Estonian Journal of Earth Sciences, 2018, **67**, 2, 133–148 https://doi.org/10.3176/earth.2018.10

The Cambrian–Ordovician succession at Lanna, Sweden: stratigraphy and depositional environments

Anders Lindskog[a,b], Anna M. L. Lindskog[b], Jan V. Johansson[c], Per Ahlberg[a] and Mats E. Eriksson[a]

[a] Department of Geology, Lund University, Sölvegatan 12, SE-223 62 Lund, Sweden; anders.lindskog@geol.lu.se, per.ahlberg@geol.lu.se, mats.eriksson@geol.lu.se
[b] Henrik Smithsgatan 15C, SE-211 56 Malmö, Sweden; anna@lindskog.one
[c] Testa Knällinge 408, SE-697 94 Sköllersta, Sweden; fossilmuseum@gmail.com

Received 10 October 2017, accepted 20 February 2018, available online 3 April 2018

Abstract. A ca 20 m thick succession of upper Furongian (Cambrian Stage 10) through Middle Ordovician (Darriwilian) strata exposed at Lanna, in the province of Närke, south-central Sweden, is described. The upper Furongian is represented by the Alum Shale Formation and reflects an overall shallowing trend that ultimately resulted in emergence above sea level and subaerial conditions. Hence, as in most other areas in south-central Sweden, the boundary between the Cambrian and the Ordovician is marked by a prominent disconformity and significant hiatus. In Närke, the hiatus spans the middle Stage 10 through the uppermost Tremadocian or lowermost Floian. The presence of stromatolites indicates quite shallow marine conditions during the latest Cambrian. The Ordovician succession is characterized by flatly bedded 'orthoceratite limestone', belonging to the 'Latorp', 'Lanna' and 'Holen' limestones ('topoformations'). Widely varying microfacies characteristics in the 'orthoceratite limestone' suggest that the depositional environment underwent substantial changes through time, largely due to changes in sea level. A long-term trend of coarsening carbonate textures and more diverse fossil assemblages is seen upwards through the Ordovician succession. Cyclic microfacies patterns probably reflect high-frequency sea-level changes. Comparisons to other parts of Sweden and Baltoscandia reveal consistent patterns in the sedimentary development across a wide geographical area.

Key words: carbonate sedimentology, microfacies, palaeoecology, palaeoenvironment, Baltoscandia.

INTRODUCTION

The Baltoscandian region hosts extensive areas with lower Palaeozoic sedimentary rocks, which are largely preserved in place, undisturbed and often richly fossiliferous. Hence, the regional sedimentary succession has become an important archive for our understanding of environmental and biotic changes, including the evolution of life, during the early Phanerozoic (e.g., Lindström 1971).

Lower Palaeozoic rocks are widely distributed in several areas in the province of Närke, south-central Sweden (e.g., Linnarsson 1875a). Närke has long been considered a key area for Ordovician stratigraphy and palaeontology. This is evident not least because several regional stages and other stratigraphic units have been named after important outcrop areas in the province. For example, the interval spanning the Hunneberg and Billingen regional stages was formerly referred to as the Latorp Stage (Jaanusson 1960a; Männil 1966) and the term Lanna Stage was long a contender for the interval that is now the Volkhov Regional Stage (e.g., Tjernvik 1972; Tjernvik & Johansson 1980; Löfgren 1995). Although the stratigraphy and palaeontology of the lower Palaeozoic of Närke have attracted numerous studies since the 19th century, the sedimentary characteristics and development of the local strata have remained poorly documented. This precludes detailed comparisons with coeval strata elsewhere. Närke is situated in the middle part of the Baltoscandian palaeobasin and forms an important area for studying the palaeoenvironmental development and sea-level history. This part of the basin likely records a relatively complete succession of events that is not preserved in more proximal settings and poorly resolved in the shale-dominated palaeo-offshore western parts.

In this study, we investigated the exposed Cambrian–Ordovician succession at the key locality Lanna in northwestern Närke. The macroscopic and microscopic characteristics of the strata are documented in detail and the sedimentary and biotic variations throughout the succession interpreted in terms of local and regional depositional dynamics and palaeoenvironmental changes.

GEOLOGICAL SETTING

Due to high global sea levels, epeiric seas covered large parts of the existing continents during most of the early Palaeozoic. There was probably an overall rising sea level during the Cambrian, albeit with second- and third-order eustatic changes that resulted in some major lowstands (e.g., Haq & Schutter 2008; Peng et al. 2012; Babcock et al. 2015). A progressive and stepwise transgression of the Baltic craton resulted in widespread submergence of the Baltoscandian region (Nielsen & Schovsbo 2011). Marine transgressions and flooding of the palaeocontinents became increasingly more pronounced during the Ordovician. The Precambrian peneplane that formed the basement in much of the Baltoscandian region offered limited weathering products and this led to an overall starvation of terrigenous siliciclastics in the palaeobasin. Much of the regional succession is thus quite condensed, with typical net sedimentation rates being only a few millimetres per millennium. Still, the Cambrian time interval was mainly characterized by siliciclastic sedimentation (e.g., Lindström 1971; Rozanov & Łydka 1987; Nielsen & Schovsbo 2011, 2015). The Ordovician was dominated by widespread deposition of carbonates, which changed from cool-water type in the early Ordovician to subtropical-tropical towards the later parts of the period (e.g., Jaanusson 1972; Dronov & Rozhnov 2007).

In Sweden, the oldest Cambrian deposits (Terreneuvian and Series 2) are characterized by sand- and siltstones (e.g., Lindström 1971; Bergström & Gee 1985; Nielsen & Schovsbo 2011). These are typically replaced by bituminous shale and limestone upwards, the well-known Alum Shale (e.g., Andersson et al. 1985). Shale deposition continued into the earliest Ordovician, but was then largely replaced by carbonates. The Lower–Middle Ordovician succession in much of Sweden is characterized by the so-called orthoceratite limestone, a stratigraphically condensed suite of rocks that encompasses a range of similar looking cool-water limestones (see Lindskog & Eriksson 2017 and references therein). As most of Sweden was submerged throughout much of the early Palaeozoic, sediments were originally deposited across large parts of the country. However, today only patches of rocks occur where conditions have provided sufficient protection against erosion (Fig. 1A; e.g., Lindström 1971).

The province of Närke in south-central Sweden hosts a relatively large area with Palaeozoic strata, resting upon the Proterozoic crystalline basement (Fig. 1B; Linnarsson 1875a, 1875b; Blomberg & Holm 1902; Thorslund 1960; Lundegårdh & Fromm 1971). Large-scale down faulting has protected the succession from complete erosion. Whereas Cambrian sandstones are the most widespread among the Palaeozoic remnants, younger deposits are patchier in their distribution. The sedimentary rock succession in Närke spans the Cambrian Series 2 through the Middle Ordovician (Darriwilian; e.g., Karis & Magnusson 1972). The rocks have been extensively quarried, for the production of building materials and shale oil (Blomberg & Holm 1902; Rönnby 1943; Eklund 1961; Fromm 1971). Today, quarrying activity is abandoned.

The Lanna area

The village of Lanna, ca 15 km west-southwest of Örebro, hosts a number of abandoned quarries in which Cambrian Alum Shale and Ordovician limestone were quarried until the 1960s (Fig. 1C; Stolpe 1874; Blomberg & Holm 1902; Ydreborg 2014). The village lies at the southeastern border of a large area where Ordovician strata are preserved on top of the Cambrian succession, referred to as the Latorp plateau (‘Latorpsplatån’ in Swedish). Today, most of the old quarries in the Lanna area are in a somewhat dilapidated state and closed off to the public (Fig. 2). The largest quarry, however, is kept open as a public recreational and swimming area, popularly referred to as ‘Lanna badgruva’ (Swedish for ‘Lanna bathing mine’). The Cambrian–Lower Ordovician succession at Lanna has previously been studied in some detail. Westergård (1922) provided a detailed description of the Cambrian part of the succession, Andersson (1895) studied the Cambrian–Ordovician boundary interval, and Wiman (1905), Tjernvik (1952, 1956) and Lindström (1954) published detailed accounts of the Lower Ordovician succession. Although Tjernvik continued to study the Middle Ordovician strata at Lanna (see Tjernvik 1952, 1972; Tjernvik & Johansson 1980), few detailed accounts found their way into the scientific literature and this part of the local succession has remained largely undocumented. Based on samples collected by Tjernvik, Löfgren (1995, 2003) more recently outlined the conodont biostratigraphy of the Middle Ordovician at Lanna.

Originally, the entire local Alum Shale succession (ca 14 m thick according to Westergård 1922) was exposed in southern Lanna, but nowadays the quarries are largely filled with water and only the uppermost 5–6 m are available for study. Where a protective limestone cover is missing, the shale is often disturbed and in places even strongly folded due to Pleistocene glacial activity (e.g., Blomberg & Holm 1902, fig. 12; Andersson & von Post 1909). Locally, also the overlying limestone beds have been disturbed and displaced. Northwards in the area, the topmost strata become successively younger and the youngest Ordovician limestone beds are thus found in the northernmost part of Lanna.

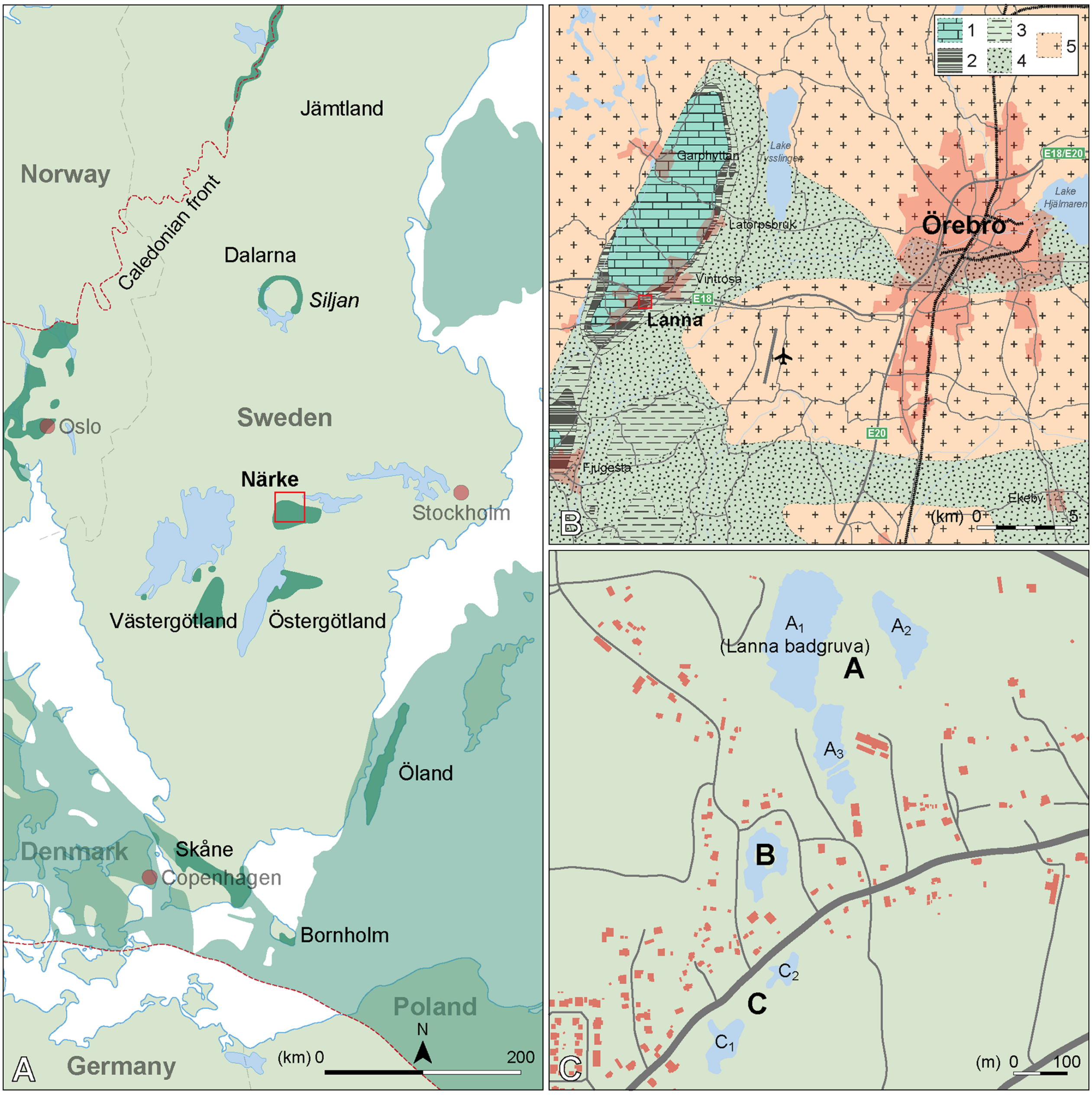

Fig. 1. Maps of Sweden, and the Örebro and Lanna areas. **A**, map of southern Sweden (modified from Lindskog & Eriksson 2017, with additional data from Sopher et al. 2016). Green shading indicates the presence of lower Palaeozoic rocks, with darker shading indicating significant outcrop areas. Geographic areas (e.g., provinces) discussed in the main text are indicated. The red quadrangle indicates the map shown in B. **B**, map of the Örebro area, with the distribution of pre-Quaternary rocks indicated (after Eklund 1961). Legend: 1, Lower–Middle Ordovician, limestone; 2, Cambrian Series 3–Furongian, bituminous shale and limestone; 3, Cambrian Series 3, mudstone; 4, Cambrian Series 2, sandstone; 5, ~Mesoproterozoic, granite/gneiss (bedrock). The quadrangle indicates the outline of C. **C**, map of the Lanna area, with abandoned quarries indicated by letters A to C.

Due to shifting ownership and use, the different quarries of the Lanna area have changed names through time both locally and in the scientific literature. Hence, for ease of reference and practicality, the different abandoned quarries in the area are here termed Lanna A to C and in part subdivided into separate outcrops (Fig. 1C). Lanna A is located in the northernmost part of Lanna (WGS coordinates 59°14′44″N, 14°55′27″E). It is the largest and most accessible quarry, and includes ‘Lanna badgruva’ (A_1) and adjacent outcrops (A_2, A_3).

Fig. 2. Field photographs. **A**, the Cambrian–Ordovician succession at Lanna C ('Stora brottet' in older literature). View towards the west-southwest. The rock wall is approximately 10 m high. **B**, detail of the succession at Lanna C, with stratigraphic units indicated. The arrow indicates a dome-like structure. Note hammer for scale. View towards the northwest. **C**, close-up of the Cambrian–Ordovician boundary at Lanna C. Numerous lithoclasts (arrows), stemming from the underlying Cambrian strata, are found in the lowermost Ordovician beds. **D**, close-up of the boundary (arrow) between the 'Latorp' and 'Lanna' limestones, which coincides closely with the Lower–Middle Ordovician boundary (conterminous with the Floian–Dapingian and Billingen–Volkhov stage boundaries). **E**, stromatolite-like interval in the uppermost part of the Alum Shale Formation. **F**, close-up showing limestone–marl alternation in the middle 'Lanna Limestone'. **G**, overview of Lanna A ('Lanna badgruva', 'Cementfabrikens brott'), with the path down to the swimming area in the foreground. View approximately towards the north. **H**, middle Ordovician strata at Lanna A, with the approximate level of the Volkhov–Kunda (~'Lanna Limestone'–'Holen Limestone') boundary indicated. The rock wall is ca 8 m high. View towards the southwest. **I**, close-up of the Volkhov–Kunda boundary interval, in the uppermost part of the succession at Lanna A. Note hammer for scale. **J**, weathered bed in the uppermost (Kundan) part of Lanna A, with numerous cephalopod conchs (arrows).

This locality corresponds to what has been called ‘Cementfabrikens brott’ (the Cement factory’s quarry) in older literature (e.g., Tjernvik 1952, 1956; Löfgren 1995). Lanna A hosts the youngest strata of the local succession (at A_1), and in total ca 8 m of Volkhovian–Kundan ‘orthoceratite limestone’ strata are available above water level. Lanna B (59°14′34″N, 14°55′19″E) contains beds that are found also in the lower part of Lanna A and the upper part of Lanna C. This locality, which is largely water-filled and only exposes a relatively thin interval (ca 5 m) of rocks, has not been studied in any detail. Lanna C (C_1, C_2) is located in the southernmost part of Lanna (59°14′25″N, 14°55′18″E). This locality corresponds to what has been referred to as ‘Stora brottet’ (the Large quarry) in older literature (Linnarsson 1875a; Tjernvik 1952), and likely also what Westergård (1922) called ‘A.-B. Svenska Skifferverkens brott’. The strata at Lanna C span the upper part of the Cambrian Alum Shale through the lower part of the Middle Ordovician ‘orthoceratite limestone’, in total ca 16 m of rocks. Together, the accessible strata in the quarries at Lanna form a composite section spanning the Furongian (lower/middle Stage 10) through the Middle Ordovician (Darriwilian, Dw2, middle Kunda Regional Stage).

MATERIALS AND METHODS

Field observations, measurements and sampling of the succession at Lanna were undertaken during several visits in 2013–2017. Fieldwork was concentrated on Lanna A (A_1) and C (C_1), which together provide a composite of the entire exposed succession at Lanna. In total, 123 samples were collected from an interval comprising ca 20 m of strata, beginning at Lanna C and continuing upwards at Lanna A (Figs 3, 4). The sample series spans the youngest Cambrian through all exposed Ordovician strata.

Thin sections were produced from every sample and numerous hand samples were polished and studied in detail for reference. Except where this was not possible due to rock characteristics, samples were cut perpendicular to bedding in order to undertake studies of grain orientation and packing, grading and other sedimentologic properties. The microfacies of thin sections were studied qualitatively and quantitatively following the general approach of Lindskog & Eriksson (2017). Carbonate textures were characterized quantitatively via point counting of 600 points per thin section (300 × 2, to assess variability), using a grid covering the entire thin-section sample area and the grain-bulk method (Dunham 1962). Fossil grain assemblages were characterized quantitatively through the identification of 600 (300 × 2) grains per thin section, using a modified form of ribbon counting (see Lindskog & Eriksson 2017). Seven categories were distinguished: Brachiopoda, Echinodermata, Gastropoda, Mollusca (other than identifiable gastropods), Ostracoda, Trilobita and Other. As they are typically difficult to distinguish from trilobites in thin sections, agnostoids are included in Trilobita. When including unidentified grains, analyses spanned more than 600 data points, but such grains typically have negligible influence on the data and, for clarity, they were not included in the visual data presentation. In total, more than 150 000 data points were registered during the quantitative analyses.

RESULTS

The observations and results are summarized in Figs 3 and 4.

General observations

At the macroscopic scale, the studied strata are largely tectonically undisturbed, with bedding being horizontal or nearly so, but local displacement and small-scale faulting occurs (see above). The uppermost surface at Lanna A has been glacially polished and is quite flat. Grooves running roughly N–S likely represent glacial striations (e.g., Blomberg & Holm 1902).

The Cambrian part of the local succession consists of bituminous shale with subordinate beds and lenses of bituminous limestone (anthraconite, ‘orsten’/‘stinkstone’), belonging to the Alum Shale Formation (Figs 2A, B, 3; Westergård 1922). The strata (both shale and limestone) are typically dark grey to black in colour, with sporadic whitish and yellowish specks from secondary mineral formation. Some horizons are distinctly rust-coloured. The shale is typically poor in fossils, but the limestone can be quite fossiliferous and some horizons abound with trilobite and agnostoid debris. Most of the limestone occurs as lenses and discontinuous beds.

The Ordovician succession is characterized by flat-bedded ‘orthoceratite limestone’, belonging to the ‘Latorp’, ‘Lanna’ and ‘Holen’ limestones (topoformations; Figs 2B, H, 3, 4). The typical facies at Lanna is as a muddy limestone with variable amounts of sand-sized grains consisting mainly of skeletal fragments, but carbonate textures span from mudstone to grainstone. Freshly cut rock surfaces reveal variations between greyish, brownish, greenish and reddish hues in the rock colour, but this is often indistinct in the outcrops as most beds quickly attain a dull greyish-beige surface during weathering. The colour of individual beds can vary between sub-localities. Parts of the succession show persistent alternation between grey and red colour and

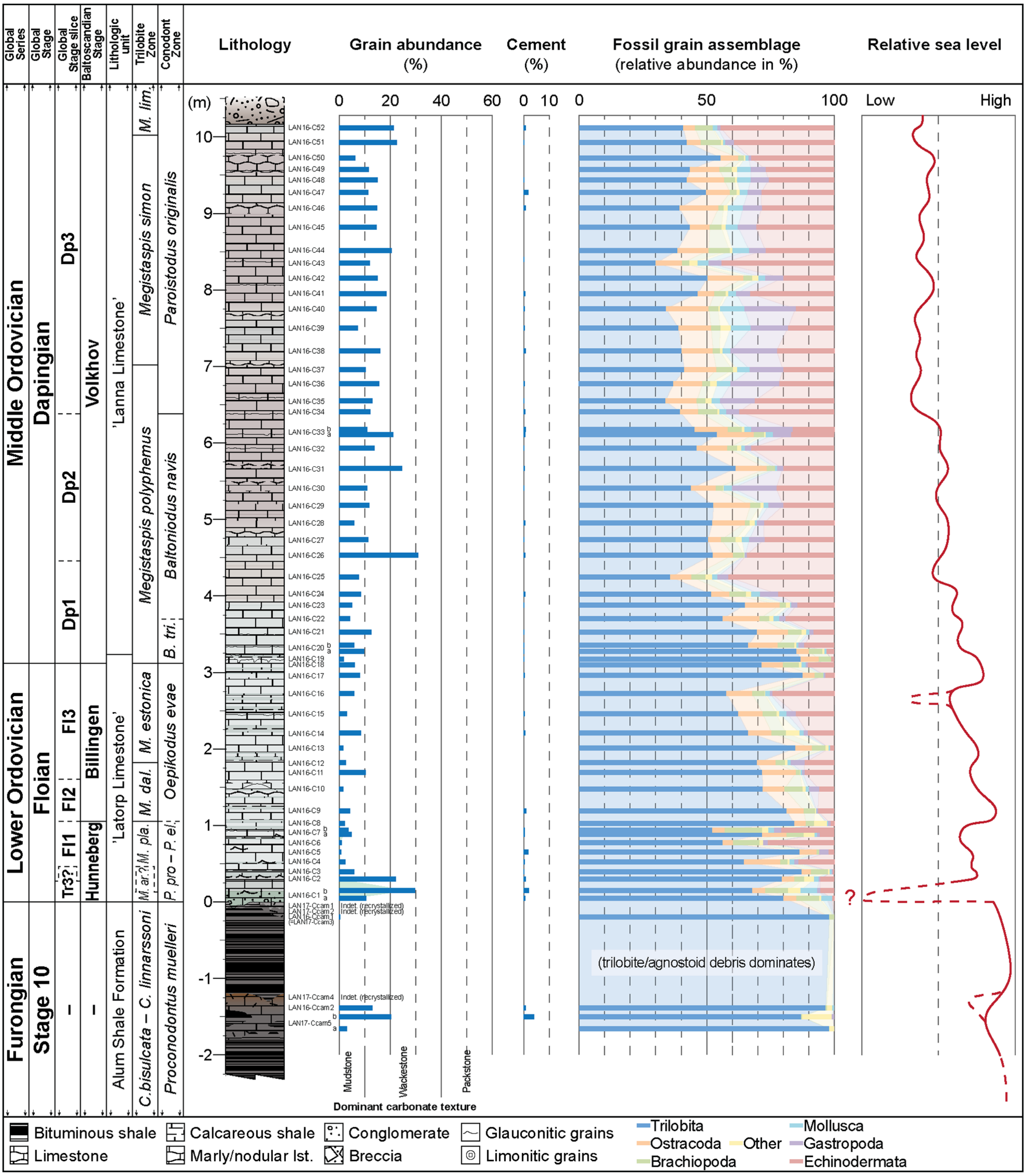

Fig. 3. Sedimentary profile of the section at Lanna C ('Stora brottet'). Variations in carbonate texture (grain abundance, cement) and fossil grain assemblages are indicated, together with an interpretation of relative sea level (stippled intervals indicate uncertain 'scenarios'). Biostratigraphy after Tjernvik (1952, 1956, unpublished notes), Löfgren (1994, 1995) and Bagnoli & Stouge (2014). Abbreviations: *B. tri.*, *Baltoniodus triangularis*; *C.*, *Ctenopyge*; *M. ar.*, *Megistaspis armata*; *M. dal.*, *Megistaspis dalecarlicus*; *M. estonica*, *Megistaspis estonica*; *M. lim.*, *Megistaspis limbata*; *M. pla.*, *Megistaspis planilimbata*; *P. el.*, *Prioniodus elegans*; *P. pro.*, *Paroistodus proteus*.

a remarkably consistent thickness of macroscopic bedding (cf. De Geer 1941). Green hues mainly result from glauconite and red hues from hematite. Silt- to sand-sized glauconite grains occur throughout the succession but are typically of insignificant abundance. Some beds contain numerous limonite-stained grains (oxidized glauconitic grains?) and brownish to blackish phosphatic grains. Pyrite is fairly common and occurs as crypto-crystalline 'dust', discrete crystals and in places centimetre-sized aggregates. Barite is also found. Carbonate textures range from mudstone to grainstone; wackestone is dominant, but packstone is also common. Much of the succession exhibits metre-scale cyclic variation between finer and coarser carbonate textures, and there is a long-term trend of coarsening textures up-section (Figs 3, 4; see below). Most beds are visibly bioturbated at various scales and some bedding surfaces are underlain by dense networks of borings and burrows reminiscent of *Balanoglossites* and/or *Thalassinoides* (cf. Lindskog & Eriksson 2017). *Planolites* burrows are relatively common in fine-textured strata.

Clay-filled seams have often developed due to pressure dissolution during compaction of the limestone. These seams are associated with minor lateral and vertical displacement, fracturing and truncation of skeletal grains. Seams tend to coincide with partings between limestone beds at the macroscopic scale, but they do not always coincide with primary bedding surfaces; they are not always laterally continuous and can migrate vertically. Jagged stylolites also occur, especially in coarser-textured beds.

The macrofauna is dominated by trilobites, brachiopods and cephalopods. Gastropods and minute echinoderm debris also occur. The cephalopod fauna contains a relatively large proportion of small (ca 5–15 cm long, juvenile?) specimens, and many conchs are slightly distorted and/or broken. The preservation of fossils is in places very good, with many multipartite types being found articulated, but they tend to be difficult to extract from their host rock (see Anderberg & Johansson 1981). Fossil grain assemblages are mainly dominated by trilobite debris, followed by echinoderm (mainly 'pelmatozoan') debris and ostracod valves. Brachiopods and molluscs are locally abundant. Other biotic components are rare but include calcareous sponge spicules, bryozoans, acritarchs, conodonts, scolecodonts, chitinozoans and various problematica (approximately listed in order of abundance).

Sedimentary and biotic variations

The basal ca 6 m of the studied succession at Lanna (C) comprise bituminous shale with lenses and intermittent beds of limestone, belonging to the Alum Shale Formation (Figs 2A–C, 3). Some of the limestone surfaces are densely strewn with arthropod sclerites (mainly disarticulated *Peltura scarabaeoides*). At the microscopic scale, the limestone typically consists of variably recrystallized mudstone to wackestone with thin horizons of skeletal (mainly trilobite/agnostoid) debris locally forming packstone and grainstone (Fig. 5A, B). Minor kolm lenses are found (coal-like deposits unusually rich in organic carbon and heavy metals; see Hedström 1923; Andersson et al. 1985). A ca 3 cm thick horizon with stromatolite-like lamination occurs intermittently in the uppermost part of the succession (Fig. 2E). Macroscopically, the laminated interval is divided into low domes, separated by furrows that taper downwards, reminiscent of domal stromatolites *sensu* Aitken (1967) and LLH-C stromatolites *sensu* Logan et al. (1964). Microscopically, the lamination consists of alternating laminae of more and less bituminous recrystallized carbonate, with no primary microbial remnants being visible (cryptalgalaminate *sensu* Aitken 1967). The topmost surface of the Cambrian succession is rugged and uneven, with topographic variations at the decimetre scale (Fig. 2B, C). The underlying ca 5–10 cm interval of rock is bleached grey and often slightly rust-coloured. The transition between the Cambrian and the Ordovician strata is thus abrupt and easily located in the outcrop; a significant hiatus occurs at this level throughout Närke, as sedimentation ceased between the early–mid Cambrian Stage 10 (~ *Ctenopyge linnarssoni* Zone) and the latest Tremadocian–earliest Floian (*Megistaspis armata* Zone–*M. planilimbata* Zone, Hunneberg Regional Stage; Westergård 1947; Tjernvik 1956; Terfelt et al. 2011; Pärnaste et al. 2013).

The Ordovician succession begins with strongly glauconitic limestone belonging to the Lower Ordovician 'Latorp Limestone' (Figs 2B, C, 3). The basal bed consists of a beige-coloured limestone with numerous cracks filled with glauconitic sediment and calcite (Fig. 5C, D). This bed and those immediately above it are slightly phosphoritic and contain variably rounded clasts – some of which are decimetre-sized – consisting of material from the underlying Alum Shale (see Andersson 1895; Lindström 1954), and also quartz grains. Glauconite concentrations decrease upwards. The most glauconite-rich bed in the basal 'Latorp Limestone' is locally absent; it mainly occurs in depressions in the underlying Cambrian strata (Tjernvik 1956). The main part of the 'Latorp Limestone' consists of beige grey, commonly slightly greenish, mudstone and subordinate wackestone intercalated with bluish-greenish grey calcareous shale (Fig. 5E, F). Bedding varies cyclically in thickness, and the 'Latorp Limestone' can be subdivided into at least three individual 'members' that are characterized by a thickening of beds up-section. These 'members' are commonly discernible in outcrops and correspond closely to the trilobite zones of the Hunneberg and Billingen regional stages (see also Tjernvik 1952, 1956). A decimetre-high dome-like structure lies in the middle part of the 'Latorp' succession at Lanna C (Fig. 2B; cf. Lindström 1963; Fedorov 2003; Lindskog & Eriksson 2017). Cryptocrystalline pyrite 'dust' occurs throughout and pyritic aggregates are seen in some horizons. Millimetre- to centimetre-sized intraclasts rimmed by glauconite are also present, especially in the middle part of the formation (Fig. 5E). Stray glauconite and quartz grains are found throughout. The limestone matrix is commonly recrystallized into a fine mesh of calcite crystals, and 'ant-egg spar' *sensu* Lindström (1979) occurs, especially near contacts between beds. The uppermost beds of the 'Latorp Limestone' consist of strongly bioturbated greyish-brown mudstone to wackestone with numerous discontinuity surfaces (Figs 2D, 5F). Macrofossil assemblages are dominated by trilobites (mainly pygidia), but some beds contain also brachiopods and cephalopods. Preservation is commonly good and in some beds even excellent, but the fossils are nonetheless difficult to extract from the well-cemented host rock. Fossil grain assemblages in the 'Latorp Limestone' are entirely dominated by trilobites, with only a few levels showing any significant variation in the fauna (Fig. 3). The individual 'members' of the 'Latorp Limestone' (see above) are reflected in the microfacies data through repeated reorganizations of the fossil grain assemblages, wherein trilobite abundance at first increases and then declines upwards. A distinct overall increase in trilobite abundance is seen in the uppermost 'Latorp Limestone'. In total, the 'Latorp Limestone' is ca 3.1 m thick at Lanna.

The boundary between the 'Latorp' and 'Lanna' limestones, which coincides closely with the Lower–Middle Ordovician boundary (conterminous with the Floian–Dapingian and Billingen–Volkhov stage boundaries), is marked in the field by a change into more weathering-resistant and thicker-bedded limestone and the disappearance of shale horizons (Fig. 2B, D; see also Tjernvik 1952, 1956, 1972). This shift in lithology is associated with a general coarsening of carbonate textures into dominant wackestone and an increase in average grain size, although this latter change is gradual. Bioturbation becomes more pervasive and burrows and borings (*Balanoglossites*/*Thalassinoides* and *Planolites*), evidently produced in relatively firm substrate and in part forming complex networks, become common (Fig. 5H). Glauconite becomes rare, but stray grains persist. A succession of deeply pitted discontinuity surfaces is developed in the 'Latorp'–'Lanna' boundary interval, although there appears to be no obvious equivalent to 'Blommiga Bladet' (cf. Lindström 1979; Olgun 1987). The basal 'Lanna Limestone' is greyish, but the colour changes into reddish brown upwards; in closer detail, the colour can be seen to alternate between reddish- and greyish-brown hues. Large trilobite pygidia occur throughout and dense collections of coarse shell debris are seen on some bedding surfaces, although the main part of the 'Lanna' succession is rather poor in fossils. Carbonate textures coarsen markedly upwards (Fig. 3). Fossil grain assemblages become more varied ('diverse') up-section and echinoderms become increasingly common. The main middle part of the 'Lanna Limestone' is characterized by alternation between compact limestone and marly/nodular limestone, occurring with quite regular spacing (Fig. 2F; see also Lindskog & Eriksson 2017). A distinct increase in the number of molluscs in grain assemblages is seen at the transition into this part of the succession (Figs 3, 5I, J). Beds thicken in the upper part of the 'Lanna Limestone' (at Lanna A) and the strata turn darker reddish-brown before the dominant rock colour rapidly changes into grey. Numerous discontinuity surfaces occur, many of which obviously represent hardgrounds. These are commonly stained by glauconite, iron and/or phosphate and are overlain by variably sized intraclasts. Carbonate textures coarsen significantly in the grey interval and the uppermost 'Lanna Limestone' is thus characterized by dense wackestone and packstone (Figs 4, 5J, K). Echinoderms continue to increase in relative abundance within fossil grain assemblages, and a temporary peak in abundance is seen in the uppermost Volkhov beds. In total, the 'Lanna Limestone' is ca 11 m thick at Lanna.

The top of the 'Lanna Limestone' topoformation is indistinct in the outcrop, but the transition into the overlying 'Holen Limestone' is indicated by an overall establishment of thicker bedding with fewer marly partings and a shift into a darker and dominantly greenish-grey rock colour (Fig. 2H, I). Beds tend to be parted by thin shale seams. Numerous blackish-brown-stained (phosphatic?) discontinuity surfaces and grains occur in the transitional interval and the carbonate textures coarsen further (Figs 4, 5L). Limonitic grains are abundant in many beds (Fig. 5M). The appearance of the trilobites *Megistaspis acuticauda*, *Illaenus sarsi* and *Asaphus expansus* (the last one being relatively rare) in this part of the succession marks the transition between the Volkhov and Kunda regional stages (e.g., Lindskog et al. 2014). The Volkhov–Kunda boundary is herein identified as a particularly well-developed hematite- and glauconite-stained discontinuity surface, which is underlain by numerous borings and overlain by an interval rich in black-stained (phosphatic?) grains and intraclasts (Fig. 4). A temporary change into a pinkish-grey rock colour is seen up-section. Macrofossil assemblages remain dominated by trilobites, but cephalopods and brachiopods

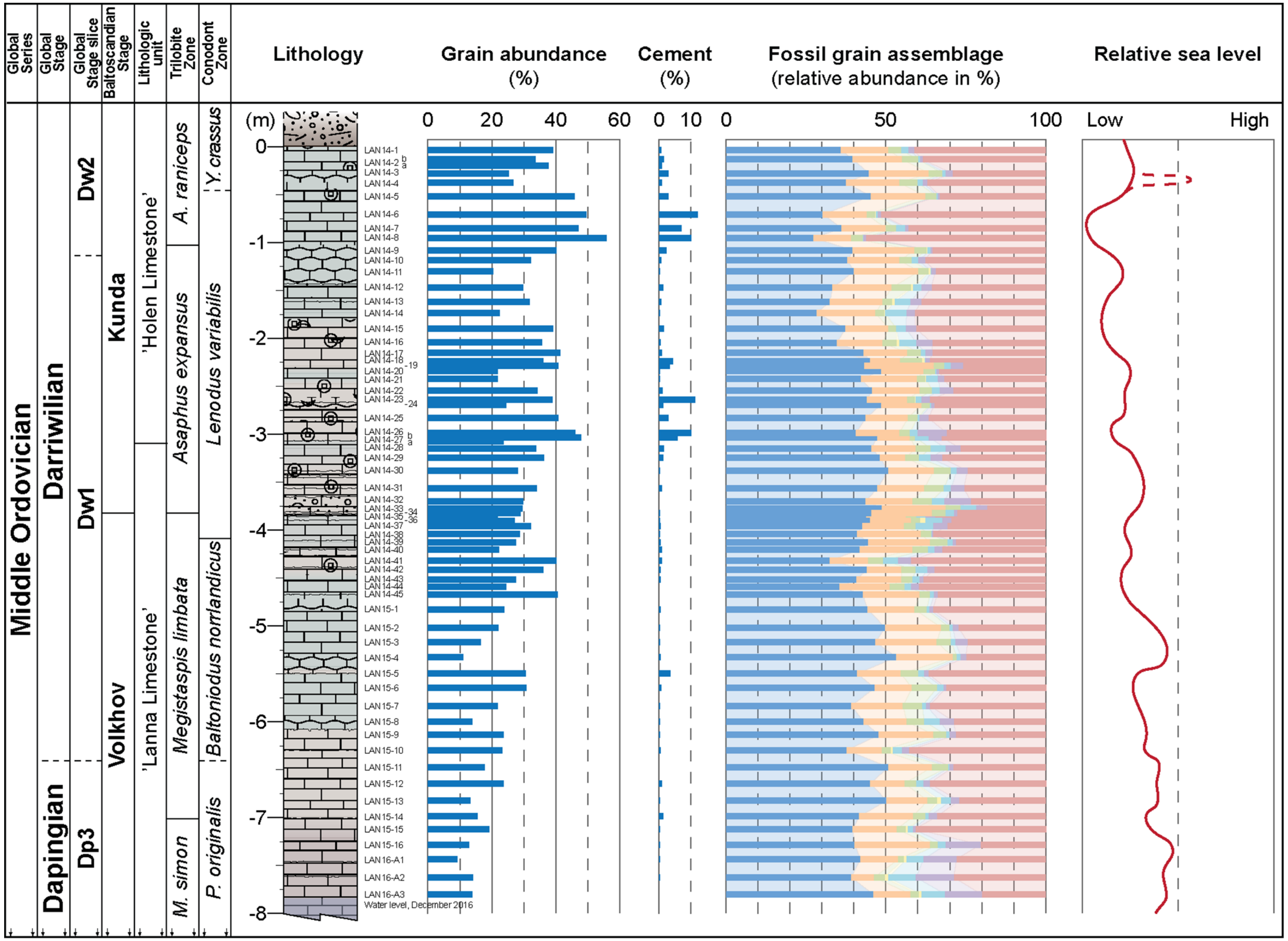

Fig. 4. Sedimentary profile of the section at Lanna A ('Lanna badgruva', 'Cementfabrikens brott'). Variations in carbonate texture (grain abundance, cement) and fossil grain assemblages are indicated, together with an interpretation of relative sea level. For legend, see Fig. 3. Biostratigraphy after Tjernvik (1952, unpublished notes), Löfgren (1995, 2003) and observations during fieldwork. Abbreviations: *A. raniceps*, *Asaphus raniceps*; *M. simon*, *Megistaspis simon*; *P. originalis*, *Paroistodus originalis*; *Y. crassus*, *Yangtzeplacognathus crassus*.

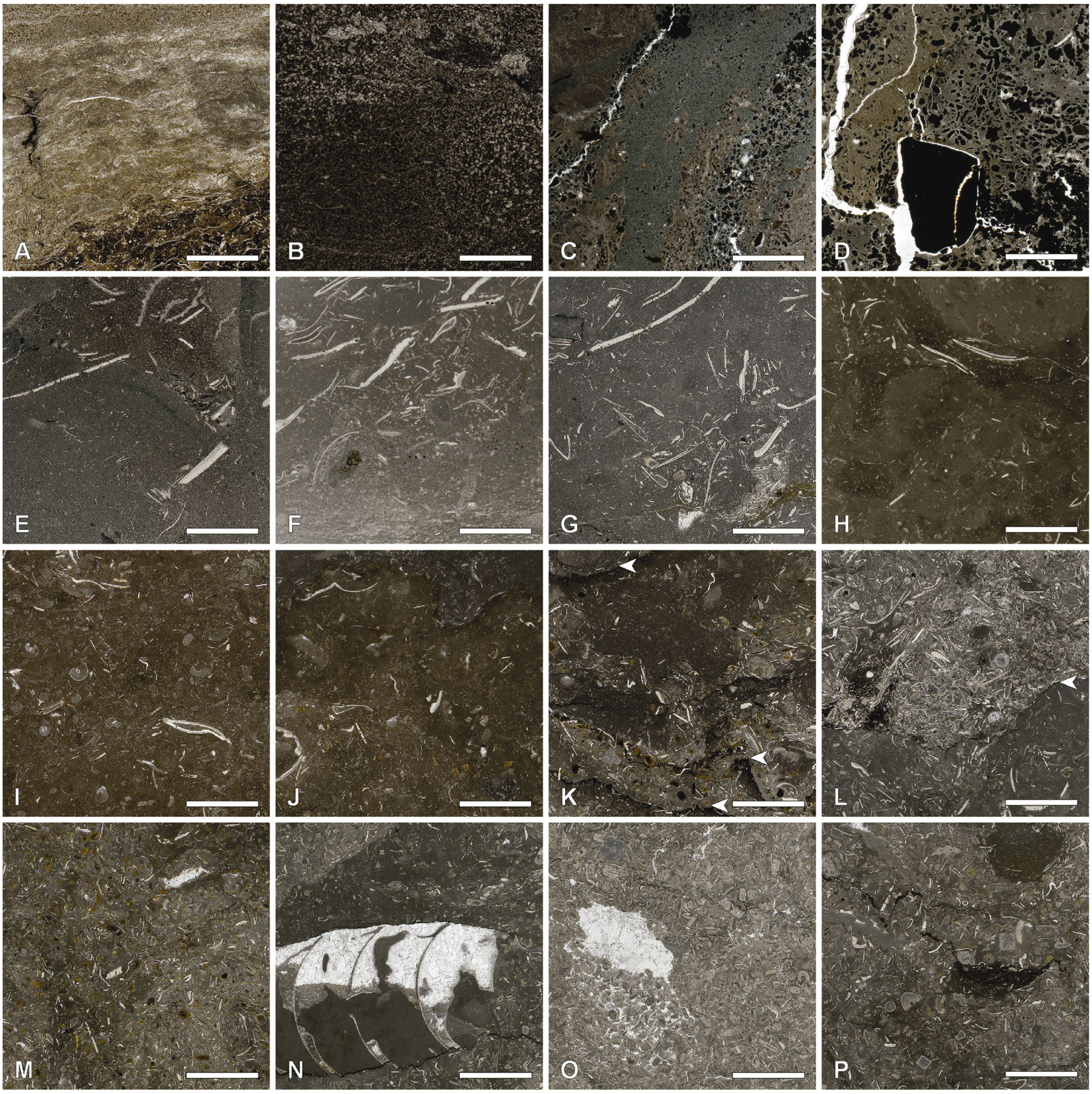

Fig. 5. Thin-section images (transmitted light). All scale bars 5 mm (images identically scaled for direct comparison). **A**, bituminous wackestone–packstone strewn with trilobite debris (Alum Shale Formation; LAN16-Ccam2). **B**, finely recrystallized bituminous limestone in the topmost Cambrian bed (LAN16-Ccam1). **C**, glauconite-strewn calcareous mudstone in the basal Ordovician bed (‘Latorp Limestone’; LAN16-C1a). **D**, glauconite-strewn calcareous mudstone with Alum Shale clast (LAN16-C1b). Numerous cracks penetrate the rock in various directions. **E**, wacke-mudstone with glauconite-stained hardground in the middle ‘Latorp Limestone’ (LAN16-C7b). **F**, mud-wackestone in the upper ‘Latorp Limestone’ (LAN16-C16). **G**, trilobite-rich wackestone in the basal ‘Lanna Limestone’ (LAN16-C21). **H**, well-bioturbated brownish mud-wackestone in the lower ‘Lanna Limestone’ (LAN16-C25). Note the many distinctly outlined burrows, which are typical for this part of the succession. **I**, gastropod-rich wackestone in the middle ‘Lanna Limestone’ (LAN16-C40). **J**, wackestone in the upper ‘Lanna Limestone’ (LAN15-9). **K**, pack-wackestone in the uppermost ‘Lanna Limestone’ (LAN14-30). Several darkly stained discontinuity surfaces (arrows) and grains occur in this part of the unit. **L**, discontinuity surface (~firmground; arrow) in the lower ‘Holen Limestone’, overlain by packstone (LAN14-27). **M**, pack-wackestone strewn with limonitic grains, in the ‘Holen Limestone’ (LAN14-15). **N**, small cephalopod conch in the ‘Holen Limestone’ (LAN14-13). **O**, densely packed grain-packstone, dominated by echinoderm debris, in the *A. expansus*–*A. raniceps* boundary interval (LAN14-8). Note cement-filled burrow to lower left. **P**, echinoderm-rich pack-wackestone in the uppermost bed at Lanna (A; LAN14-1).

become quite common upwards. Gastropods are also abundant in places. Dense collections of skeletal debris, including numerous cephalopod conchs, occur at some levels and some horizons can even be described as coquinoid (Fig. 2J). Conchs commonly show a preferential orientation towards the SSW, and some levels appear to show bimodal orientations (at ~90° angle). Articulated trilobites are relatively common, especially in the middle *A. expansus* Zone. Overall, the 'Holen Limestone' is characterized by coarse carbonate textures, typically packstone with subordinate grainstone. Fossil grain assemblages gradually become dominated by echinoderm debris, and such grains become rock-forming in the uppermost beds of the succession at Lanna (Fig. 5O, P). The outcrop at Lanna (A) terminates in the lower part of the *Asaphus raniceps* trilobite Zone, corresponding to a level in the middle Kunda Regional Stage (basal Dw2).

DISCUSSION

The collective results of this study, combined with previously published data, reveal details about the palaeoenvironmental development throughout the late Cambrian (Furongian)–mid Ordovician. Both the macroscopic and microscopic characteristics of the strata at Lanna show that significant changes occurred in the local depositional environment during this time interval, and many distinct changes and 'events' in the local rocks correspond to palaeoenvironmental changes recorded also in other parts of Sweden and Baltoscandia.

Sedimentary and palaeoenvironmental development

The presence of putative stromatolites in the upper Alum Shale interval at Lanna indicates that quite shallow, possibly intertidal (e.g., Aitken 1967), marine conditions prevailed in this area during the latest Cambrian (provisional Age 10), although this is otherwise not particularly well expressed in the shale-dominated facies and the stromatolite-like deposits remain to be investigated in closer detail. Overall, the upper Furongian strata appear to record a gradual shallowing (see also Newby 2012), but this trend is abruptly cut off by the discontinuity surface that separates the Cambrian from the Ordovician. It appears that the Lanna area was subaerially exposed sometime during the earliest Ordovician. This is indicated by the decimetre-scale topographic variations in the topmost Cambrian surface, which were induced by substantial erosion and/or dissolution, chemical alterations and subsequent discolouration of the underlying strata (due to percolation of meteoric solutions), and the conglomeratic appearance of the oldest Ordovician strata. The same interpretation is reasonable for the entire province of Närke and it appears that large parts of Sweden were laid bare at this time (e.g., Westergård 1941a, 1941b; Tjernvik 1956; Egenhoff & Maletz 2012; Ahlberg et al. 2016). Well-developed desiccation cracks in the topmost Cambrian surface in the Hunneberg area of Västergötland (see Egenhoff & Maletz 2012, fig. 4), which arguably represents a deeper-water environment than Närke, provide convincing evidence of subaerial conditions. The formation of large collapse and solution structures in the Västergötland area further imply subaerial conditions during the Tremadocian (Teves & Lindström 1988). Unless the changes in sea level were of extreme amplitude, the regional epeiric sea must have been fairly shallow for such widespread emergence to occur (cf. Chen & Lindström 1991). The Cambrian–Ordovician boundary is typically associated with variably long hiatuses in Sweden and the one developed in Närke is particularly extensive. Any possible sedimentation that may have taken place between the latest Cambrian and the mid Early Ordovician has been lost in time. As is apparent from the drastic shift in facies, the depositional and palaeoenvironmental conditions in the Närke area – and the Baltoscandian region overall – changed considerably between the Cambrian and the (recommencement of sedimentation in the) Ordovician. This may in large part be attributed to a combination of sea level changes and an overall depletion of weathering products, but it cannot be excluded that the overall setting of the palaeobasin changed due to tectonic activity (in fact, this is implied by significant differences in the sedimentary development regionally). Sea level appears to have risen in the latest Tremadocian and/or earliest Floian, resulting in the glauconite-rich bed that is commonly found at the base of the Ordovician succession in Närke.

Although this is not always immediately obvious in the field, the widely varying microfacies characteristics of the Ordovician limestones at Lanna indicate that the depositional environment underwent significant changes through time (Figs 3–5). The Ordovician succession shows both short- and long-term trends, and in part unmistakably cyclic patterns, in carbonate textures and fossil grain assemblages that can largely be attributed to changes in (relative) sea level (see discussion in Lindskog & Eriksson 2017; cf. Thorslund 1960). As such, the 'Latorp Limestone' records at least three sea-level cycles throughout the Hunnebergian–Billingenian, each giving rise to shallowing upwards sequences that terminate with a relatively massive limestone bed containing a rather diverse fauna (see also Tjernvik 1952). After an interval of relatively high sea level, water depth appears to have decreased during the Volkhovian, but regional patterns are somewhat contradictory as this time interval is particularly well developed in many areas (e.g., Olgun 1987; Dronov 2004; cf. Nielsen 1995, 2011). This may in part be a result of increasing bioproductivity through time, however, with the establishment of a fairly 'healthy' carbonate environment resulting in a more persistent deposition of sediment. The uppermost part of the succession at Lanna records a distinct lowering of the sea level during the Kundan, expressed through an overall coarsening of carbonate textures and more diverse fossil assemblages (e.g., Lindström 1971; Nordlund 1989; Lindskog & Eriksson 2017). Abrupt shifts in microfacies in this interval reflect diastems due to discontinuous sedimentation. The lower Kundan is associated with significant stratigraphic gaps in the proximal areas of the Baltoscandian palaeobasin (e.g., Lamansky 1905; Dronov & Holmer 1999; Dronov 2017). Overall, the tentative sea-level history deduced from the Lanna area is largely consistent with previous interpretations for the Baltoscandian region (e.g., Nielsen 1995, 2011; Dronov & Holmer 2002; Dronov 2004, 2017; Dronov et al. 2011; Lindskog & Eriksson 2017), although inter-continental comparisons remain problematic especially at higher stratigraphic resolution (Haq & Schutter 2008).

The water depth at which the 'orthoceratite limestone' was formed, and indeed much of the Baltoscandian palaeobasin, has long been a point of scientific debate and it remains a contentious issue. Based on the characteristics of imploded cephalopod shells (known as Septal Strength Index, SSI), Chen & Lindström (1991) estimated that it was ca 200 m deep in the Närke area during the early Volkhovian (*Baltoniodus navis* interval). Given the overall reactivity of the depositional environment to palaeoenvironmental changes such a great depth appears exaggerated, and in light of the general state of preservation of cephalopods in the 'orthoceratite limestone' it is questionable if primary breakage (during purported shell implosion) can be confidently separated from secondary breakage (during deposition, sediment filling, diagenesis). The SSI approach in itself, with its standardized formulas, is also problematic (see Mutvei 2017). The local strata commonly show a contrasting set of features that indicate both relatively low- and high-energy conditions during deposition. For example, many beds have a very fine-grained matrix but contain numerous lithoclasts, in places several centimetres in size (Figs 2C, 3D). In terms of absolute numbers, especially the deeper end of the depth range is difficult to pinpoint, whereas the shallower end is easier to assess; the most coarse-textured strata at Lanna were clearly deposited in a very shallow environment with more or less constant wave activity. The orientations of cephalopod conchs attest to this (see above; e.g., Grahn 1986). It is likely that the shallowest-water conditions were on the order of only a few metres deep and in some cases the water depth may have been close to or effectively at zero.

Regional comparisons

As noted already by Linnarsson (1875a), the Palaeozoic succession in Närke shows particularly close similarity to that in the Billingen-Falbygden area in Västergötland, some 125 km south-southwest of the Lanna area. There are also distinct similarities with coeval successions in Dalarna (see Hessland 1949), Östergötland and southern Öland (Lindskog, unpublished data). This suggests that these areas represent quite similar depositional settings. In both Närke and the Billingen-Falbygden area, the Cambrian–Ordovician succession is similarly developed stratigraphically, and a comparable gap separates the strata of the two systems (e.g., Westergård 1947; Olgun 1987; Ahlberg et al. 2016). The uppermost beds at Lanna, which are of Kundan age, clearly correspond to the 'Täljsten' interval of Västergötland (see Eriksson et al. 2012), and the unusually hematite-rich beds in the uppermost *A. expansus* Zone represent a regionally traceable feature, possibly related to proliferation of microbial mats (Lindskog et al. 2015; Lindskog & Eriksson 2017). Some beds in the 'Täljsten' interval and coeval strata are packed with *Sphaeronites* cystoids, but such fossils were not found in this study. However, loose slabs with *Sphaeronites* have been documented from the Lanna area (Regnéll 1948) and the local rock interval corresponding to the 'Täljsten' interval is characterized by abundant echinoderm debris. The macroscopic characteristics of the rocks in the Hunneberg and Kinnekulle areas of Västergötland, only 50–75 km west and northwest of the Billingen-Falbygden area, differ somewhat from the Närke area. Most notably, the Lower Ordovician is mainly characterized by mudstone and shale. This is likely due to deeper-water conditions at Hunneberg and Kinnekulle and most areas west and south of there (including Norway and southernmost Sweden). Still, the overall sedimentary development in the Volkhovian–Kundan interval at Lanna is quite similar to that at Kinnekulle (see Lindskog & Eriksson 2017). Carbonate textures and fossil grain assemblages show closely similar variations, but the amplitude of changes appears to be most distinctly expressed at Lanna (likely due to shallower water). The fossil grain assemblages form a series of 'zones' characterized by a certain composition at both localities, separated by distinct faunal reorganizations (but the relative proportion of grain types differs and assemblages at Lanna appear to be more diverse). For example, a distinct increase in the abundance of gastropods is seen in the middle 'Lanna

Limestone' and echinoderms increase up-section into the 'Holen Limestone'. The collective data indicate that microfacies and fossil grain assemblages can reveal much information about the palaeoenvironmental development and even be employed for ecostratigraphic purposes (cf. Põlma 1982; Olgun 1987; Lindskog et al. 2015; Lindskog & Eriksson 2017), although further studies are needed in order to enable more direct comparisons between localities within Sweden and abroad.

The thickness of the Ordovician limestone succession in some drill cores indicates that younger Ordovician beds than those exposed in the Lanna area are present in the central parts of the Latorp plateau (~north of Lanna), but the youngest strata are yet to be studied in detail (e.g., Karis & Magnusson 1972). Boulders of variegated reddish-grey limestone apparently belonging to the *Megistaspis obtusicauda* and *Megistaspis gigas* trilobite zones of the upper Kunda Regional Stage can be found in the Vintrosa area, ca 3–5 km north of Lanna.

Prospects for the 'Latorp', 'Lanna' and 'Holen' limestones to become formal lithoformations

Recently, a call was made to review the Swedish geologic nomenclature and to establish a database of formally described and ratified geologic features in the country (Kumpulainen et al. 2017). With this, a national guide for geologic nomenclature was introduced (Kumpulainen 2017). The guide deems the traditional topostratigraphic framework obsolete, thus affecting the validity of the 'Latorp', 'Lanna' and 'Holen' limestones, as well as many other regional Ordovician units (for reference, topostratigraphy employs a mixture of lithologically and palaeontologically defined boundaries in stratigraphic units; Jaanusson 1960b). It is quite clear that many of the topostratigraphic units are difficult to discern and delimit without detailed knowledge of the taxonomy of fossil faunas and other relatively inconspicuous features (e.g., Nielsen 1995; Karis 1998), so this is a necessary and reasonable way forward. Still, fossils form an integral feature of many Phanerozoic sedimentary rocks and can hardly be neglected in any proper description and definition of stratigraphic units even outside the topostratigraphic method (cf. Jaanusson 1960b). Therefore, it should be possible to define a fossiliferous rock unit at least in part based on fossil content, although any palaeontologic information in formal lithostratigraphic descriptions and definitions should of course be kept at a non-specialist level (cf. Kumpulainen 2017, p. 9). As most limestones consist largely of biogenic material, observations on rock-forming fossils are quite essential for adequate description of their lithologies.

Although the 'Latorp' and 'Lanna' limestones stem from the topostratigraphic tradition (see Jaanusson 1982a, 1982b), they have good prospects of being formally introduced into the Swedish stratigraphic framework as lithoformations. These would be placed within a group corresponding to some version of the 'orthoceratite limestone', or alternatively as members should the latter be regarded as a single large formation. The observations and data here, together with those of, for example, Fromm (1971), Karis & Magnusson (1972), Bruun & Dahlman (1980), Karis (1998), Ahlberg et al. (2016), Lindskog & Eriksson (2017) and many of our yet unpublished results, show that the 'Latorp' and 'Lanna' limestones possess several characteristics that carry between outcrops even when there are superficial differences in appearance (such as dominant colour). These characteristics include distinct bedding, abundance and types of authigenic minerals and unique microfacies details (and fossil fauna), allowing for confident identification of these units throughout much of Sweden. The 'Holen Limestone' is clearly more problematic to discern, however, especially from overlying topoformations. In short, although work remains to be done before they can be adequately described and defined, both the 'Latorp' and 'Lanna' limestones may transfer into a formal lithostratigraphic framework with only minor amendments in stratigraphic distribution compared to their topostratigraphic meaning. Formalization with retained names and type areas/localities would minimize confusion and errors when going back in the historic literature and optimize the usefulness of previously published scientific studies.

CONCLUSIONS

The Lanna area of Närke, south-central Sweden, hosts an easily accessible and instructive succession of Cambrian–Ordovician sedimentary rocks, offering an excellent opportunity for scientific studies. The strata record a distinct shallowing in the late Cambrian (provisional Cambrian Age 10). In the Lanna area and much of Sweden this shallowing ultimately resulted in emergence and subaerial conditions throughout the Cambrian–Ordovician transition, now marked by a significant hiatus in the succession. Sedimentation recommenced with rising sea level in the early Ordovician and continued relatively steadily into Middle Ordovician times. The microfacies characteristics of the Ordovician 'orthoceratite limestone' at Lanna vary considerably throughout the studied succession, likely in large part due to changes in (relative) sea level. A long-term trend of coarsening carbonate textures and more varied fossil grain faunas is seen upwards through the succession. Cyclic patterns likely correspond to high-frequency sea-level changes. Comparisons with other parts of Sweden and Baltoscandia reveal consistent patterns in the sedimentary development.

Acknowledgements. This paper is dedicated to the memory of Torsten Tjernvik (1902–1991). The study was funded by the Royal Physiographic Society in Lund (to A. L. and P. A.) and the Swedish Research Council (grant No. 2015-05084 to M. E. E). Frans Lundberg is thanked for many helpful discussions about stratigraphic details and the development of the regional sedimentary succession during the Palaeozoic. Ingvor and Åke Pettersson are thanked for generous lodging and for providing transport possibilities during fieldwork. Andrei Dronov and Arne T. Nielsen are thanked for thorough reviews, which helped to strengthen the final manuscript. This paper is a contribution to IGCP project 653 'The onset of the Great Ordovician Biodiversification Event'. The publication costs of this article were partially covered by the Estonian Academy of Sciences.

REFERENCES

Ahlberg, P., Eriksson, M. E., Lundberg, F. & Lindskog, A. 2016. Cambrian stratigraphy of the Tomten-1 drill core, Västergötland, Sweden. *GFF*, **138**, 490–501.

Aitken, J. D. 1967. Classification and environmental significance of cryptalgal limestones and dolomites, with illustrations from the Cambrian and Ordovician of southwestern Alberta. *Journal of Sedimentary Petrology*, **37**, 1163–1178.

Anderberg, A. & Johansson, J. 1981. *Trilobiterna i Närke*. Kambria, Örebro, 182 pp.

Andersson, J. G. 1895. Über cambrische und silurische phosphoritführende Gesteine aus Schweden. *Bulletin of the Geological Institution of the University of Upsala*, **2**, 133–236.

Andersson, J. G. & von Post, L. 1909. 2. Exkursionen i västra Närke och till Loka-dalen den 14–16 maj. *Geologiska Föreningens i Stockholm Förhandlingar*, **31**, 404–411.

Andersson, A., Dahlman, B., Gee, D. G. & Snäll, S. 1985. The Scandinavian Alum shales. *Sveriges Geologiska Undersökning*, **Ca 56**, 1–50.

Babcock, L. E., Peng, S. C., Brett, C. E., Zhu, M.-Y., Ahlberg, P., Bevis, M. & Robison, R. A. 2015. Global climate, sea level cycles, and biotic events in the Cambrian Period. *Palaeoworld*, **24**, 5–15.

Bagnoli, G. & Stouge, S. 2014. Upper Furongian (Cambrian) conodonts from the Degerhamn quarry road section, southern Öland, Sweden. *GFF*, **136**, 436–458.

Bergström, J. & Gee, D. G. 1985. The Cambrian in Scandinavia. In *The Caledonide Orogen – Scandinavia and Related Areas* (Gee, D. G. & Sturt, B. A., eds), pp. 247–271. Wiley, Chichester.

Blomberg, A. & Holm, G. 1902. Geologisk beskrifning öfver Nerike och Karlskoga bergslag samt Fellingsbro härad. *Sveriges Geologiska Undersökning*, **Ca 2**, 1–124.

Bruun, Å. & Dahlman, B. 1980. Den paleozoiska beskrivningen. In *Beskrivning till berggrundskartbladet Örebro SV* (Wikman, H., Bruun, Å. & Dahlman, B., eds), *Sveriges Geologiska Undersökning*, **Af 119**, 68–103.

Chen, J. & Lindström, M. 1991. Cephalopod Septal Strength Indices (SSI) and the depositional depth of Swedish Orthoceratite limestone. *Geologica et Palaeontologica*, **25**, 5–18.

De Geer, G. 1941. Om ortovarv, ett slags aglacial varvighet inom ortocerkalken. *Arkiv för Kemi, Mineralogi och Geologi*, **15**, 1–9.

Dronov, A. 2004. Magnitude of sea-level changes in the Ordovician of Baltoscandia. In *WOGOGOB-2004 Conference Materials* (Hints, O. & Ainsaar, L., eds), pp. 21–22. Tartu University Press, Tartu.

Dronov, A. 2017. Chapter 5 – Ordovician sequence stratigraphy of the Siberian and Russian platforms. In *Advances in Sequence Stratigraphy. Special Issue: Stratigraphy & Timescale, Vol. 2* (Montenari, M., ed.), pp. 187–241. Elsevier, Oxford.

Dronov, A. & Holmer, L. E. 1999. Depositional sequences in the Ordovician of Baltoscandia. In *Quo vadis Ordovician? Short Papers of the 8th International Symposium on the Ordovician System* (Kraft, P. & Fatka, O., eds), *Acta Universitatis Carolinae – Geologica*, **43**, 1133–1136.

Dronov, A. & Holmer, L. 2002. Ordovician sea-level curve: Baltoscandian view. In *The Fifth Baltic Stratigraphical Conference "Basin Stratigraphy – Modern Methods and Problems", September 22–27, 2002, Vilnius, Lithuania: Extended Abstracts*, pp. 33–35. Geological Survey of Lithuania, Vilnius.

Dronov, A. & Rozhnov, S. 2007. Climatic changes in the Baltoscandian basin during the Ordovician: sedimentological and palaeontological aspects. *Acta Palaeontologica Sinica*, **46**, S108–S113.

Dronov, A. Ainsaar, L., Kaljo, D., Meidla, T., Saadre, T. & Einasto, R. 2011. Ordovician of Baltoscandia: facies, sequences and sea-level changes. In *Ordovician of the World* (Gutiérrez-Marco, J. C., Rábano, I. & Garcia-Bellido, D., eds), *Publicaciones del Instituto Geológico y Minero de España, Cuadernos del Museo Geominero*, **14**, 143–150.

Dunham, R. J. 1962. Classification of carbonate rocks according to depositional texture. *American Association of Petroleum Geologists Memoir*, **1**, 108–121.

Egenhoff, S. & Maletz, J. 2012. The sediments of the Floian GSSP: depositional history of the Ordovician succession at Mount Hunneberg, Västergötland, Sweden. *GFF*, **134**, 237–249.

Eklund, J. (ed.). 1961. *Kumlabygden: Forntid – nutid – framtid. I: Berg, jord och skogar*. Kumla tryckeri, Kumla. 475 pp.

Eriksson, M. E., Lindskog, A., Calner, M., Mellgren, J. I. S., Bergström, S. M., Terfelt, F. & Schmitz, B. 2012. Biotic dynamics and carbonate microfacies of the conspicuous Darriwilian (Middle Ordovician) 'Täljsten' interval, south-central Sweden. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **367–368**, 89–103.

Fedorov, P. 2003. Lower Ordovician mud mounds from the St. Petersburg region, northwestern Russia. *Bulletin of the Geological Society of Denmark*, **50**, 125–137.

Fromm, E. 1971. Den kambro-siluriska berggrunden. In *Beskrivning till berggrundskartbladet Örebro SV*

(Lundegårdh, P. H. & Fromm, E., eds), *Sveriges Geologiska Undersökning*, **Af 101**, 26–69.

Grahn, Y. 1986. Orthocone nautiloid orientations in Arenig and Llanvirn limestones of Öland, Sweden. *Geologiska Föreningens i Stockholm Förhandlingar*, **108**, 321–330.

Haq, B. U. & Schutter, S. R. 2008. A chronology of Paleozoic sea-level changes. *Science*, **322**, 64–68.

Hedström, H. 1923. Om vanadinhaltigt stenkol i Västergötlands kambro-silur. *Sveriges Geologiska Undersökning*, **C 318**, 1–30.

Hessland, I. 1949. Investigations of the Lower Ordovician of the Siljan district, Sweden I. Lower Ordovician ostracods of the Siljan district, Sweden. *Bulletin of the Geological Institutions of the University of Uppsala*, **33**, 97–408.

Jaanusson, V. 1960a. Graptoloids from the Ontikan and Viruan (Ordov.) limestones of Estonia and Sweden. *Bulletin of the Geological Institutions of the University of Uppsala*, **38**, 289–366.

Jaanusson, V. 1960b. The Viruan (Middle Ordovician) of Öland. *Bulletin of the Geological Institutions of the University of Uppsala*, **38**, 207–288.

Jaanusson, V. 1972. Aspects of carbonate sedimentation in the Ordovician of Baltoscandia. *Lethaia*, **6**, 11–34.

Jaanusson, V. 1982a. The Ordovician of Sweden. In *Field Excursion Guide. 4th International Symposium on the Ordovician System* (Bruton, D. L. & Williams, S. H., eds), *Paleontological Contributions from the University of Oslo*, **279**, 1–9.

Jaanusson, V. 1982b. The Siljan district. In *Field Excursion Guide. 4th International Symposium on the Ordovician System* (Bruton, D. L. & Williams, S. H., eds), *Paleontological Contributions from the University of Oslo*, **279**, 15–42.

Karis, L. 1998. Jämtlands östliga fjällberggrund. In *Beskrivning till berggrundskartan över Jämtlands län, Del 2: Fjälldelen* (Karis, L. & Strömberg, A. G. B., eds), *Sveriges Geologiska Undersökning*, **Ca 53:2**, 1–184.

Karis, L. & Magnusson, E. 1972. Paleozoisk berggrund. In *Beskrivning till berggrundsgeologiska kartbladet Örebro NV* (Lundegårdh, P. H., Hübner, H., Wikman, H., Karis, L. & Magnusson, E., eds), *Sveriges Geologiska Undersökning*, **Af 102**, 156–186.

Kumpulainen, R. A. (ed.) 2017. Guide for geological nomenclature in Sweden. *GFF*, **139**, 3–20.

Kumpulainen, R. A., Bergman, S. & Claesson, S. 2017. Sweden to review its geological nomenclature. *GFF*, **139**, 1–2.

Lamansky, W. 1905. Die aeltesten silurischen Schichten Russlands (Etage B). *Mémoires du Comité Géologique, Nouvelle Serie, Livraison.*, **20**, 1–203 [in Russian, with German summary].

Lindskog, A. & Eriksson, M. E. 2017. Megascopic processes reflected in the microscopic realm: sedimentary and biotic dynamics of the Middle Ordovician 'orthoceratite limestone' at Kinnekulle, Sweden. *GFF*, **139**, 163–183.

Lindskog, A., Eriksson, M. E. & Pettersson, A. M. L. 2014. The Volkhov–Kunda transition and the base of the Holen limestone at Kinnekulle, Västergötland, Sweden. *GFF*, **136**, 167–171.

Lindskog, A., Eriksson, M. E., Tell, C., Terfelt, F., Martin, E., Ahlberg, P., Schmitz, B. & Marone, F. 2015. Mollusk maxima and marine events in the Middle Ordovician of Baltoscandia. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **440**, 53–65.

Lindström, M. 1954. Conodonts from the lowermost Ordovician strata of south-central Sweden. *Geologiska Föreningens i Stockholm Förhandlingar*, **76**, 517–604.

Lindström, M. 1963. Sedimentary folds and the development of limestone in an Early Ordovician sea. *Sedimentology*, **2**, 243–275.

Lindström, M. 1971. Vom Anfang, Hochstand und Ende eines Epikontinentalmeeres. *Geologische Rundschau*, **60**, 419–438.

Lindström, M. 1979. Diagenesis of Lower Ordovician hardgrounds in Sweden. *Geologica et Palaeontologica*, **13**, 9–30.

Linnarsson, G. 1875a. Öfversigt af Nerikes öfvergångsbildningar. *Sveriges Geologiska Undersökning*, **C 21**, 1–47 [also published in *Kongliga Vetenskaps-Akademiens Förhandlingar*, 5].

Linnarsson, G. 1875b. Beskrifning till kartbladet "Latorp". *Sveriges Geologiska Undersökning*, **Aa 55**, 1–41.

Löfgren, A. 1994. Arenig (Lower Ordovician) conodonts and biozonation in the eastern Siljan district, central Sweden. *Journal of Paleontology*, **68**, 1350–1368.

Löfgren, A. 1995. The middle Lanna/Volkhov Stage (middle Arenig) of Sweden and its conodont fauna. *Geological Magazine*, **132**, 693–711.

Löfgren, A. 2003. Conodont faunas with *Lenodus variabilis* in the upper Arenigian to lower Llanvirnian of Sweden. *Acta Palaeontologica Polonica*, **48**, 417–436.

Logan, B. W., Rezak, R. & Ginsburg, R. N. 1964. Classification and environmental significance of algal stromatolites. *Journal of Geology*, **72**, 68–83.

Lundegårdh, P. H. & Fromm, E. 1971. Beskrivning till berggrundskartbladet Örebro SV. *Sveriges Geologiska Undersökning*, **Af 101**, 1–70.

Männil, R. M. 1966. *Istoriya razvitiya Baltijskogo bassejna v ordovike* [*Evolution of the Baltic Basin During the Ordovician*]. Eesti NSV Teaduste Akadeemia Geoloogia Instituut, Tallinn, 199 pp. [in Russian].

Mutvei, H. 2017. The new order Mixosiphonata (Cephalopoda: Nautiloidea) and related taxa; estimations of habitat depth based on shell structure. *GFF*, **139**, 219–232.

Newby, W. 2012. *Facies Patterns and Depositional Environments of the Peltura scarabaeoides Trilobite Biozone Sediments, Upper Cambrian Alum Shale Formation, Southern Sweden*. MSc thesis, Fort Collins, Colorado, 52 pp.

Nielsen, A. T. 1995. Trilobite systematics, biostratigraphy and palaeoecology of the Lower Ordovician Komstad Limestone and Huk formations, southern Scandinavia. *Fossils and Strata*, **38**, 1–374.

Nielsen, A. T. 2011. A re-calibrated revised sea-level curve for the Ordovician of Baltoscandia. In *Ordovician of the World* (Gutiérrez-Marco, J. C., Rábano, I. & Garcia-Bellido, D., eds), *Publicaciones del Instituto Geológico y Minero de España, Cuadernos del Museo Geominero*, **14**, 399–401.

Nielsen, A. T. & Schovsbo, N. H. 2011. The Lower Cambrian of Scandinavia: depositional environment, sequence stratigraphy and palaeogeography. *Earth-Science Reviews*, **107**, 207–310.

Nielsen, A. T. & Schovsbo, N. H. 2015. The regressive Early-Mid Cambrian 'Hawke Bay Event' in Baltoscandia: epeirogenic uplift in concert with eustasy. *Earth-Science Reviews*, **151**, 288–350.

Nordlund, U. 1989. Lithostratigraphy and sedimentology of a Lower Ordovician limestone sequence at Hälludden, Öland, Sweden. *GFF*, **111**, 65–94.

Olgun, O. 1987. Komponenten-Analyse und Conodonten-Stratigraphie der Orthoceratenkalksteine im Gebiet Falbygden, Västergötland, Mittelschweden. *Sveriges Geologiska Undersökning*, **Ca 70**, 1–78.

Pärnaste, H., Bergström, J. & Zhou, Z. 2013. High resolution trilobite stratigraphy of the Lower–Middle Ordovician Öland Series of Baltoscandia. *Geological Magazine*, **150**, 509–518.

Peng, S., Babcock, L. E. & Cooper, R. A. 2012. The Cambrian Period. In *The Geologic Time Scale 2012* (Gradstein, F. M., Ogg, J. G., Schmitz, M. D. & Ogg, G. M., eds), pp. 437–488. Elsevier, Oxford.

Põlma, L. 1982. *Sravnitel'naya litologiya karbonatnykh porod ordovika Severnoj i Srednej Pribaltiki* [*Comparative Lithology of Ordovician Carbonate Rocks in North and Central East Baltic*]. Valgus, Tallinn, 152 pp. [in Russian].

Regnéll, G. 1948. An outline of the succession and migration of non-crinoid pelmatozoan faunas in the Lower Paleozoic of Scandinavia. *Arkiv för Kemi, Mineralogi och Geologi*, **26A**, 13, 1–55.

Rönnby, E. 1943. Kvarntorp: Sveriges största skifferoljeindustri. *Svensk Geografisk Årsbok 1943*, 59–73.

Rozanov, A. Yu. & Łydka, K. (eds). 1987. *Palaeogeography and Lithology of the Vendian and Cambrian of the Western East-European Platform*. Publishing House Wydawnictwa Geologiczne, Warsaw, 114 pp.

Sopher, D., Erlström, M., Bell, N. & Juhlin, C. 2016. The structure and stratigraphy of the sedimentary succession in the Swedish sector of the Baltic Basin: new insights from vintage 2D marine seismic data. *Tectonophysics*, **676**, 90–111.

Stolpe, M. 1874. Beskrifning till kartbladet "Riseberga". *Sveriges Geologiska Undersökning*, **Aa 54**, 1–29.

Terfelt, F., Ahlberg, P. & Eriksson, M. E. 2011. Complete record of Furongian polymerid trilobites and agnostoids of Scandinavia – a biostratigraphical scheme. *Lethaia*, **44**, 8–14.

Teves, R. & Lindström, M. 1988. The Brattefors plugs: collapse structures initiated during a Tremadocian regression. *Geologiska Föreningens i Stockholm Förhandlingar*, **110**, 55–66.

Thorslund, P. 1960. Notes on the geology and stratigraphy of Närke. In *The Cambrian, Ordovician, and Silurian in Västergötland, Närke, Dalarna, and Jämtland, Central Sweden. International Geological Congress XXI Session, Norden 1960, Guide to Excursions No:s A 23 and C 18* (Thorslund, P. & Jaanusson, V., eds), pp. 19–22. Sveriges Geologiska Undersökning, Uppsala.

Tjernvik, T. 1952. Om de lägsta ordoviciska lagren i Närke. *Geologiska Föreningens i Stockholm Förhandlingar*, **74**, 51–70.

Tjernvik, T. 1956. On the early Ordovician of Sweden. Stratigraphy and fauna. *Bulletin of the Geological Institutions of the University of Uppsala*, **36**, 107–284.

Tjernvik, T. 1972. Volkhov Stage – Limbata Limestone. *Geologiska Föreningens i Stockholm Förhandlingar*, **94**, 301–310.

Tjernvik, T. E. & Johansson, J. V. 1980. Description of the upper portion of the drill-core from Finngrundet in the South Bothnian Bay. *Bulletin of the Geological Institutions of the University of Uppsala*, **8**, 113–204.

Westergård, A. H. 1922. Sveriges olenidskiffer. *Sveriges Geologiska Undersökning*, **Ca 18**, 1–205.

Westergård, A. H. 1941a. Nya djupborrningar genom äldsta ordovicium och kambrium i Östergötland och Närke. *Sveriges Geologiska Undersökning*, **C 437**, 1–72.

Westergård, A. H. 1941b. Skifferborrningarna i Yxhultstrakten i Närke 1940. *Sveriges Geologiska Undersökning*, **C 442**, 1–20.

Westergård, A. H. 1947. Supplementary notes on the Upper Cambrian trilobites of Sweden. *Sveriges Geologiska Undersökning*, **C 489**, 1–35.

Wiman, C. 1905. Ein *Shumardia*schiefer bei Lanna in Nerike. *Arkiv för Zoologi*, **2**, 1–20.

Ydreborg, B. (ed.). 2014. *Lannaboken: Berättelser om livet i Lanna*. NärkeTryck AB, Hallsberg, 176 pp.

Kambriumi ja Ordoviitsiumi läbilõige Lannas Rootsis: stratigraafia ning settekeskkond

Anders Lindskog, Anna M. L. Lindskog, Jan V. Johansson, Per Ahlberg ja Mats E. Eriksson

Kirjeldatud Lanna läbilõikes, mis asub Närke piirkonnas Lõuna-Rootsi keskosas, paljandub 20 m kivimeid alates Kambriumi Furongi ladestiku ülaosast kuni Kesk-Ordoviitsiumi Darriwili lademeni. Furongi esindab Alumi kilda kihistu, mis näitab settebasseini jätkuvat madaldumist kuni merepõhja kerkimiseni õhualustesse tingimustesse. Seega siin nagu ka paljudes muudes kohtades Lõuna-Rootsis markeerib mainitud ladestute piiri prominentne lünk. Närkes hõlmab see lünk intervalle alates 10. lademe keskosast kuni Tremadoci lõpuni või Flo lademe alguseni. Stromatoliitide esinemine viitab üsna madalmerelistele tingimustele hilises Kambriumis. Ordoviitsiumis esinevad horisontaalselt lasuvad "orthoceratiit-lubjakivi" kihid, mida klassifitseeritakse kui "Latorpi", "Lanna" ja "Holeni" topostratigraafilisi üksusi. Nende väga muutlik mikrofatsiaalne iseloom viitab settekeskkonna olulistele muutumistele, mis on suuresti tingitud mere veetaseme varieerumisest. Nähtav on kestev struktuuriosakeste terasuuruse ja fossiilikoosluste mitmekesisuse kasv. Fatsiaalsete muutuste tsüklilisuse sagedus viitab veetaseme muutuste kiirusele. Võrdlused analoogiliste sedimentatsiooniliste nähtustega mujal Rootsis kui ka Baltoskandias laiemalt näitab sama iseloomu kehtivust küllaltki laial alal.