Algae, calcitarchs and the Late Ordovician Baltic limestone facies of the Baltic Basin

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Abstract

The Late Ordovician succession of the Baltic Basin contains a characteristic fine-grained limestone, which is rich in calcareous green algae. This limestone occurs in surface outcrops and drill-cores in an extensive belt reaching from Sweden across the Baltic Sea to the Baltic countries. This limestone, which is known in the literature under several different lithological names, is described and interpreted, and the term “Baltic limestone facies” is suggested. The microfacies, from selected outcrops from the Åland Islands, Finland and Estonia, consists of calcareous green algae as the main skeletal component in a bioclastic mudstone-packstone lithology with a pure micritic matrix. Three types of calcitarch, which range in diameter from c. 100–180 µm, are common. Basinward, the youngest sections of the facies belt contain coral-stromatoporoid patch reefs and *Palaeoporella*-algal mounds. The Baltic limestone facies can be interpreted as representing the shallow part of an open-marine low-latitude carbonate platform.

Keywords Lithographic limestone · Shallow-water carbonates · Dasycladaceles · Calcitarch · Ordovician

Introduction

The Ordovician succession of the Baltic region is characterized by a drastic change from siliciclastic sediments and cold-water carbonates in the Early Ordovician to warm-water carbonates, with reefs and mud mounds, with little siliciclastic input, in the Late Ordovician. A unique and enigmatic lithofacies within the Late Ordovician warm-water carbonates consists of a dense, hard, stylolitic, fine-grained limestone, with a specific conchoidal fracture and very even texture. Commonly the limestone has been referred to as “calclutitic”, “aphanitic” or “lithographic” (e.g. Jaanusson and Martna 1948; Spjeldnæs and Nitecki 1994; Hints et al. 2005). It is best described as a fine-grained

bioclastic carbonate mudstone—packstone. Its most conspicuous and commonly most abundant skeletal elements are fragments of benthic green algae (e.g. Wiman 1893; Stolley 1896, 1897; Martna 1955; Huckle and Voigt 1967; Kozłowski and Kazmierczak 1968; Vingisaar 1971; Põlma 1972, 1982; Kõrts et al. 1990; Spjeldnæs and Nitecki 1994; Hints et al. 2005).

In view of its relatively wide spatial distribution (Fig. 1) and stratigraphic range (Fig. 2), and its widespread occurrence as erratic boulders across northern Europe, this lithofacies is known under various lithostratigraphical names, including Baltic or Östersjö limestone (Wiman 1893; Thorslund 1960), Knyckelkalk or Masur limestone (Warburg 1910), Ostseekalk or Paläoporellakalk (Huckle and Voigt 1967), Rägavere Formation (Hints and Meidla 1997), Saunja Formation (Männil 1958), and Slandrom limestone (Jaanusson and Martna 1948), and various units of the eastern Baltic Pirgu Stage, such as the Moe Formation (Hints et al. 2005). These names do not necessarily reflect well-defined lithostratigraphical units, but in some cases just denominate the characteristic lithology (as in Baltic limestone or *Palaeoporella* limestone).

Herein, the term “Baltic limestone facies” is used to cover all these names. Baltic limestone lithologies occur stratigraphically in an interval that ranges from the Keila

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Fig. 1 Map of Baltoscandia showing the maximum extent of the Baltic limestone facies and localities in southwestern Finland and Estonia discussed herein (based on Männil 1966; Winterhalter 1972; Jaanusson 1976; Raukas and Teedumäe 1997; Hints et al. 2005; Calner et al. 2010). Note: occurrences of the Slandrom Limestone in Sweden are not depicted for simplicity

Regional Stage (late Sandbian Stage) towards the higher Pirgu Stage (late Katian Stage or lowermost Hirnantian) (Fig. 2). They are stratigraphically most persistent in a wide belt, which reaches from Bothnian Bay and the Åland Islands in the west to northern Gotland in the south and the Saaremaa Island and central Estonia in the east (Fig. 1). The greatest extension of this facies towards the south was reached during the time of Nabala and Rakvere regional stages. During this time the Slandrom Formation extended as far west as to the Siljan area in central Sweden (e.g. Calner et al. 2010) and the Saunja Formation as far south as central Lithuania (Männil 1966).

One particular feature of the Baltic limestone facies is its proximity to mud mounds and reefs, which are especially widespread and thick during the Pirgu Stage (Kröger et al. 2016b) but are also reported from the Rakvere Stage, as in the Puhmu drill core from central Estonia (Kaljo et al. 2017). Notably, green algae such as *Palaeoporella*, *Vermiporella* and dasycladaceans are abundant in these structures and in some places they are the dominant skeletal element (Jux 1966; Kröger et al. 2016a, b).

Here, a microfacies analysis of limestone samples from selected localities from the Baltic limestone facies belt is presented. The aim of this study is to understand better the formation processes that led to the widespread deposition of pure limestones in the region. The potential role of algae in producing the Baltic limestone facies is investigated. Spherical calcareous microfossils, which have been mentioned but

not previously figured (Spjeldnæs and Nitecki 1994: p. 270), are abundant in some samples. These fossils are determined as calcitarchs and interpreted as algal spores. Calcitarchs are spherical calcareous microfossils (< 550 µm) of unknown and varied biological affinities, previously often subsumed under the more diffuse and less well defined term “calci-sphere” (Versteegh et al. 2009). They have been implicated in regional-scale micrite production in later Palaeozoic marine basins, and here we assess the possibility that they were important carbonate sources in the Ordovician Baltic Basin.

Material and sampling

All samples are from Late Ordovician limestones of the pericratonic Baltic Basin, of northeastern Europe. The basin is situated between the Scandinavian shield in the present north and the Sarmatian shield in the present south (Sliaupa et al. 2006) and records a thick early Palaeozoic succession. The Ordovician sediments of the basin have been spatially subdivided by faunal and lithological differences into a number of zones, termed “confacies belts” (Männil 1966; Jaanusson 1976). The confacies belts roughly correspond to the spatial lithofacies distribution along a proximal—distal gradient (e.g. Männil 1966; Jaanusson 1982; Raukas and Teedumäe 1997; Harris et al. 2004; Kröger et al. 2016b). Samples examined here are from drill cores, surface outcrops and erratic boulders of the Åland Islands, Finland and from western and southern Estonia (Fig. 1).

A number of samples were analysed as polished surfaces, in thin-sections under optical light, and under scanning electron microscopy (SEM). For SEM analysis the samples were polished and slightly etched following the methods described in Munnecke et al. (2000).

Tranvik-Lumparn borehole nr. 6, Åland Islands, Finland

The drilling of this core took place during a mainly off-shore drilling campaign of the Partek company (now Nordkalk Oy Ab) in 1964, which produced c. 25 drill-cores from the Lumparn bay area. Core no. 6 was drilled in northern Lumparn Bay, ~ 250 m south of the tip of Tranviknäs (60°10'20.24"N, 20°9'55.55"E) and has been previously mentioned or briefly described (Merrill 1980; Tynni 1982). The core covers a thickness of 34.5 m, but the stratigraphy of the section cannot be resolved in detail because of a lack data.

The topmost beds of borehole no. 6 are composed of a nodular, reddish fine-grained limestone with a Baltic limestone lithology, rich in *Vermiporella* with ~ 1 mm diameter branched thalli. The succession contains several strongly

Fig. 2 Schematic overview on the geographic and stratigraphic extent of selected lithostratigraphic units of the Baltic limestone facies (based on Jaanusson and Martna 1948; Merrill 1980; Tynni 1982; Ainsaar 1991; Hints and Meidla 1997; Hints et al. 2005; Ebbestad

and Högström 2007; Calner et al. 2010). The hatched line marks non-established borders. Stars represent reef occurrences, filled stars with green algae present

brecciated horizons, which are almost mylonitic with cm-sized angular intraclasts. The reddish nodular Baltic limestone lithology ranges down to the base of the preserved part of the core at 33 m, where it is rich in recrystallized microgastropods and *Vermiporella* sp. Generally, the section represents a metre-scale to tens of metre-scale alternation between reddish, argillaceous and lime-rich sections with calcareous algal, gastropod mudstone—wackestone lithologies. Merrill (1980), who described conodonts from older sediments in the Lumparn drill-cores, found none in the drill-core no. 6 samples. Tynni (1982) described the long ranging (upper Haljala Regional Stage, Sandbian–Juuru Regional Stage, Rhuddanian) *Tasmanites* aff. *verrucosus* from 21.2 m as the only determinable acritarch and *Leiosphaeridia* from the argillaceous interval 21.8–19.9 m. In Estonia *Leiosphaeridia* is not known from Ordovician beds younger than the Keila Regional Stage (uppermost Sandbian) (which is traditionally used as a stratigraphically significant pattern, e.g. Hints et al. 2016), which gives an upper Sandbian (Jõhvi-Keila Stage) age constraint for the 21.2–19.9 m interval. An upper age constraint for borehole

no. 6 can be given from the nearby Tranvik-Lumparn borehole no. 7 and the Tranvik Udde outcrop, which produced *Amorphognathus superbis* zone, Rakvere-Nabala Regional Stage conodonts (Merrill 1980).

Erratic boulders from southwestern Finland

Pleistocene erratic boulders with Baltic limestone lithologies are among the most widespread and abundant type of Palaeozoic erratics in southwestern Finland. The age and dispersal of these boulders have been described in detail (Uutela 1989; Nölvak et al. 1995). Two types of Baltic limestone have been distinguished, an older yellowish-grey and a younger reddish-grey variant. A Rakvere Stage age was determined for both types of boulder based on acritarchs, chitinozoans and ostracods. Four samples have been collected from Åland Island: the Jomala area, samples A3, A5, from 60°9'32.90"N, 19°59'6.39"E; from Önningsby, sample A7 (= FMNH-P6698), from 60°07'01"N, 20°00'29.8"E; from Svibyvik, Mariehamn, sample A1, from 60°6'03"N, 19°55'23"E (Fig. 3a). Two samples came from Kustavi,

Fig. 3 Polished samples of examples of Baltic limestone facies. **a** Mudstone lithology, Baltic Limestone, Lumparn drillcore no. 6, Åland Islands, Finland, depth 11.70 m (sample Lump-6.11), early Katian. **b** Wacke-packstone lithology, sample Vm02, Võhma drill-core, Estonia, depth 220.55 m, Rakvere Stage, early Katian. Note the syndepositional cracks (see text for discussion). **c** Packstone lithology, sample Vm06, Võhma drill-core, Estonia, depth 218.78 m, Rakvere Stage, early Katian. Note the heavy bioturbation. Similar scale in all figures

Vakka-Suomen county, southwestern Finland, sample A6 (= FMNH-P23586), and A8 (= FMNH-P28717) from 60°32'42"N, 21°21'19"E. Boulders with macrofossils were selected. Sample A6 contains *Hedstroemina inaequiclina* (Alichova), which is known from Oandu and Rakvere Stage levels from Estonia (Hints et al. 2016). Samples A2, A5, and A8 contain *Hedstroemina* sp. The age of erratic boulder samples can only be approximated as between late Keila

to Nabala stages based on drill-core data (see above), brachiopod fossils and the few published analyses of similar boulders.

Hoitberg reef, Vormsi Island, Estonia

The Hoitberg reef is a natural surface outcrop in the centre of western Vormsi Island, Estonia, at 59°0'16"N, 23°10'58"E. The outcrop consists of an overgrown 5–10 m high elongate hill with a width of c. 30 m, length of c. 80–100 m, and a maximum expansion in NNW/SSE -direction. The reef is lithologically embedded within an algal-rich fine-grained limestone of the Moe Formation (Hints et al. 2005). Several large (metre-scale) blocks of the reef are exposed mostly on its northern part and provide insight into the composition of the reef core and flanks. The core consists of a coral-boundstone with a non-skeletal matrix content of 56–72%. The most abundant skeletal reef-builder is the heliotid tabulate *Eocatenipora*, which comprises 18–41% of the rock volume in the sampled areas. Stromatoporoids and bryozoans, mostly dendroid growth forms, were minor skeletal reef-builders with less than 5% of the rock volume. The matrix consists of mudstone—wackestone lithologies, in several places with a fenestral-microbial texture. The skeletal components of the matrix are *Vermiporella* algae and ostracods, calcitarchs, sponge spicules and bryozoan fragments are abundant.

Kaugatuma 509 borehole, Saaremaa Island, Estonia

The Kaugatuma 509 drill hole is situated close to the north-east coast of the Sõrve Peninsula at 58°7'25.572"N, 22°11'39.4794"E, on the southern Saaremaa Island, Estonia. The core is ~466 m deep and ranges from the Upper Silurian down to the Middle Ordovician. Parts of the Ordovician section have been previously described and figured (Põlma 1973; Oraspõld 1982; Oraspõld and Kala 1982; Nõlvak 1989; Kaljo 2001; Brenchley et al. 2003; Ainsaar et al. 2010). Herein, two samples are described: Kaug-2 from 411.38 m, Rägavere Formation, Rakvere Stage, and Kaug-3, 387.6 m from the upper part of the Saunja Formation, Nabala Stage. The top of the Keila Stage Kahula Formation at Kaugatuma 509 is a distinct hardground at 413.7 m, which marks an abrupt facies change from greenish-grey argillaceous wackestone toward a decimetre-scale intercalation of nodular fine-grained limestone and dark grey argillaceous interlayers of the Tõrremägi Member. The Tõrremägi Member grades toward the top into pure pale pinkish-grey nodular stylolitic, fine-grained limestone with a bioclastic mudstone-wackestone lithology. From 413.1 to 411.1 m a pure fine-grained limestone with bioclastic mudstone-wackestone lithology of the Piilse Member prevails. Its top, at 411.1 m, is a pyrite stained planar hardground with

distinct *Trypanites* burrows. Sample Kaug-2 is from 0.18 m below this hardground. The overlying Paekna Formation of the Nabala Stage is again an alternation of decimetre-scale intercalation of nodular fine-grained limestone and dark green argillaceous interlayers. The top of the Paekna Formation is relatively abrupt, with a hardground forming the base of the Saunja Formation at 407.4 m. The Saunja Formation consists of a massive, pure, pale pinkish-grey bioturbated stylolitic, fine-grained limestone with bioclastic mudstone-wackestone lithology; its top is a karstic, heavily burrowed and eroded surface at 387.1 m. Sample Kaug-3 is from 0.5 m below the top Saunja hardground.

Niibi trench, western Estonia

The outcrop is a shallow trench on both sides of the unpaved road that leads from Niibi hamlet to road 16,122, c. 150–400 m west of Niibi, Lääne county, western Estonia at 59°2′29.60″N, 23°39′28.89″E. The trench exposes the top of a number of small patch reefs, each with a maximum diameter of less than 5 m. Similar reefs also crop out on a fallow land ~ 50 m south of the road and have been described from a now nearly overgrown quarry ~ 180 m to the west of the road. Fossils collected from these and probably from other shallow reef outcrops in the direct vicinity have been described (Kaljo 1961; Nestor 1964; Klaamann 1966; Preobrazhensky and Klaamann 1975).

The reefs occur within the Moe Formation, Pirgu Stage, late Katian. Some of these patch reefs are covered and surrounded by a coarse, partly argillaceous greenish echinoderm packstone—echinoderm grainstone. The reefs themselves are composed of a matrix-rich coral-boundstone. The matrix has a skeletal mudstone—wackestone lithology, in several places with a fenestral-microbial texture. The dominant skeletal element of the boundstone is the heliotid coral *Eocatenipora* (see Klaamann 1966) and locally large colonies of *Sarcinula*. Stromatoporoid colonies are common (see Nestor 1964). The most abundant skeletal elements in the matrix are dasycladal green algae, echinoderm ossicles and fragments of bryozoan skeletons.

Valga 10 borehole, southern Estonia

The Valga 10 drill-hole is located in southern Estonia, near the Latvian border at 57°48′14.4″N, 26°04′39″E on the NE outskirts of the town of Valga. The section was described in detail in a monographic treatment (Põldvere 2001); it is 424.4 m deep and penetrates Quaternary, Devonian, Silurian and Ordovician sediments. Since 2001 individual sections of the core have been described and discussed in numerous publications from which a few are relevant herein because they give additional age constraints and lithological information (Ainsaar and Meidla 2001; Nõlvak and Bauert 2006;

Ainsaar et al. 2010). Sample Vg-1 is from 379.65 m, from 0.25 above the base of the Rägavere Formation, Rakvere Stage. The Rägavere Formation, ~ 6.7 m thick at Valga 10, is unconformity bounded and consists of greenish to brownish, wavy thin-bedded fine-grained limestone with a skeletal mudstone lithology, and with finely dispersed pyrite and dolomite mainly in its upper parts. The limestone is cracked and contains predominantly sub-centimetre to centimetre-thick sparite-filled veins which contain geopetal argillaceous crystal dolomitic silt (see also Ainsaar and Meidla 2001) which we interpret as palaeokarst following Calner et al. (2010).

Võhma borehole, central Estonia

The Võhma drill-hole is located south of the parish Võhma, Viljandi county, central Estonia, at 58°36′44.136″N, 25°33′34.056″E. The drill-core section is 438 m deep with a stratigraphic range from the Proterozoic crystalline basement up to the lower Silurian Adavere Stage. Parts of the section have been described in publications; most relevant are Oraspõld (1982) and Kröger et al. (2016a, b), which cover the parts of the Pirgu Stage. The Pirgu Stage is exceptional at the Võhma drill-core, because it exposes ~ 52 m of a *Palaeoporella* mud mound.

Here, seven samples, Vm01–Vm07, are analysed ranging stratigraphically from the Rakvere Stage to the upper part of the mound. The samples Vm02 and Vm06 are from 220.55 m and 218.78 m, Rakvere Stage, which ranges in the Võhma drill-core from 221.75 to 214.50 m (Fig. 3b, c). The position of the lower boundary of the Rakvere Stage is not fully resolved because the lithology grades from a predominantly argillaceous decimetre-scale intercalation of greenish-grey nodular fine-grained limestone and dark-grey argillaceous interlayers toward massive pinkish fine-grained limestone in a ~ 0.5 m interval. Here, the notebook no. 6 of Põlma (<http://geokogud.info/doi/10.15152/GEO.126>) is followed where the boundary is positioned at the base of the lowermost pinkish nodular fine-grained limestone bed. The upper boundary of the Rägavere Formation is a distinct, pyrite-stained hardground, which marks a sharp lithological boundary towards the more argillaceous greenish limestone of the Paekna Formation, Nabala Stage. The limestone of the Rägavere Formation is cracked at some levels and contains predominantly sub-centimetre to centimetre-thick sparite-filled veins containing partly gravitationally filled argillaceous crystal dolomitic silt which is interpreted as a palaeokarst following Calner et al. (2010). Samples from the algal-mud mound, Pirgu Stage, are from depths 144.20 m (Vm04), 155.37 m (Vm03), 160.15 (Vm07); 187.29 m (Vm01) and comprise the two key lithologies of the mound. Samples Vm01 and Vm03 are from fenestral, stromatactis-rich bioclastic wackestone—packstone lithologies and

Fig. 4 Calcitarchs and other spheroidal microfossils from the Baltic limestone facies, Katian Stage. **aa–ab** Type-I calcitarchs. **ac–ba** Type-II calcitarchs. **bb, bc, ca–eb** Type-III calcitarchs. Similar scale in all figures. **bd** Type-III lower right corner, *Apidium* sp. upper left corner. **ec–fb, fc, fd**, *Apidium* sp. **aa** from Valga 10 drill-core, Estonia, depth 379.65 m (sample Vg-1), Rakvere Stage. **ab** from Kaugatuma 509 drill-core, Estonia, depth 387.6 m (sample Kaug-3), Nabala Stage. **ac** from erratic boulder, Sviibyiken, Mariehamn, Åland islands, Finland (sample A1), early Katian. **ad, bc, ca, da, dd, eb** from Võhma drill-core, Estonia, depth 155.37 m (sample Vm03), algal-mud mound, Pirgu Stage. **ae, bb, bd, cb–cd, ea, ec, ed, fa, fb, fd** from Hoitberg reef, Vormsi island, Estonia (samples H4a–c), Pirgu Stage. **ba, ce, db, de** from Võhma drill-core, Estonia, depth 144.20 m (sample Vm04), algal-mud mound, Pirgu Stage. **dc** from Võhma drill-core, Estonia, depth 220.55 m (sample Vm02), Rakvere Stage. **fc** from Hoitberg reef, Vormsi island, Estonia (sample H3), Pirgu Stage

samples Vm04 and Vm07 represent originally algal-rich parts of the mound.

Results

Description of the calcitarchs

Type-I calcitarchs. Small spar-filled spheres, circular in cross-section, with no or a very thin wall. Diameter ~ 100 µm (median, 106 µm; 1. quantile, 80 µm; 3. quantile, 135 µm) (Figs. 4aa–ab, 5e, f). Occur predominantly in mudstone lithologies of the Baltic limestone facies.

Type-II calcitarchs. Small spheres with thin, simple wall. Diameter ~ 130 µm (median, 131 µm; 1. quantile, 103 µm; 3. quantile, 174 µm) (Fig. 4ad, ae, ba). Wall thickness ~ 0.05–0.15 of sphere diameter. Occur in most samples of the Baltic limestone facies and in the mounds and reefs.

Type-III calcitarchs. Spheres with wall with radially arranged structures. Diameter c. 180 µm (median, 182 µm; 1. quantile, 159 µm; 3. quantile, 207 µm) (Figs. 4bb–ec, 6a–d). This group comprises three subgroups. A first group has simple radial walls, c. 0.10–0.15 of sphere diameter. A second group has simple thick radial walls with thickness of > 0.2 of sphere diameter that form irregularly shaped internal cavities commonly with radial margins. A third group has a bilayered, thinner outer and thicker inner layer. Commonly the inner layer has twice the thickness of the outer layer. The three groups are not sharply distinguished and their determination depends on fine differences in preservation and the position of the cross section. Occur in most samples of the Baltic limestone facies and in the mounds and reefs. Type-III calcitarchs are most abundant in the reef and mound facies.

Description of the microfacies

Baltic limestone, Sandbian—early Katian. The samples from the Baltic limestone range in lithology from mudstone to packstone. The matrix is a very fine homogenous micrite with a weakly floccose texture (Fig. 7). Individual flakes have a size of < 50 µm and are composed of different grain sizes. Finely dispersed pyrite/limonite and organic matter occur in spots (< 1%).

The only non-matrix component in the mudstone lithology consists of round microspar dots (diameter < 50 µm) with diffuse margins and type-I calcitarchs (Figs. 3a, 5e). The skeletal wacke-packstone lithology contains abundant ostracod shell hush and fragments of *Moniliporella* sp. thalli (Fig. 5d). The thalli are partly strongly disintegrated and marginally micritized. Shell fragments of brachiopods, trilobites and echinoderms occur. The packstone lithology contains predominantly skeletal fragments of *Moniliporella* sp. and strongly disintegrated and marginally micritized fragments of *Vermiporella* sp. Few type-I and type-II calcitarchs occur.

Rägavere Formation, Rakvere Regional Stage, early Katian Stage. The samples from the Rägavere Formation range in lithology from mudstone to skeletal packstone. The matrix is similar to the Baltic limestone samples. The skeletal components of the mudstone (sample Vg-1, Fig. 5f) are rare type-I calcitarchs, disintegrated shell fragments of ostracods and monaxial and triaxial sponge spicules. In the wacke-packstone (sample Vm02, Figs. 3b, 5b), dasyclad algae (*Moniliporella* sp.) are predominant; disintegrated ostracod shell fragments and microgastropods are abundant and a few echinoderm ossicles occur. Type-I and type-III calcitarchs are rare. The sample Vm06 (Figs. 3c, 5a) has a skeletal packstone lithology with c. 50% fragments of green algal skeletons. Fragments of thalli of *Vermiporella* sp. are predominant, *Moniliporella* sp. are second abundant. The partly strongly disintegrated fragments are marginally micritized to different degrees. Ostracod shell hash, microgastropods and echinoderm ossicles occur. Type-I and type-II calcitarchs, and brachiopod shell fragments are rare.

Saunja Formation, Nabala Regional Stage, early Katian Stage. Two samples from the Saunja Formation were analysed (samples Kaug-2, Kaug-3) with mudstone–packstone lithologies. The matrix is similar to the Rägavere Formation samples. The mudstone contains only a few echinoderm ossicles and type-II calcitarchs. The skeletal components of the wacke-packstone lithologies contain predominantly fragments of *Moniliporella* sp. and strongly disintegrated

Fig. 5 Thin-sections of examples of Baltic limestone facies. **a** Packstone lithology from Võhma drill-core, Estonia, depth 218.78 m (sample Vm06), Rakvere Stage, early Katian. **b** Wacke-packstone lithology from Võhma drill-core, Estonia, depth 220.55 m (sample Vm02), Rakvere Stage, early Katian. **c** Wacke-packstone lithology from Kaugatuma 509 drill-core, Estonia, depth 411.38 m (sample Kaug-2), Nabala Stage. **d** Wacke-packstone lithology from erratic boulder, Svibyvik, Mariehamn, Åland islands, Finland (sample

A1), early Katian. **e** Mudstone lithology from Lumparn drill-core no. 6, Åland Islands, Finland, depth 11.70 m (sample Lump-6.11), Baltic Limestone, early Katian. **f** Mudstone lithology from Valga 10 drill-core, Estonia, depth 379.65 m (sample Vg-1), Rakvere Stage. Similar scale in all figures, except f. *cs* calcitarch, *e* echinoderm ossicle, *g* gastropod, *mp* *Monilipora* sp., *o* ostracod, *rc* rugose coral, *tr* trilobite, *um* unknown mollusc, *vp* *Vermiporella* sp

Vermiporella sp. Shell fragments of brachiopods and bryozoans occur; microgastropods and type-II calcitarchs are rare.

Algal-mud mound, Pirgu Regional Stage, late Katian Stage. The algal mound samples from Võhma comprise boundstone to skeletal packstone lithologies with a complex diagenetic history (Fig. 8a–d). The algal-thalli in the boundstone occur only as ghosts with original features preserved at the

micritized thallus margins. They are interpreted from size and shape as *Palaeoporella* sp. and contain gravitational infills of peloidal packstone of crystal silt to micrite, massive sparite and botryoidal cements. The matrix between the thalli ghosts is a peloidal micritic packstone with individual peloid size < 50 µm that contains abundant complete ostracods, bryozoan and echinoderm fragments. Type-III calcitarchs are abundant and type-II calcitarchs occur in the matrix and partly in the infill. The packstone sample contains

Fig. 6 SEM images of the ultrastructure of the Baltic limestone facies, of calcitarchs, and of the microproblematic *Ovummurus duoportius* Minoura and Chitoku. All images are parallel to bedding surface. **a–e** Calcitarchs with shell consisting of radially arranged calcite crystals, some with pores (arrows). **a** *O. duoportius* preserved

within a calcitarch. **d** *O. duoportius*, detail of **a**. **f** Detail of the micritic matrix, from Valga 10 drill-core, Estonia, depth 379.65 m (sample Vg-1), Rakvere Stage. Note the common pores within the micrite crystals. **a–e** from Võhma drill-core, Estonia, depth 155.37 m (sample Vm03), algal-mud mound, Pirgu Stage

mostly echinoderm ossicles, fragmented recrystallized shells of molluscs and marginally micritized fragments of *Vermiporella* sp. and less abundant other dasycladaceans such as *Dasyporella* sp., *Moniliporella* sp. and *Mastopora* sp. Type-II and type-III calcitarchs are abundant. The occurrence of *Ovummurus duoportius* Minoura and Chitoku 1979, from a Pirgu-age algal-mud mound (Fig. 6a, e, sample Vm03) is,

to our knowledge, the oldest record of the microproblematic family Ovummuridae (Munnecke et al. 2000).

Coral-stromatoporoid reefs, Pirgu regional stage, late Katian. The samples from the Hoitberg reef are boundstone to packstone lithologies with the tabulate *Eocatenipora vormsiense* Klaamann, as the main skeletal component and

Fig. 7 Close-up of micritic matrix of limestone from Rakvere Stage, Valga 10 drill-core, Estonia, depth 379.65 m (sample Vg-1)

abundant fragments of bryozoans and ostracod shells as secondary skeletal components (Fig. 8e–f). The matrix of the boundstone consists of a mudstone-wackestone lithology with a clotted fabric and partly with irregular fenestrae that are filled with sparite and a gravitational micritic infill. Type-II and type-III calcitarchs occur. Notably patches and individual thalli of questionable *Apidium* sp. occur in this matrix. The intraclastic, fenestral packstone lithology is rich in fragments of dasycladaceans, predominantly *Vermiporella* sp. Type-II and type-III calcitarchs occur. Similar skeletal components and calcitarchs occur also in the matrix of the boundstone and packstone lithologies of the Niibi reefs.

Interpretation

The micritic matrix of the Baltic limestone facies

One of the distinctive features of the Baltic limestone facies is its fine-grained, homogenous micritic matrix. In macroscopic view, patches commonly occur with different colours between pink and yellow, probably tracing bioturbation patterns. These patches are caused by differences in organic matter and skeletal content, or the distribution of finely dispersed pyrite and locally by the occurrence of dolomite, all probably related to minor differences in original porosity. In thin-section, centimetre-sized burrows are commonly preserved with perfect circular cross-sections in a horizontal or subhorizontal direction, which indicate little or no diagenetic compaction of the limestone and hence early lithification. Early lithification is also indicated by swiss-cheese karst features crossing down from the top Rägavere and top Saunja formation surfaces, respectively, and from the uncompressed fossils themselves. Under high magnification the micritic

matrix commonly shows flake-like, angular patches or lumps with sizes of less than 50 µm consisting of µm-sized clusters of micrite crystals.

The relatively high abundance of non-disintegrated, marginally micritized dasycladacean thalli among the skeletal fragments in the limestones is evidence for a shallow-water environment with a depositional depth of less than 25 m within the shallow euphotic zone (Granier 2012). This is an environment in which other calcareous green algae could have flourished with less rigid skeletons, such as *Acetabularia*. Recent calcareous green algae are known to produce 750 g CaCO₃/m² (*Acetabularia*, Marszalek 1975) to up to 2400 g CaCO₃/m² (Freile et al. 1995). Under SEM several micritic samples exhibit a microporous texture, which is very similar to the one described in Lasemi and Sandberg (1984) and Munnecke et al. (1997), probably representing relics of aragonite needles within a µm-range, and which can be interpreted as representing a texture of an original aragonite-dominated lime-mud (Fig. 6f).

It is, therefore, coherent to assume a green algal, aragonitic origin and rapid recrystallisation of the micritic matrix of the Baltic limestone facies analogous to the diagenetic process known from recent aragonite-dominated tropical platform sediments (Munnecke et al. 1997). Our interpretation is also in accordance with the long-standing opinion that the appearance of a widespread micrite-rich limestone facies is related to the palaeogeographical drift of the Baltica continent toward lower latitudes and warmer climatic conditions (Dronov and Rozhnov 2007; see also Nestor and Einasto 1997).

Comparison and interpretation of Late Ordovician calcitarchs

Few descriptions of Palaeozoic calcitarch occurrences exist. The specimens described and figured herein are unique and differ from previously described forms in terms of size and partly in wall structure. The spores found in situ in the thalli of Late Ordovician *Vermiporella* sp. are smaller (~ 35 µm, Kozłowski and Kazmierczak 1968). The spherical microfossils from the Silurian Visby and Höglint formations are also generally smaller (< 100 µm, Munnecke and Servais 2008; Servais et al. 2009). The simple-walled spherical microfossils described from the Devonian Choteč and Třebotov formations are similar in general appearance and structure to our type-II calcitarchs but are also smaller (80–120 µm, Berkýová and Munnecke 2010). Late Palaeozoic radiospheres (Kazmierczak and Kremer 2005) differ in having external spines.

The calcitarchs described herein, show no signs of organic walls in thin-section or under SEM observation and, therefore, cannot be interpreted as calcified acritarchs. However, all three calcitarch groups distinguished herein are

Fig. 8 Thin-sections of examples of reef limestone from reefs and mounds of Pirgu age, late Katian, Estonia. **a, b** *Palaeoporella* boundstone from Võhma drill-core, Estonia, depth 160.15 m (sample Vm07) **c** *Palaeoporella* boundstone from Võhma drill-core, Estonia, depth 144.20 m (sample Vm04). **d** skeletal intraclastic packstone from Võhma drill-core, Estonia, depth 155.37 m (sample Vm03). **e**

Eocatenipora boundstone with *Apidium* sp. (sample H4c). **f** fenestral intraclastic packstone from Hoitberg reef, Vormsi island, Estonia (sample H3). *ap* *Apidium* sp., *bryo* bryozoa indet., *cs* calcitarch, *dc* dasycladal algae indet., *e* echinoderm ossicle, *ms* *Mastopora* sp., *rc* rugose coral, *vp* *Vermiporella* sp

close to the size range known from recent calcified spherical non-motile asexual spores (aplanospores) of chlorophyceans, such as *Acetabularia* (140–185 µm, Marszałek 1975). Notably, all these Ordovician calcitarchs co-occur with green algae and have their mass occurrences, where green algae are abundant. This co-occurrence is not a taphonomic effect

of preferred preservation within specifically fine-grained micritic matrix, because calcitarchs occur also in peloidal and intraclastic packstones of the algal-rich reef facies (see above).

The calcitarchs, described herein, occur together with calcified green algae as the most conspicuous skeletal

component of the Baltic limestone facies and its associated reefs. It appears likely that the calcitarchs described herein are aplanospores of various green algae, probably of taxa that are not preserved as articulated fossils, like the fast disintegrating *Acetabularia*. This interpretation is in accordance with the idea that the characteristic fine-grained and homogenous micritic matrix of the Baltic limestone facies originated from aragonitic algal mud.

Comparison of the Baltic limestone facies with similar Palaeozoic carbonates elsewhere

Probably the most similar facies to the Baltic limestone facies can be found in the algal-rich platform carbonates of the Ordos-Basin (northwest China) within the early Katian Beiguoshan Formation (Zheng et al. 2018). Zheng et al. (2018) described a situation with coral-stromatoporoid patch reefs, a platform margin-reef belt and micritic carbonates in a back-reef shallow-water environment, which is rich in dasycladaceans, other green algae, gastropods and crinoids.

Algal-rich massive limestone deposits, algal mounds and reefs are also described from the Katian Lianglitage Formation of the western Tarim Basin (northwest China) and are interpreted as tropical shallow-water carbonates (Zhang et al. 2014; Shen and Neuweiler 2016). Notably the Ordos Basin and the Tarim Basin carbonates contain *Vermiporella* sp. as the dominant algal constituent, similar to the Baltic limestone facies. Calcitarchs are not described from these northwest China carbonate platforms.

They are described from the micritic limestone of the marl-limestone alternations of the Upper Visby and Högklint formations (latest Llandovery to early Wenlock, Munnecke et al. 1999; Servais et al. 2009). These occurrences are also from a shallow tropical carbonate environment with small patch reefs but differ in lacking the abundant green algal component and in being generally more argillaceous than the massive and pure Baltic limestone facies. The calcitarch bearing Devonian Choteč and Třebotov formations represent different depositional environments ranging from relatively deep to extremely shallow, and do not contain reefs, mounds or green algae.

In conclusion, the Baltic limestone facies appears to be related to time-equivalent tropical shallow platform carbonates, probably reflecting primarily similar climatic conditions such as high temperatures and extremely low terrigenous sediment input.

Conclusions

Along the eastern and northeastern margin of the Baltic Basin a wide facies-belt developed during the Late Ordovician, characterised by an extremely pure limestone with

a fine homogenous micritic matrix. The limestone is rich in dasycladacean algae and contains abundant calcitarchs. This algal-rich micritic limestone which comprises several regional chronostratigraphic zones and lithostratigraphic units is combined under the new term “Baltic limestone facies”. Three types of calcitarchs and a number of genera of green algae (*Apidium* sp., *Dasyporella* sp., *Mastipora* sp., *Moniliporella*, *Vermiporella* sp.) can be distinguished within the samples analysed in our study. The dasycladaceans indicate an original deposition of the limestone within the shallow euphotic and euryhaline zone under low-latitude climatic conditions. Basinward the limestone contains coral-stromatoporoid patch reefs and *Palaeoporella*-algal mounds. The Baltic limestone facies can be interpreted as representing the shallower part of an open-marine carbonate platform.

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