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The *Girvanella* oncoids from Upper Ordovician deposits in northern Estonia - evidence of the beginning of microbial carbonate factory prior to the Hirnantian glaciation in Baltica.

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Abstract: Oncoids are widespread components of Phanerozoic carbonate systems, however, their occurrence in the Ordovician of Baltoscandia has remained poorly documented. This study presents the first detailed description of oncoids from the Upper Ordovician (Katian–Hirnantian) of Estonia, based on a unique historical collection assembled over nearly three decades by the Estonian scientist L. Põlma that has not previously been available for detailed scientific analysis. The material originates from northern and central Estonia. Macroscopically, the oncoids occur within lenticular interlayers of oncolitic grainstones and are predominantly spheroidal to ellipsoidal in shape, with typical diameters of 1–2 cm and rare specimens reaching up to 10 cm. Petrographic analysis indicates that the oncoids belong to the porostromatic type. Well-preserved filamentous and tubular microstructures attributable to the calcareous cyanobacteria *Girvanella* were identified. Oncoid nuclei consist mainly of strongly micritized fragments of skeletal fauna. The extreme rarity of oncoids in the Katian–Hirnantian successions of Estonia is interpreted not as an environmental limitation, but rather as a consequence of preservation bias related to platform morphology and sediment bypass on Ordovician shoals. The association of *Girvanella* oncoids with peloids and cortoids indicates an intense microbial activity and suggests the operation of a microbial carbonate factory on shallow, high-energy platform highs prior to the Hirnantian glaciation. These findings provide new insights into Late Ordovician carbonate production on the Baltoscandian platform and highlight the importance of unique legacy collections for reconstructing underrepresented depositional environments.

Keywords: Ordovician; oncoids; microbial carbonate factory; *Girvanella*; Baltica; microbialites

Introduction

Oncoids are rounded, coated grains characterized by a nucleus, commonly a fossil fragment, surrounded by a thick cortex composed of irregular, non-concentric micritic laminae. Unlike ooids, they do not exhibit a systematic increase in sphericity during growth (Flügel, 2010). Their common size ranges from <1 mm to a few decimeters, however that some authors define them as coated grains commonly larger than 2 mm in diameter (Tucker and Wright, 1990). Based on the internal fabric and microstructural characteristics, oncoids are traditionally subdivided into two principal morphological types: spongiostromatic and porostromatic forms (Peryt, 1981; Monty, 1981). Spongiostromata comprise nodules or heads with clearly defined growth forms but lacking, or only rarely preserving, preserved organic microstructures. In contrast, porostromata display well-preserved tubular or filamentous microstructures (Flügel, 2010). Among porostromatic oncoids (cyanoids), calcareous cyanobacteria of the genus *Girvanella* are particularly common (Peryt, 1981).

Oncoids can be formed by different species, but the dominant biota are usually microbes, algae, calcified cyanobacteria, and, rarely, encrusting foraminifera, as well as their associations (Flügel, 1982; 2010). Due to the prevalence of microbial and calcified cyanobacterial origin of oncoids, several authors (e.g. Peryt, 1981; Riding, 2000; Whalen et al. 2002; Olivier et al, 2011) consider them as a type of microbialites. Oncoids are widespread in the geological record being widely dispersed in time and facies (e.g. Maslov, 1960; Zhuravleva, 1964; Dahanayake, 1978; Peryt, 1981; Flugel, 2010; Sequero et al, 2020; Zafar et al, 2024; Akbaş, 2025). Furthermore, oncoids are a common type of carbonate grain used for paleoenvironmental reconstructions, as their morphology, size, and internal structure are controlled by a variety of environmental factors (e.g. Dahanayake, 1977; 1978; Flugel, 2010; Sequero et al, 2020). Although oncoids generally occur in shallow-marine deposits in a wide range of environments with different hydrodynamic regimes, from intertidal, lagoon, shoal to open-marine settings (e.g. Zhuravleva, 1964; Gaśiewicz, 1983; Shi and Chen, 2006; Han et al, 2007; Védrine et al, 2007; Yuehua et al, 2010; Sequero et al, 2019; 2020; Zhu, 2024; Zafar et al, 2024; Akbaş, 2025; Lykov et al, 2025) — they have also been reported from deeper-water environments at depths of approximately 100–150 m (Gygi, 1992; Cozar et al, 2003). In addition, oncoids are characteristic components of reefal systems, where they may form in close association with build-ups (Olivier et al., 2011; Pederson, 2015).

In the Baltoscandian region, oncoids are well documented in the scientific literature from the Silurian period onward (e.g. Radionova and Einasto, 1986; 1988; Kõrts, 1991; Qvarnström, 2012), in the Phanerozoic. The only previously published record of oncoids in the Ordovician deposits of Baltoscandia is a brief reference by L. Põlma (1982), who noted their presence without providing a detailed description. In this paper, we present the first detailed description of oncoids from Upper Ordovician deposits of Baltoscandia, focusing on their material composition and petrographic characteristics, and discuss possible mechanisms of their formation within a regional paleoenvironmental framework.

Geological background and locality

During the Katian and Hirnantian stages of the Late Ordovician, the area of present-day Estonia was submerged beneath a shallow epicontinental sea that covered much of the Baltoscandian region. This sea was wide, low-gradient, and connected to the global ocean system, allowing marine conditions to prevail across northern and central Estonia for an extended interval. The sedimentary succession deposited during this time is dominated by carbonate rocks, reflecting warm-water marine environments with a limited siliciclastic input. These limestones and related

facies are characteristic of a carbonate platform setting typical of low-latitude seas (Hints and Meidla 1997; Kröger 2007).

The Katian and Hirnantian Baltic Basin was located in the tropics (Torsvik and Cocks 2013). As warming intensified in the early Katian, carbonate accumulation increased markedly (Nestor and Einasto 1997). Enhanced productivity of carbonate-secreting organisms, together with favorable chemical conditions in warm, shallow waters, led to thicker and more laterally extensive carbonate successions. These deposits indicate relatively stable platform conditions, where accommodation space and sediment supply were broadly balanced. The reduction of terrigenous input further promoted the dominance of carbonate lithologies across the region (Nestor and Einasto 1997).

These environmental shifts were closely followed by biotic changes. Faunal assemblage characteristic of tropical settings began to appear in the early Katian, marking a clear ecological transition (Nestor and Einasto 1997). Organisms such as tabulate corals and stromatoporoids, which thrive in warm, shallow, well-lit waters, became increasingly common. By the Hirnantian, these tropical faunal elements were widely distributed across the Estonian shelf, forming important components of reefal and peri-reefal communities (Nestor and Einasto 1997).

Vasalemma quarry (Fig. 1) is located in northwestern Estonia, immediately to the west of the Keila–Riisipere railway line. Quarrying activities expose carbonate rocks of the Vasalemma Formation, which are extracted down to the uneven, ripple-marked upper surface of the Pääsküla Member belonging to the Kahula Formation. This stratigraphic contact provides a clear sedimentological marker within the quarry walls.



Figure 1 Localities: 1) Vasalemma quarry, 2) V-1026 borehole, 3) Röa quarry, and 4) Võhma borehole. The author of the map is Gennadi Baranov.

The Vasalemma Formation is composed predominantly of biodetrital grainstones and reaches a maximum thickness of approximately 15 m. These grainstones are interspersed with numerous reefal bodies that vary in internal composition and structure. The reefs include bryozoan framestone–bindstone, echinoderm-rich bindstone, mixed receptaculitid–bryozoan–microbial framestone, and tabulate coral bafflestone. Individual reef bodies are laterally extensive and may exceed 50 m. in diameter, indicating a sustained and localized carbonate production on the shelf (Kröger et al. 2014).

Chemostratigraphically, the middle to upper portion of the Vasalemma Formation coincides with the early Katian Guttenberg carbon isotope excursion (GICE). According to sequence-stratigraphic interpretations, reef development within the formation occurred under generally lowered sea-level conditions. Initial reef growth took place during a lowstand phase, followed by a partial onlap as relative sea level began to rise. Ultimately, the reefs were terminated and submerged around the time of transition from the latest Oandu to the earliest Rakvere stages (Kröger et al. 2014). More specifically, reef construction in the Vasalemma Formation corresponds to the early phase of the GICE, which forms part of a highstand systems tract within a broader late Sandbian to early Katian depositional cycle. Reef growth was abruptly halted during the Frognekilen Lowstand Event, which occurred in the latest Keila to earliest Katian time slice. During this interval, some reef structures experienced subaerial exposure, indicating a temporary but significant drop in relative sea level (Kröger et al. 2014).

Following this interruption, the inactive reef bodies were rapidly drowned during the subsequent Nakkholmen Drowning Event in the Oandu and Rakvere stages. This rapid deepening prevented renewed reef growth and led to the preservation of the reef framework beneath younger sediments. Spatially, the reefs formed a relatively narrow belt on the shelf, positioned along the southern margin of a shallow local basin that opened toward the northwest (Kröger et al. 2014).

The pronounced development of reefs during the GICE interval suggests that environmental conditions at that time were particularly favorable for reef-building communities. This reef proliferation is most plausibly linked to an increase in nutrient availability across the carbonate platform, which would have enhanced biological productivity and supported the growth of complex reef ecosystems over a short but distinctive stratigraphic interval (Kröger et al. 2014).

Röa quarry (Fig. 1) showed the most complete section (Fig. 2) of the dolomites of the Röa Member (Porkuni Regional Stage, Hirnantian) and was exposed in a quarry near the Röa-Jaagupi farmstead. The quarry is located along the Tallinn–Viljandi highway, immediately to the east of the road, on the northern slope of a low, gently dipping cuesta-like elevation (Rõõmusoks, 1991). The quarry was backfilled in the late 1960s. In 1948, it was possible to measure a section up to 2.61 m thick in the deeper part of the quarry (Rõõmusoks 1991):

– 1.20 m of yellowish-gray, hard dolomite;

– 0.60 m of brownish-gray dolomitized limestone;

– 0.04 m of brownish-gray marl;

– 0.77 m of strongly dolomitized, yellowish-gray limestone.

In the eastern part of the quarry, the lowermost beds of the Vohilaid Member are exposed, with a thickness of 0.4 m. These beds consist of light-gray, clastic detrital limestones. Beneath them, the uppermost part of the Röa Member is exposed, composed of yellowish-gray dolomite similar to unit 1 of the previously described section, with a thickness of 0.4 m. The boundary between the Röa and Vohilaid members is relatively sharp from a lithological point of view (Rõõmusoks1991).

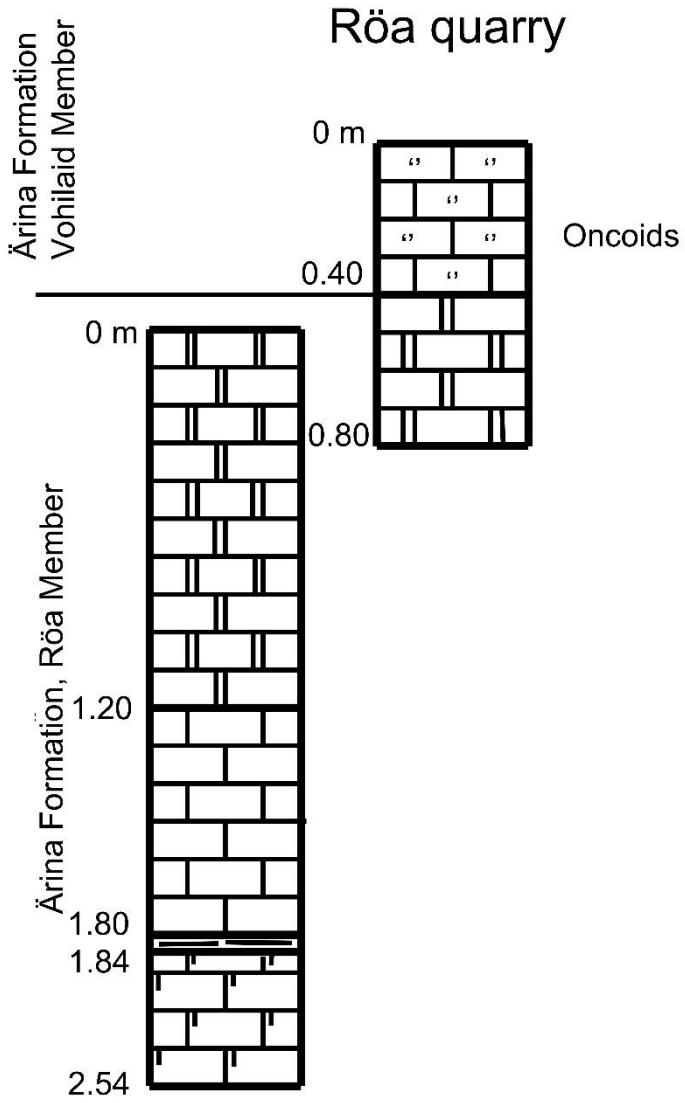


Figure 2. Section of the former Röa quarry (According to data by Rõõmusoks 1991),

Material and Methods

All the material on Ordovician oncoids was collected by the Estonian geologist L. Põlma (Fig. 3) over 27 years of research. The collection was transferred to the Geological Institute of the Russian Academy of Sciences on March 22, 1985; however, due to various circumstances, this material was subsequently lost to the scientific community within the extensive collections of the Institute.

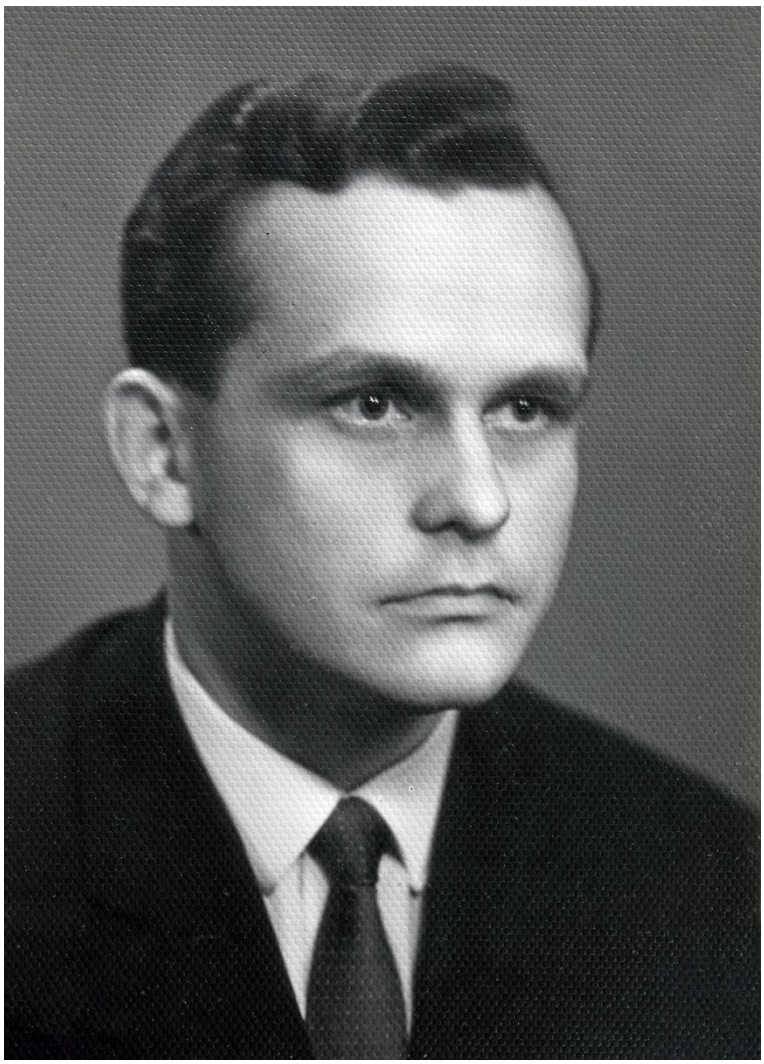


Figure. 3 Lembit Põlma (1934–1988) Estonian geologist and lithologist, a specialist in Ordovician carbonate rocks of Baltoscandia. He worked at the Institute of Geology of the Estonian Academy of Sciences and made significant contributions to the study of Ordovician stratigraphy and carbonate lithology of the Baltic region.

The collection comprises samples from drill cores and outcrops in central and northern Estonia. Material from the Röa outcrop (northern Estonia; Porkuni Regional Stage, Hirnantian) includes four macro samples, two polished slabs, and three thin sections (2.5 × 2.5 cm). One sample derives from the Võhma drill core (central Estonia) at a depth of 130.4 m (Hirnantian). In addition, one polished slab originates from the Vasalemma quarry (northern Estonia; Oandu Regional Stage, lower Katian). Another macro sample was obtained from the nearby V-1026 drill core at a depth of 5.5 m (Keila Regional Stage, lowermost Katian) (Fig. 4).

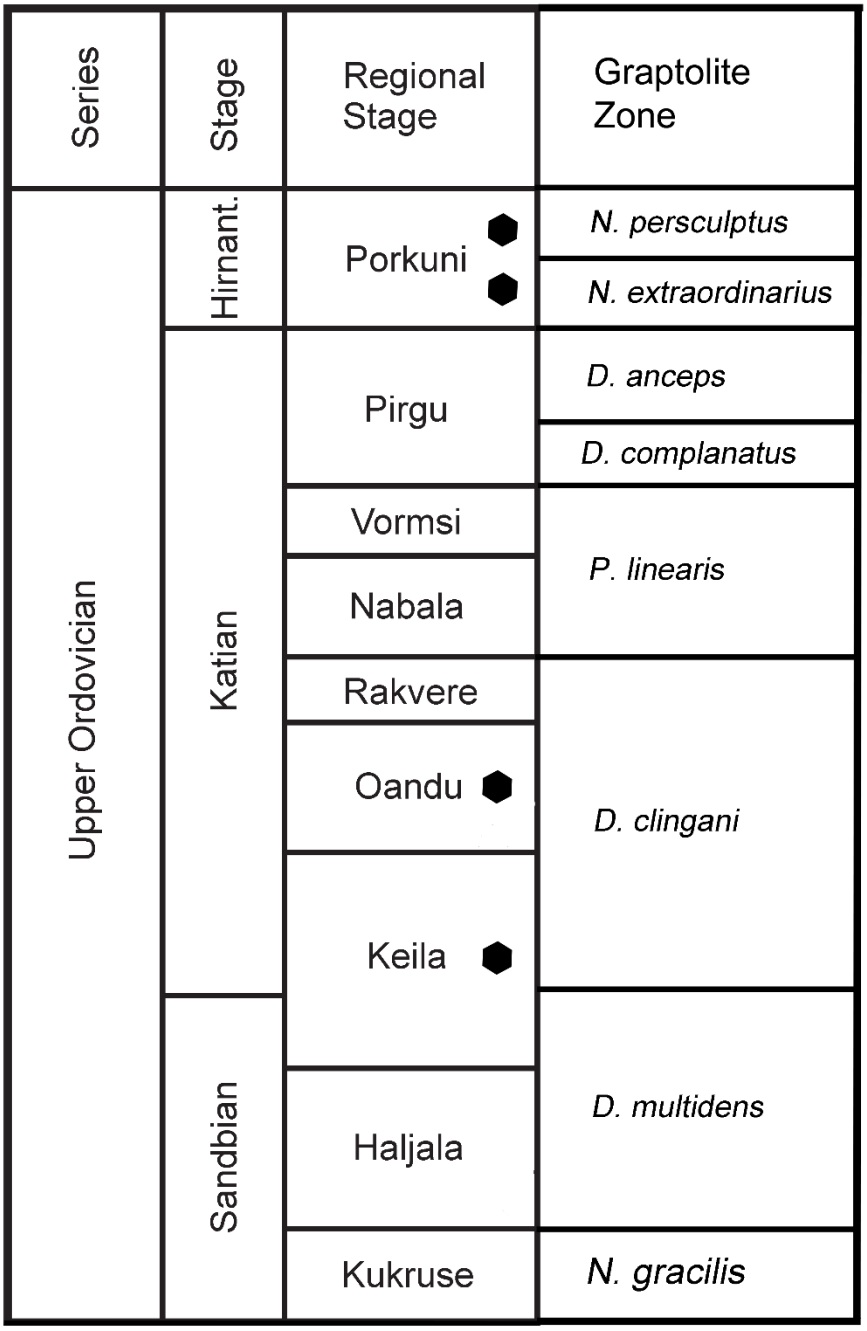


Figure 4. Stratigraphy of oncoids in the Late Ordovician of Estonia. Location of samples shown by polygons.

All samples were preliminarily studied under a binocular microscope, and the available thin sections were studied under a light microscope, BioOptic CP-400, to identify the main textural and structural features of oncolites (sedimentary rocks composed of oncoids according to Teichert (1970)). Microphotographs were captured using a 6.3 Mpx, USB 3.0 Aptina camera. When describing the thin sections, the names of the formal components were given according to the methodological literature on carbonate rocks (Scholle and Ulmer-Scholle, 2003; Flügel, 2010).

Results

Oncoids are found in interlayers (lenses) of limestones (Fig. 5). According to Dunham classification, these rocks can be defined as grainstones (oncolites), as most of the components are sand-sized, and carbonate mud is absent from the rock matrix. Components larger than 2 mm are less than 10%. They are represented by oncoids, intraclasts, and coated shells of different fossils (Fig. 5,6). The most common size of oncoids is 1-2 cm in diameter. The largest oncolite was found in the Vasalemma quarry. Its diameter is up to 10 cm. All oncoids have spheroidal and ellipsoidal shapes. On some of them, several generations of newly formed layers indicate possible redeposition (Fig. 5).

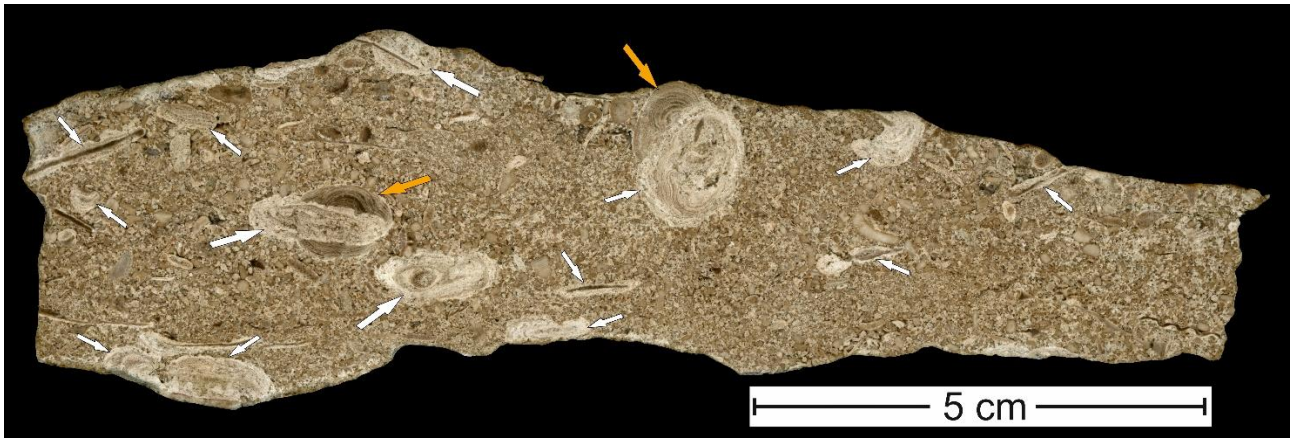


Figure 5 The Polished slab with *Girvanella* oncoids (cyanoids) highlighted by arrows. White arrows indicate the oncoids, orange arrows indicate the with several generations of layer formation.

In thin sections (Fig. 6) the studied samples are predominantly composed of sandy-sized cortoids and peloids, which together constitute up to approximately 80% of the rock volume. The remaining components include micritized bioclasts larger than 1 mm, with or without micritic envelopes, represented mainly by bryozoans, bivalve molluscs, intraclasts, and subordinate oncoids. In most cases, the nuclei of cortoids are poorly preserved or indistinct; where discernable, they consist of fragmentary remains of bryozoans, molluscs, algae, brachiopods, and, less often, ostracods. Intergranular spaces are consistently filled with sparry calcite cement, which is present in all the investigated samples. The described microfacies shows a close correspondence to the Standard Microfacies Type SMF 11 (Coated bioclastic grainstone with sparry cement) sensu E. Flügel (2010).

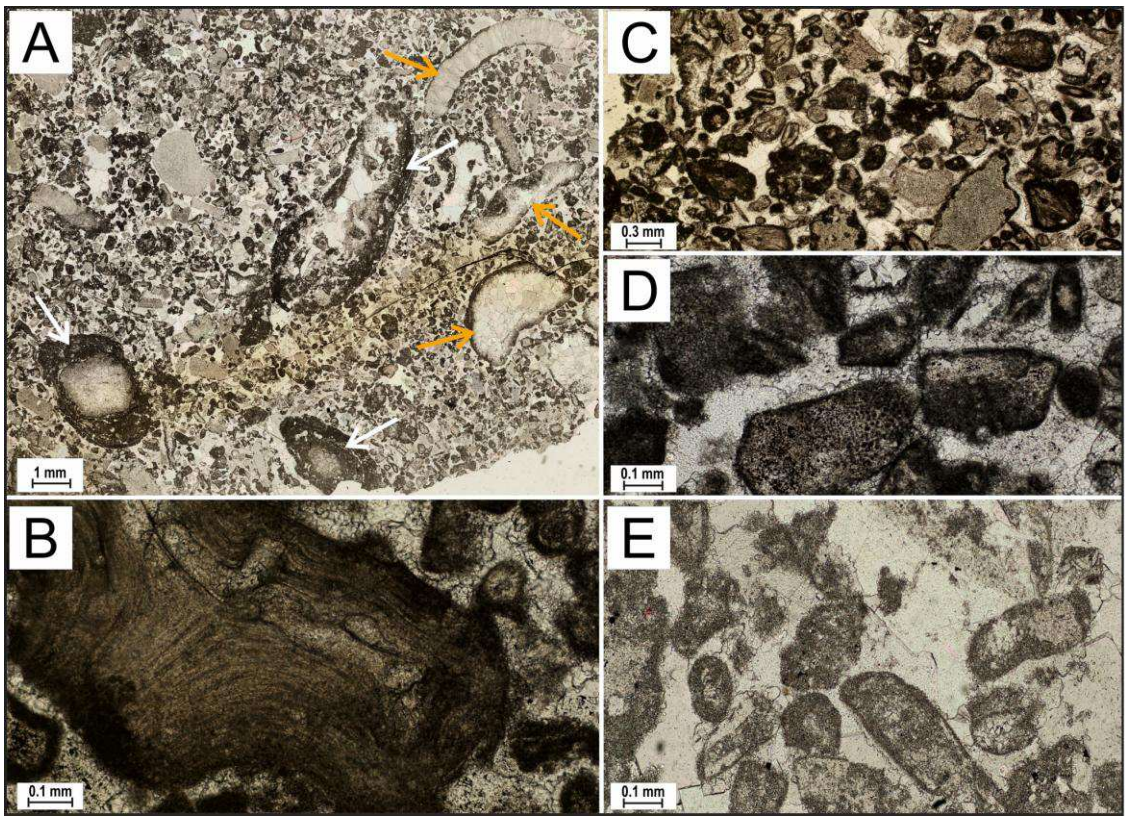


Figure 6 Microphotographs of studied limestones with oncoids. A. General view of polybioclastic limestone with *Girvanella* oncoids (cyanoids) highlighted by white arrows; large cortoids (micrite envelopes around skeletal grains sizes from 1 mm) by orange arrows. B. Algae cortoid. C. Cortoids and peloids in sparite matrix. Skeletal grains are generally poorly preserved; however, they contain discernable fragments of bryozoans, crinoids, and mollusks. D. Crinoids with micrite envelopes (cortoids) and peloids in sparite matrix. E. Poorly preserved skeletal grains with micrite envelopes (cortoids) in sparite matrix.

The studied oncoids in thin sections (Fig. 7) exhibit predominantly spheroidal to ellipsoidal shapes, commonly reflecting the morphology of the bioclastic nuclei from which they developed. In most specimens, the nuclei are poorly preserved or indistinct due to intense micritization; however, in some cases, large skeletal fragments of brachiopods, bryozoans, and crinoids can be clearly identified (Fig. 7 B, E). The cortices of the oncoids consist of irregularly developed, non-concentric micritic laminae showing a porostromatic fabric (Fig. 7 A-E). Well-preserved filamentous and tubular microstructures attributable to calcareous cyanobacteria of the genus *Girvanella* are locally visible within the laminae (Fig. 7 F, G). The laminated cortices are characterized by abundant primary porosity in the form of small, irregular pores and cavities (Fig. 7 C, D) that are commonly filled with clear sparry calcite cement.

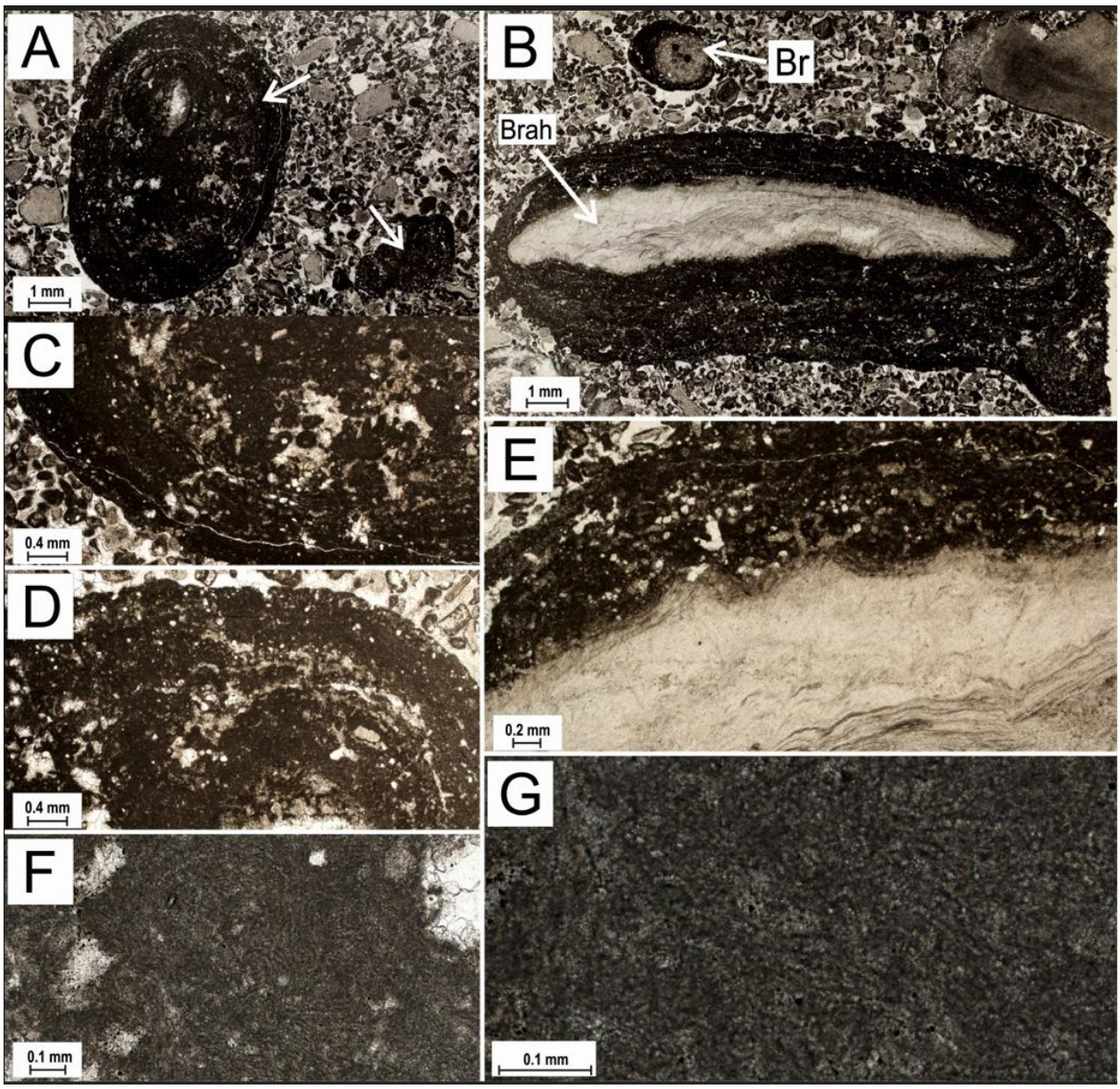


Figure 7 Microphotographs of studied oncoids. A. Spheroidal *Girvanella* oncoids highlighted by white arrows. B. Spheroidal *Girvanella* oncoids with highlighted bryozoan (Br) bioclast in its nuclei by white arrow and ellipsoidal *Girvanella* oncoids with highlighted brachiopoda (Brah) bioclast in its nuclei by white arrow. C-D. Micritic crust of spherical oncoids with numerous calcite-filled pores. E. Micritic crust of ellipsoidal oncoids from B. F-G. *Girvanella* porostromatic fabric of the studied oncoids.

Discussion

In the Silurian of the Baltic Basin, oncolites are a characteristic and relatively common sedimentary feature, especially in Wenlock (Kaljo 1970; Einasto 1962), reflecting the specific environmental conditions under which they formed. Oncolites typically develop in very shallow marine settings, particularly on shoals where water depths are minimal, and the hydrodynamic energy is high. Such environments are marked by constant agitation from waves and currents, which is essential for oncolite growth. The rolling motion of nuclei on the sea floor allows for the concentric accretion of microbial and carbonate laminae, producing the distinctive coated grains that define oncolites. In the Silurian Baltic Basin, these conditions were widespread and, crucially, the resulting shoal sediments were frequently preserved in the stratigraphic record (Kaljo 1970).

By contrast, oncolites are extremely rare in the Katian and Hirnantian (Late Ordovician) successions of Estonia. The scarcity can hardly reflect the lack of suitable climatic or broad depositional conditions, as the Ordovician Baltic Basin, like its Silurian successor, was situated in tropical latitudes and served as a carbonate platform. Warm water temperatures, high carbonate productivity, and generally low siliciclastic input prevailed during both periods (Nestor and Einasto 1997). Instead, the rarity of Katian oncolites is best explained by differences in the basin topography and sedimentation regime, which strongly influenced the preservation potential of the shallowest environments.

The shallowest parts of the Ordovician Baltic Basin—particularly shoals and wave-agitated platform highs - may be poorly represented or entirely absent from the preserved stratigraphic record (Nestor and Einasto 1997). These shoals may have functioned largely as non-depositional or erosional areas during the Katian. In high-energy settings, the sediment can be repeatedly reworked, transported away, or prevented from accumulating altogether. As a result, even if oncolites did form locally on Ordovician shoals, the lack of net sediment accumulation would have severely reduced their chances of preservation. Over geological timescales, such areas would leave little to no stratigraphic trace, creating an apparent absence of oncolites in the rock record. According to the results obtained, these hypothetical Ordovician shoals are characterized not only by the presence of *Girvanella* oncoids, but also by numerous peloids and cartoids. The latter are the products of microbial activity, which encrust detritus in the course of their life cycle (Flügel, 2010). Although the microbial origin of peloids is difficult to prove, based on studies of modern shallow-water environments where peloids are formed (Suosaari et al, 2022), it can be assumed that this statement also applies to the grains under consideration. Similar ideas about the possible microbial genesis of peloids in ancient deposits have been put forward by other authors (e.g. Adachi et al, 2004; Flügel, 2010; Lai et al, 2025). Everything mentioned above points to active microbial activity during carbonate accumulation, which could lead to the idea that these Ordovician shoals were an example of variation in the Microbial carbonate factory. This allows us to take a modern look at carbonate accumulation in the Late Ordovician period, since the very concept of carbonate factories is aimed at viewing this process as a unified system between seawater temperature and nutrient levels in the Earth system evolution (James and Jones, 2025).

In contrast, Silurian shoals in the Baltic Basin were more frequent sites of active sediment accumulation (Nestor and Einasto 1997). This suggests a change not so much in sediment supply but in basin morphology. A flatter or a more gently differentiated topography during the Silurian would have allowed shallow-water sediments to accumulate and be retained, even in high-energy settings. A slightly deeper accommodation space on shoals, or a more effective trapping of carbonate grains, would favor the preservation of oncolitic and other shallow-marine facies. Consequently, Silurian successions often include grainstones, packstones, and oncolite-bearing limestones that directly record these environments.

The difference between the Late Ordovician and Silurian records, therefore, most probably reflects contrasting platform architectures. During the Katian, the Baltic Basin may have been characterized by a more pronounced relief, with somewhat sharper bathymetric gradients between deeper shelf areas and elevated shoals. Such topography would enhance sediment bypass from shallow highs into deeper parts of the basin, leaving the shoals themselves underrepresented in preserved sections. During the Silurian, basin filling (Nestor and Einasto 1997) may have reduced this relief, promoting a more continuous sedimentation across the platform.

Conclusion

In summary, the extreme rarity of oncolites in the Late Ordovician of Estonia does not imply fundamentally different environmental or climatic conditions compared to the Silurian. Both intervals represent tropical carbonate platforms capable of supporting oncolite formation. Rather, the key controlling factor was the basin topography, which influenced sedimentation and preservation. The Ordovician shoals were likely the zones of non-sedimentation or erosion, whereas the Silurian shoals were more commonly the sites of sediment accumulation. This distinction underscores the importance of preservation bias in interpreting the sedimentary record and cautions against equating the absence of evidence with evidence of absence in paleoenvironmental reconstructions.

Acknowledgments This study is dedicated to the Estonian geologist L. Põlma, whose lifelong research focused on the Lower Paleozoic of the Baltica region. Much of the material examined in this work derives from his collections.

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Competing interests. The authors declare that they have no competing financial interests or personal relationships that could have appeared to influence the work reported in this paper

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