biostratigraphically the 'Folkeslunda limestone' spans the *Pygodus serra* conodont Zone and the *Eoplacognathus reclinatus* Subzone (Bergström 1971, 2007).

The 'Furudal limestone' represents a period of more stable depositional conditions in deeper water settings (Jaanusson 1982b). It is a topoformation with a lithologically distinct base whereas the upper boundary is transitional to the 'Dalby limestone' (Jaanusson 1947, 1963b, 1982b, Holmer 1989). A number of fossil groups have been recorded from the unit (see Ebbestad & Högström 2007). The boundary between the *Pygodus serra* and *P. anserinus* conodont zones occurs about 5 m below the top of the 'Furudal limestone' (Bergström 1971, 2007).

The uppermost unit exposed in the Kårgärde section is the topoformation 'Dalby limestone'. Holmer (1989) placed the boundary in the Kårgärde profile about 1 m below that of Karis (in Jaanusson 1982b). The lower 6.6 m ('lower member', Jaanusson 1982b) consists of greenish grey thick-bedded limestone whereas the overlying 13.3 m ('upper member', Jaanusson 1982b) is more nodular or thin bedded. 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 seven K-bentonite beds (Jaanusson 1960, 1982b, Holmer 1989), representing the Kinnekulle K-bentonite (the name was introduced by Bergström et al. 1995, p. 4).

The 'Dalby limestone' is rich in both micro- and macrofossil remains with the 'crystal apples' of cystoid echinoderms being conspicuous (see Ebbestad & Högström 2007). Biostratigraphically the 'Dalby limestone' falls within the short-ranged middle to upper *Laufeldochitina stentor* to the *Spinachitina cervicornis* chitinozoan zones (Laufeld 1967, Nõlvak & Grahn 1993, Nõlvak et al. 1999). The 'Dalby limestone' also encompasses the *Amorphognathus tvaerensis* conodont Zone with three subzones (Bergström 1971, 2007). This conodont taxon also marks the lower boundary of the regional Dalbyan Stage, but it occurs at 5.25 m above the base of the 'Dalby limestone' (Nielsen et al. 2023).

Stop 8. Amtjärn quarry

Overview. An abandoned limestone quarry northwest of Rättvik, just southeast of the pond Amtjärn (60.936361, 15.076361). It is now a nature preserve and hammering is not allowed but loose samples may be collected. The section exposes the Sandbian Kullsberg limestone and the Katian Skålberg limestone, 'Slandrom limestone', Fjäcka shale, and Jonstorp formation. The older 'Dalby limestone', below the Kullsberg limestone is no longer exposed here. Being one of the earliest commercial quarries, starting operations in the 1920's, it attracted considerable interest among geologists because of the

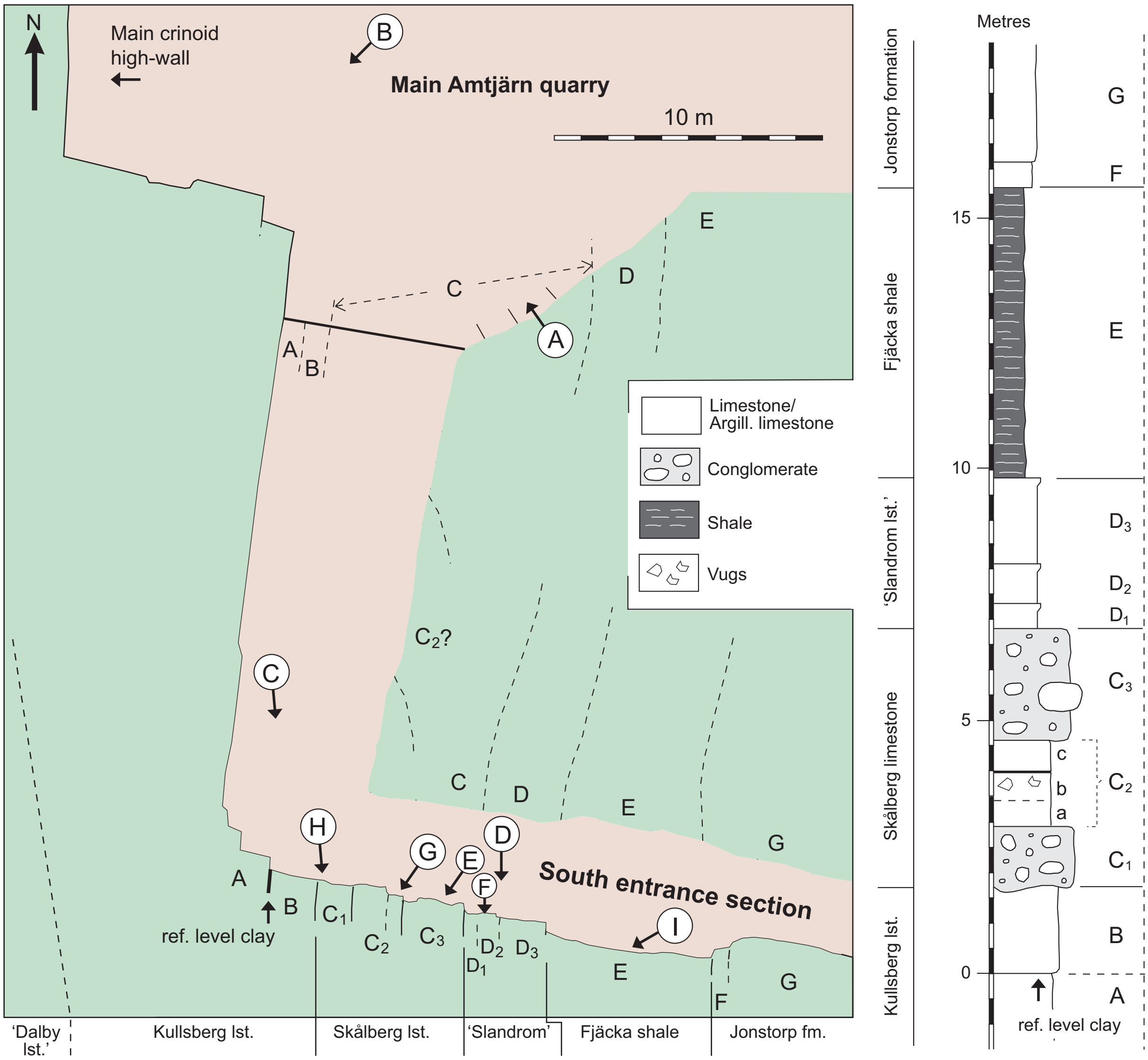


Figure 22. Sketch map of the gully that forms the southern entrance section at Amtjärn quarry. The beds are nearly vertical with younger strata towards the east. Encircled letters with arrow indicate the position for photographs A–I in Figure 23. The profile to the right is from the southern wall. Modified from Calner et al. (2010a, fig. 3).

contact between the mound and the surrounding 'normal facies'.

Description. The beds at this quarry are virtually vertical, becoming younger towards the east (Figs 22, 23). The main body of the Kullsberg limestone has been quarried but the original mound was lentil shaped, about 260 m long and with a thickness of 34–35 m (Thorslund 1935, 1936, p. 28). Today only the southern half of the quarry is accessible. The basal beds of the mound are composed of abundant, sometimes semi-articulated, crinoid stems, in beds that were formed *in situ* from colonies of crinoids (Fig. 23A). Smaller-sized crinoids probably lived on the flanks of the growing mud mound, and the pelmatozoan limestones forming the flank facies were formed through enrichment caused by current activity and reworking (Ruhrmann 1971). The larger crinoid type is absent in the flank facies, but in places with less turbulence, colonies of cystoids lived. The Kullsberg limestone facies suggests shallow water (< 50 m) deposition, above storm wave base within the photic zone (Tobin et al. 2005). The mounds grew during the rising limb of the Guttenberg Isotope Carbon Excursion (GICE) and were truncated shortly after the peak

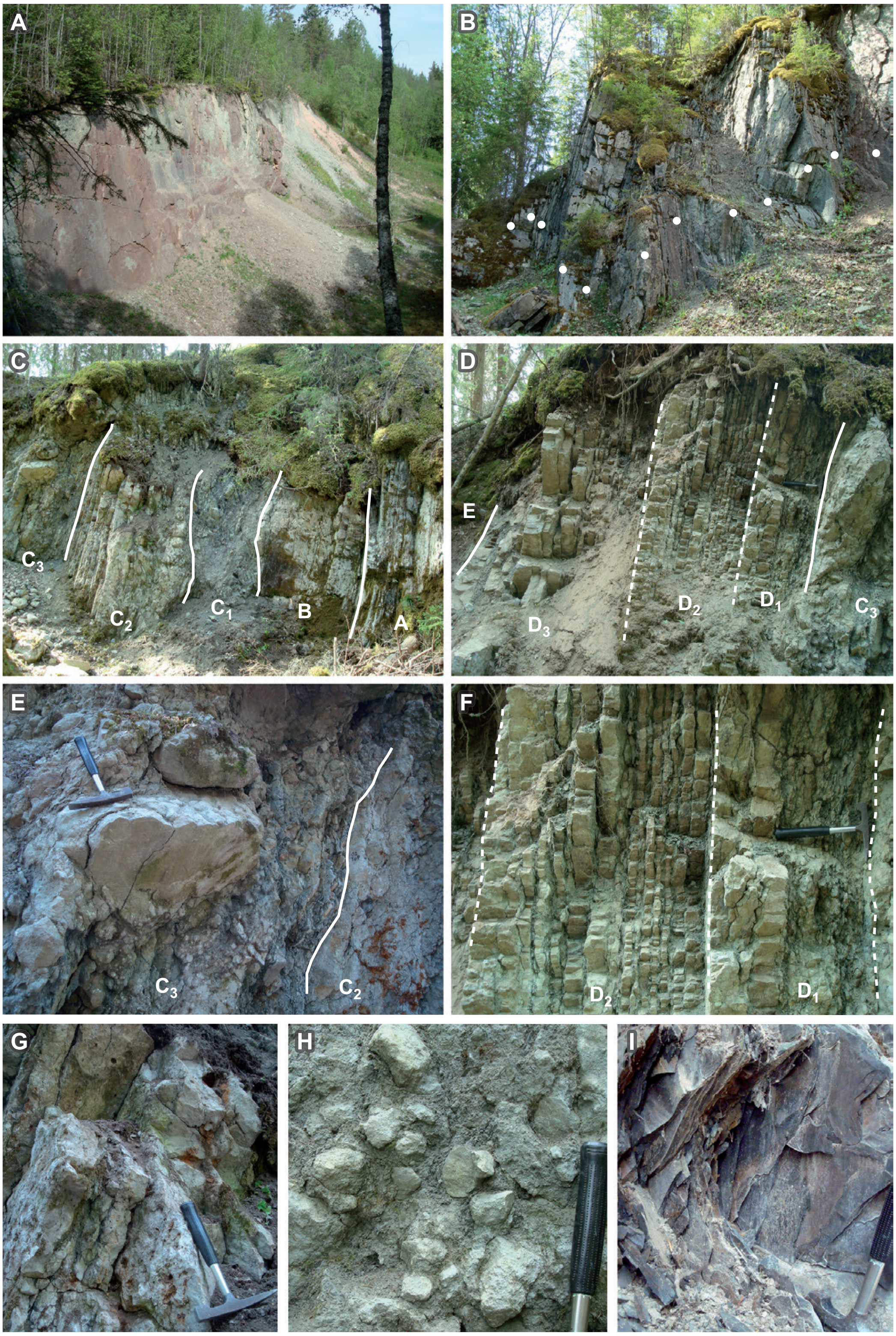


Figure 23. A. View from southeast of the western quarry wall at Amtjärn, exposing steeply dipping crinoidal packstone facies. **B.** Lowermost portion of the studied section (younger strata towards the left). White dots mark the positions of stable isotope samples 1–12 in Calner et al. (2010a). **C.** Lower part of the section. **D.** Middle part of the section, mainly showing the well-bedded 'Slandrom limestone' (D_1–D_3). Note the successive, upward increase in bed as well as parasequence thicknesses. Hammer for scale. **E.** Detail of C_3 conglomerate. The large clast below hammer is 0.64 m across. **F.** Detail of the two lowermost parasequences in the 'Slandrom limestone'. **G.** Detail of the uppermost part of unit C_2 represented by skeletal packstone with abundant solution vugs and rust. **H.** Detail of C_1 conglomerate. Note matrix-supported fabric and rounded lithoclasts. **I.** Detail of the Fjäcka shale. Photos: M. Calner. Modified from Calner et al. (2010a, fig. 4).

of the GICE (Calner et al. 2010a). It encompasses the upper *Amorphognathus tvaerensis* and the lower *A. superbus* conodont zones (Bergström 2007). The Kullsberg mounds and contemporaneous mound or reef formations in Estonia and Norway, the Vasalemma and Mjøsa reefs/mounds respectively, are recognized as a marked Baltoscandian event at the Sandbian-Katian transition (Kröger et al. 2014).

Flank facies associated with the mound are exposed in the gully on the southern part of the quarry (Figs 22, 23; south entrance of Bergström 2007). The oldest of these units is the Skålberg limestone which is developed as a polymict carbonate conglomerate (Fig. 23E, G, H). It is placed low on the flanks of the Kullsberg carbonate mound, and the overlying units of the 'Moldå' and 'Slandrom' limestones successively onlap the mounds. Eventually the Fjäcka shale transgressed the top of the mound. Besides the transgressive Fjäcka facies, the older beds record two separate major regressions and widespread sea-level lowstands (Calner et al. 2010a).

The Skålberg limestone conglomerate itself formed during the termination of the Kullsberg mound facies, just after the peak of the GICE, and the top marks a sequence boundary (Calner et al. 2010a). It represents a major regression with probable development of karstic fissures in the mounds and at the same time the formation of the conglomerate laterally (Fig. 24). These developments encompass three subunits that reflect different sedimentary environments surrounding the mounds (see Calner et al. 2010a). The Skålberg limestone falls entirely within the *A. superbus* conodont Zone (Bergström 2007), corresponding to the upper parts of the Kullsberg limestone. Mound termination and subaerial exposure of these can be seen across Baltoscandia and is associated with the second-order sea-level lowstand named the Frognerkilen Lowstand Event (Nielsen 2004, Kröger et al. 2014).

The 'Slandrom limestone' at Amtjärn quarry is only 3 m thick, whereas it is 7.2 m thick in the Fjäcka section (Calner et al. 2010b; 8.4 m thick according to Jaanusson 1953b, 1982b). It is well-bedded, consisting of fine-grained (cryptocrystalline) mudstone to packstone, with thin intercalations of calcareous mudstone and shale (Fig. 23F). The upper boundary is sharp and truncated; in the Fjäcka section the upper beds are disturbed and brecciated. In other Swedish sections of the 'Slandrom limestone', Calner et al. (2010b) reported pronounced karstic features. These can also be traced into the East Baltic area, signifying a major regional palaeokarst horizon (Calner et al. 2010b). The karst morphology is developed in the upper part of the 'Slandrom limestone'. Biostratigraphically, most of the unit falls within the *A. superbus* conodont Zone but the base of the *A. ordovicicus* Zone is 1 m below the top of the unit (Bergström 2007)

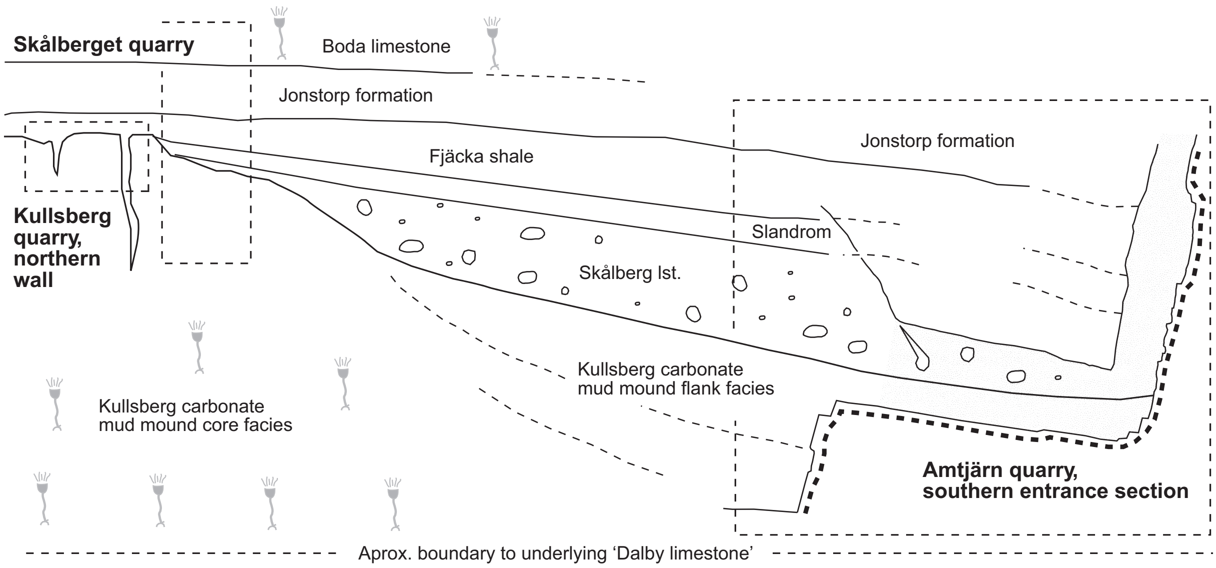


Figure 24. Inferred stratigraphical relationships based on the Amtjärn quarry. The southern entrance section is in the rightmost part of the figure. The insets to the left give an idealized interpretation of the stratigraphy as seen in the nearby quarries at Skålberget (stop 9) and Kullsberg (not visited). Modified from Calner et al. (2010a, fig. 9).

and thus in the range of the palaeokarst (Calner et al. 2010b). The karst development was associated with glaciation and also marks the end of carbonate deposition at this time. Macrofossils are still poorly known in the 'Slandrom limestone' (Ebbestad & Högström 2007).

Traditionally, both the Skålberg and 'Slandrom' limestones have been referred to as intermound facies, but as the development of the Kullsberg mound facies had ceased, these sediments formed independently of the mounds (Calner et al. 2010a).

The Fjäcka shale is 6.1 m thick at Amtjärn quarry and remains the best exposure of this unit in Dalarna (Fig. 23I). The Fjäcka shale lies unconformably on the 'Slandrom limestone', and was deposited during a major transgression known as the Linearis Drowning-2 Event (Nielsen 2004). The Fjäcka shale is also recognized in Estonia and Norway (as the Vennstøp Formation). Depositionally, the Fjäcka shale shows persistently euxinic bottom conditions (Lu et al. 2017) and the organic-rich shale is the source rock for the seep oil and solid bitumens seen in the Boda limestone (Vlierboom et al. 1986, Schrayer in Hedberg 1988, Ahmed et al. 2014). The shale is highly fossiliferous with a diverse shelly fauna (see Ebbestad & Högström 2007). The Fjäcka shale corresponds to the lower *Amorphognathus ordovicicus* conodont Zone and middle to upper *Pleurograptus linearis* graptolite Zone (Skoglund 1963, Bergström 1971, Jaanusson 1963b, 1982b).

The poorly exposed Jonstorp formation is 15.5 m thick at Amtjärn quarry (Ebbestad & Högström 2007). The lower boundary is marked by the sharp transition from the dark shale of the Fjäcka shale. The upper part (upper Jonstorp member of Jaanusson 1963a) 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 (Jaanusson 1963a, 1982b). Few fossils are described from the Jonstorp formation and its subunits (Ebbestad & Högström 2007) and the unit is generally poorly studied.

The stratigraphically important trilobite *Mucronaspis (Dalmanitina) mucronata* has been found in the Hirnantian Loka formation in no longer exposed parts of Kullsberg and Amtjärn quarries (Thorslund 1935).

Stop 9. Skålberget quarry

Overview. An abandoned quarry north of the pond Bysjön at Glisstjärna (60.943028, 15.095722). It is now a nature preserve which means that no hammering is allowed. Both the Kullsberg and Boda limestones occur here but little remains of the actual mounds. Earlier also the associated flank facies and the contact to the Silurian Kallholn formation were exposed, but nowadays only the transitional beds between the mounds are accessible.

Description. The beds here are again nearly vertical with the Kullsberg limestone to the north and the Boda limestone to the south (Fig. 25). Both mound facies are quarried, leaving only a marginal exposure of the mound facies. This is one of five so-called twin mounds, where the Boda limestone facies developed geographically on the same site as the previous Kullsberg limestone, the others being the Dalhalla (formerly Ungskarsheden), Jutjärn, Osmundsberget and Änderärvet quarries. This signifies the prolonged stability of mound carbonate development despite being perturbated by two major drawdowns (Skålberg and 'Slandrom' limestones) and a transgression (Fjäcka shale).

Skålberget is the type locality of the Skålberg limestone (section 4 of Jaanusson 1982b) and other beds previously exposed were also described by Jaanusson (1982b). This unit first appeared in a figure by Jaanusson (1973, fig. 3), and was considered to be a wedge of the 'Moldå limestone' (Jaanusson 1982b). However, it is entirely restricted to the Kullsberg mounds and thins out laterally away from the mounds (Calner et al. 2010a). The lateral equivalent of the 'Moldå limestone' spans the *Amorphognathus tvaerensis* and *A. superbus* conodont zones, whereas the Skålberg limestone is within the *A. superbus* conodont zones (Bergström 2007).

Today only the transitional beds between the mounds are accessible (Figs 25–27; southern entrance and section 5 of Jaanusson 1982b: here called the passage). The transitional beds are here taken to include all facies between the top of the Kullsberg limestone and the base of the Boda limestone. Thus, the Fjäcka shale and Jonstorp formation are

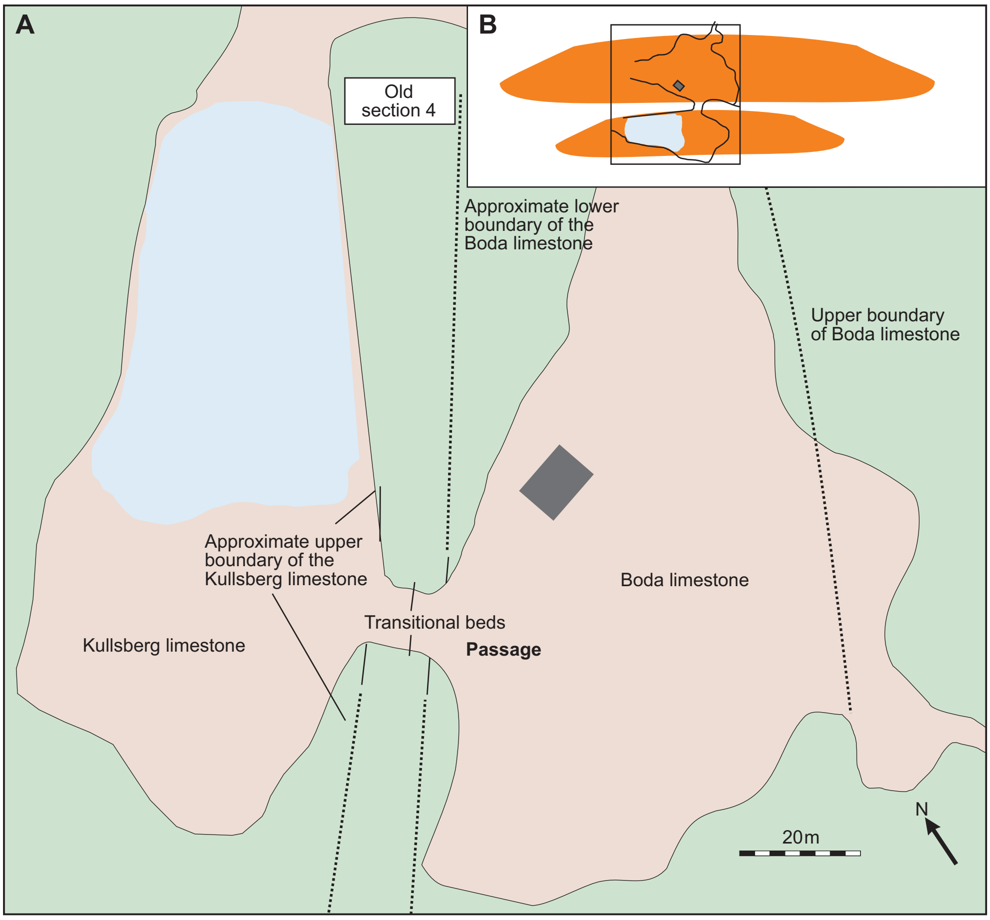


Figure 25. A. Sketch map of Skålberget quarry. All beds are nearly vertical. The transitional beds are exposed at the passage between the mounds. Earlier the Skålberg, 'Slandrom', Fjäcka and Jonstorp units were exposed at section 4 (Jaanusson 1982b; type locality for the Skålberg limestone). All units are fairly thin, and are thinning out towards the passage. The Fjäcka shale is only 40 cm thick at section 4 compared to 6 m at Amtjärn quarry, which suggests that the onlap is positioned high on the Kullsberg mound. At the passage the shale is about 20 cm thick. **B.** Tentative reconstruction of the configuration, shape and size of the twin mounds at Skålberget.

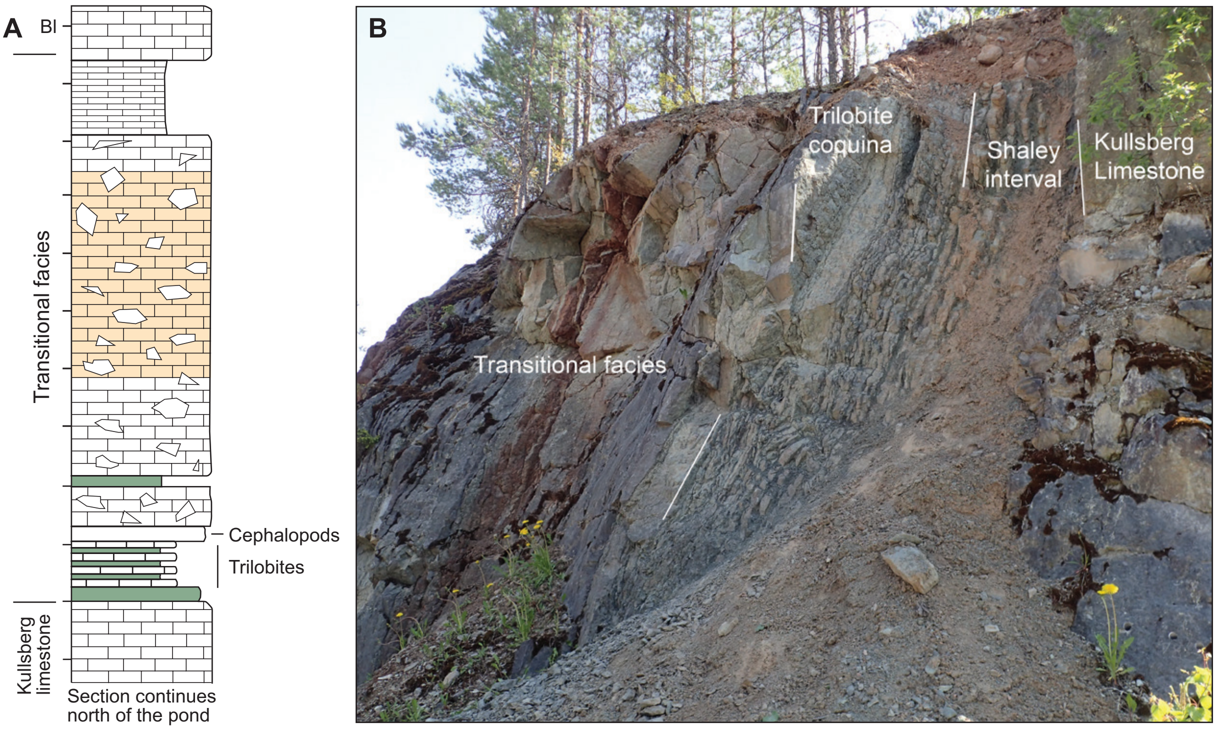


Figure 26. A. Composite log of the beds at the passage between the mounds. **B.** Detail of the southern wall and the lower shaley facies of the transitional beds. Bl = Boda limestone. Photo: J.O.R. Ebbestad.

Figure 27. Skålberget quarry. **A.** View of the southern wall of the passage. **B.** View of the northern wall of the passage. Photos: N. Ahanin.

included in this (Figs 26, 27). Both the upper beds of the Kullsberg limestone and the lower beds of the Boda limestone are composed of thick-bedded limestone, distinct and with sharp boundaries to the transitional facies. The initial post-Kullsberg mound facies is a 50 cm thick unit with thin limestones interbedded with black shale equivalent to the Fjäcka shale, best developed towards the base (Fig. 27). These are dominated by crinoid ossicles. Above lies a 60 cm thick interval with thin limestone beds alternating with thin beds of calcareous mudstone and shale. At the south wall, this interval is largely developed as a trilobite coquina with cranidia and pygidia of a large undescribed illaenid. The

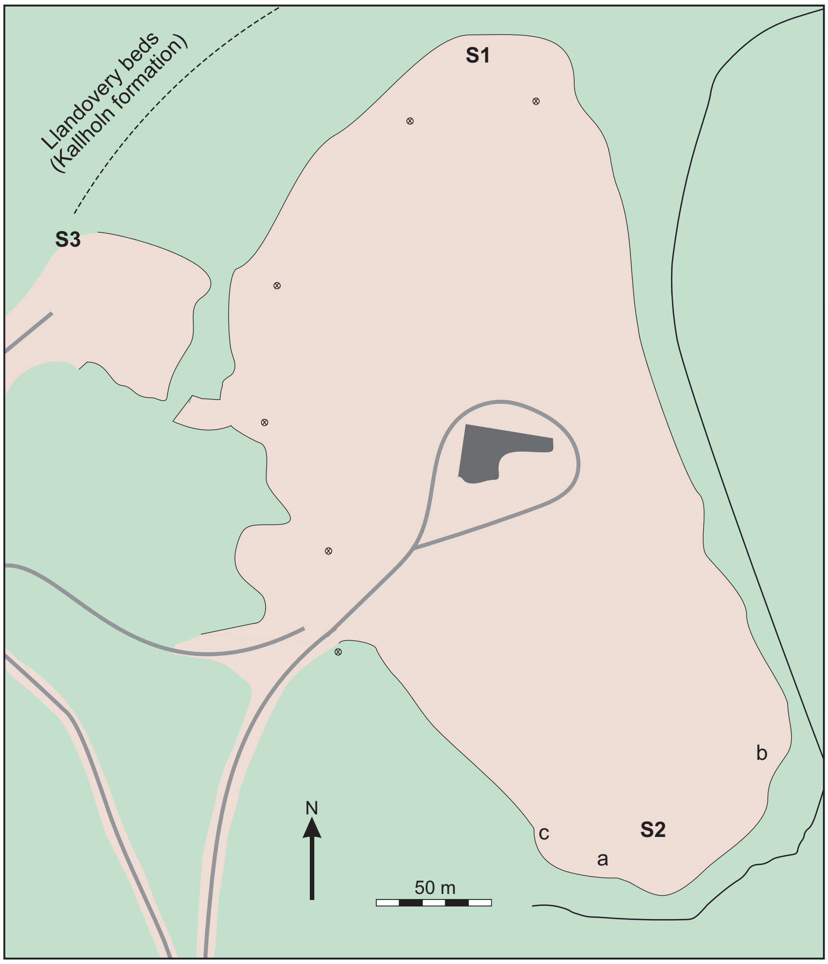


Figure 28. Sketch map of Solberga quarry. Locality numbers from Ebbestad & Högström (2007).

same species is found in Osmundsberget quarry, in the transitional mound facies above the Fjäcka shale (locality OB 3 of Ebbestad & Högström 2007). At the northern wall, this interval contains abundant orthoconic cephalopods – single examples were also seen at this level at the southern wall. Furthermore, on the south side the transitional beds show signs of being thrusted and are folded, which is associated with impact related deformation. Above the trilobite and cephalopod beds, the beds consist of grey bedded limestone followed by thin-bedded red pelmicritic limestone beds (grey and red Jonstorp beds cf. Jaanusson 1982b). The upper beds are thin-bedded grey limestone with shale partings. Jaanusson (1982b) noted the brecciated nature of the limestone clasts in the upper beds, but this is a feature that seems to occur above the lower shaley beds. Both sides of the passage, and the northern wall of the pond, have been sampled for palaeomagnetic studies (Ahanin & Gilder 2022, Ahanin et al. in prep.).

Stop 10. Solberga quarry

Overview. Non-operational quarry located just west of regional road 301 at Ovanmyra, Rättvik municipality, on the east side of the Siljan ring (60.983583, 15.216639). This is a quarry in the Katian Boda limestone, where the core material has been partly removed. The contact with the lower Silurian (Llandovery) Kallholn formation is preserved.

Description. The mound is essentially flat-lying, with Llandovery shale of the Kallholn formation exposed and in contact on the north-western flank (Solberga 3; Fig. 28). A number of small wells are situated on the quarry floor, and some are yielding crude oil. Biomarkers and carbon isotope analyses suggest that the oil was sourced mainly from the Fjäcka shale (Vlierboom et al. 1986, Ahmed et al. 2014). Hydrocarbon maturation was associated with the Devonian meteorite impact (Stein et al. 2014).

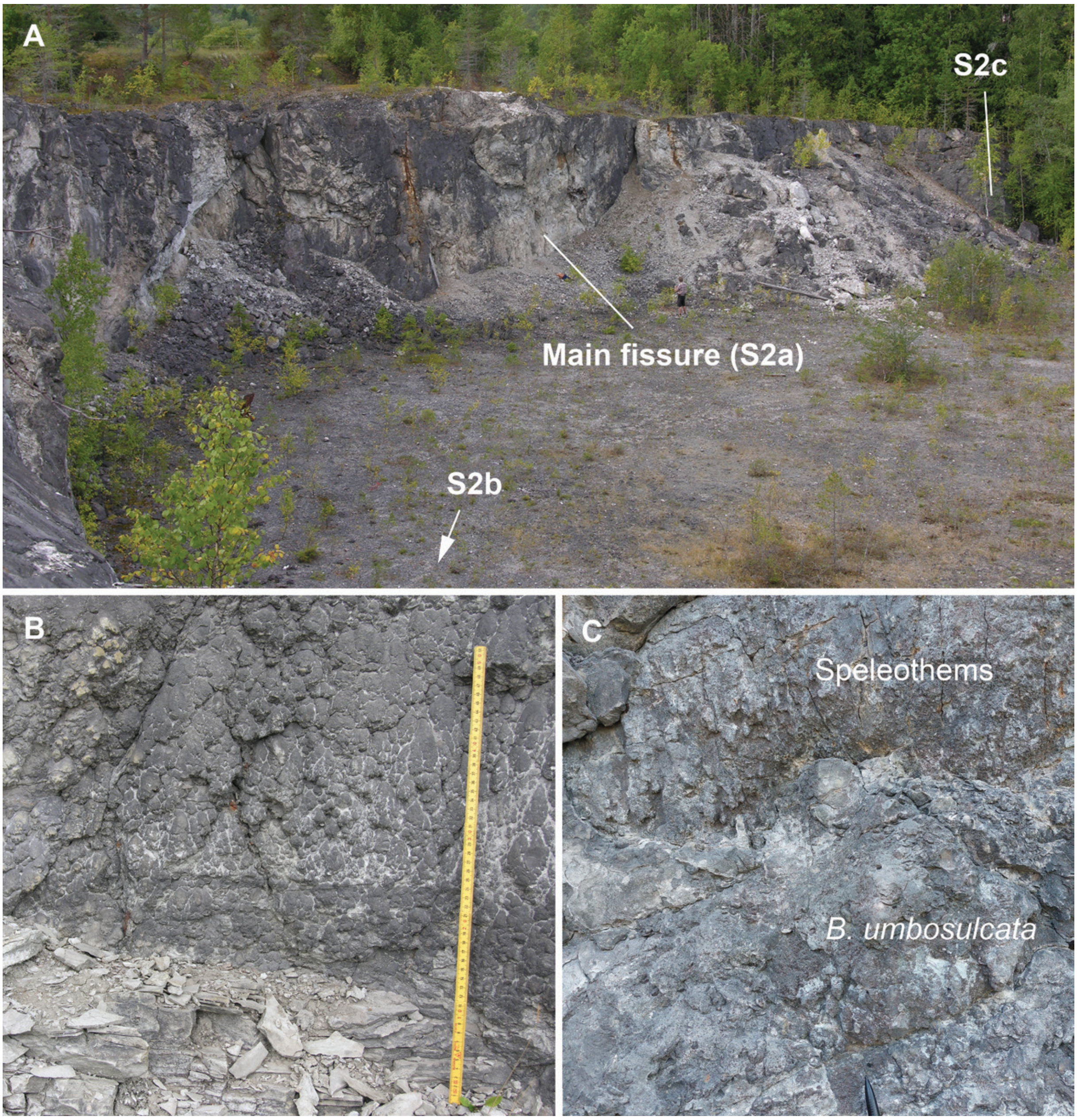


Figure 29. A. Overview of the southern wall of the quarry, locality Solberga 2. **B.** Locality Solberga 2b, speleothems overlain by platy siltstone. **C.** Locality Solberga 2c, speleothems overlain by *B. umbosulcata* coquina. Photos: J.O.R. Ebbestad.

In the northeastern wall of the quarry the brachiopod *Holorhynchus giganteus* occurs near the top of the escarpment, associated with corals (locality Solberga 1; Fig. 28). The species is of late Katian age with no confirmed Hirnantian records (Rasmussen et al. 2010). The top of the Boda limestone is missing in this quarry, as well as the Hirnantian Osmundsberget formation. Thus, the characteristic Hirnantian *Hindella terebratulina* bed is not seen and the Hirnantian Carbon Isotope Excursion (HICE) is not recorded in the mound sediments (Ebbestad et al. 2015). However, other Hirnantian faunal elements are found in the fissures; isotope dates confirm an Hirnantian age of the brachiopod *Brevilamnulella umbosulcata* which is abundant at locality Solberga 2 (Fig. 28; Rasmussen et al. 2010, Kröger et al. 2015).

In the southern wall, an exceptionally large composite pocket is found (locality Solberga 2a; Figs 28, 29A). Part of the pocket is filled with layered in-

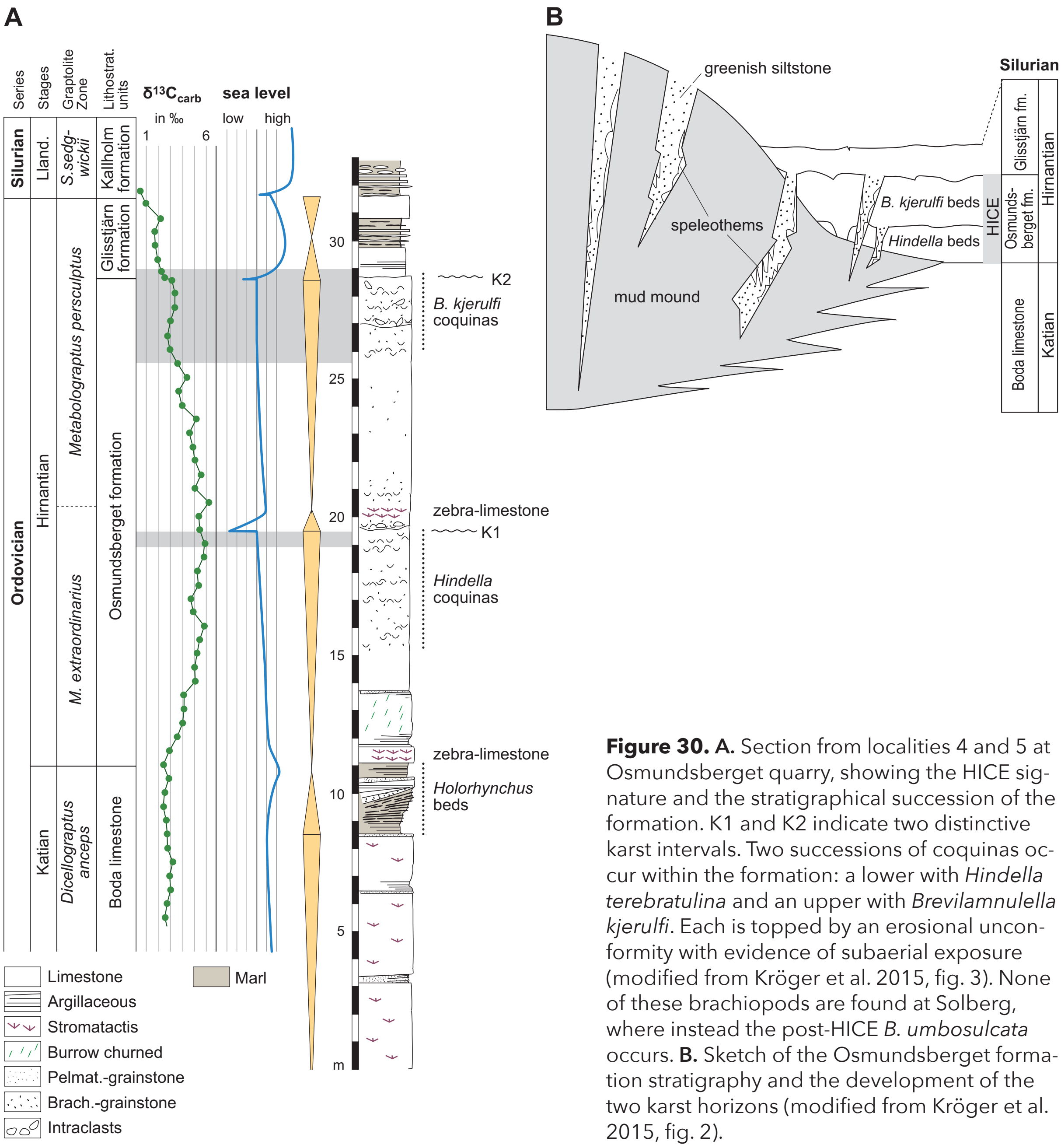


Figure 30. A. Section from localities 4 and 5 at Osmundsberget quarry, showing the HICE signature and the stratigraphical succession of the formation. K1 and K2 indicate two distinctive karst intervals. Two successions of coquinas occur within the formation: a lower with *Hindella terebratulina* and an upper with *Brevilamnulella kjerulfi*. Each is topped by an erosional unconformity with evidence of subaerial exposure (modified from Kröger et al. 2015, fig. 3). None of these brachiopods are found at Solberg, where instead the post-HICE *B. umbosulcata* occurs. **B.** Sketch of the Osmundsberget formation stratigraphy and the development of the two karst horizons (modified from Kröger et al. 2015, fig. 2).

ternal sediment, while other parts are filled with pygidia of the Katian trilobite *Eobronteus laticauda* in particular. The locality is also rich in gastropods, especially *Platyceras crispum*, which at the Ordovician–Silurian boundary in Osmundsberget quarry occurs in association with the Hirnantian *Hindella* coquina. In addition, a trilobite association in the fissure at locality Solberga 2a (Fig. 28) is similar to that described by Suzuki et al. (2009) from the Osmundsberget formation in Osmundsberget quarry. Inter-relationships thus allow reconstruction of several different episodes of infilling of the fissure.

On the eastern side (Solberga 2b, Figs 28, 29B), the Hirnantian speleothems are exposed covered by platy greenish, calcareous siltstone. These are formed in syndepositional fissures in the Boda limestone. The speleothems represent the only known Ordovician occurrence of its kind. They appear as decimetre-sized irregular cone-shaped layers lining the walls of the fissures. The stromatolite-like fabric suggests that they are microbially mediated speleothems in a dark environment and Sr and C isotope values suggest formation from meteoric water without influence of a significant soil horizon (Kröger et al. 2015). The siltstone covering the speleothems has not yet yielded any fossils, but $\partial^{13}C$ bulk-rock isotope values between 2.6 and 4.4 ‰ suggest deposition during the late HICE.

On the western side (Solberga 2b, Figs 28, 29C), speleothems in the fissure wall are overlain by a coquina of the post-HICE brachiopod *Brevilamnulella umbosulcata* (Rasmussen et al. 2010, Kröger et al. 2015). Thus, the Solberga speleothems formed synsedimentary with the Osmundsberget formation and encompass the two major unconformities seen early and late within the HICE interval (Fig. 30).

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