

## Ripple marks as indicators of Late Ordovician sedimentary environments in Northwest Estonia

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**Abstract.** Late Ordovician sedimentary environments promoting the development of ripple marks in shallow shelf carbonate deposits of northern Estonia are analysed. Ripple marks are described using different parameters (wavelength, height, and wave and asymmetry indexes). Rippled bedding is exposed in a large area in the uppermost Keila Stage, on the upper boundary of micritic-peloidal limestones (Pääsküla Member of the Kahula Formation). Beds with ripples are overlain by organodetrital limestones (Saue Member of the Kahula Formation) transitional to grainstones or mud mounds of the Vasalemma Formation. The content of peloids in the Pääsküla Member is relatively high and their size (0.04–0.06 mm) corresponds to the grain size of sediments capable of forming ripple marks. Weakly asymmetrical sinusoidal ripple marks are oriented in a north–south direction and have likely been formed in the shallow-water zone of the shoal at some distance from the shore. The wave-current origin of the studied ripples can be inferred from ripple indexes. Ripples were subjected to some erosion and in the shallowing-upwards conditions a rocky bottom with the *Trypanites* ichnofacies evolved. The rippled surface terminates a small-scale cycle (parasequence) of the depositional sequence.

**Key words:** ripple marks, Upper Ordovician, Estonia.

### INTRODUCTION

Fossil ripple marks are important features indicative of a specific depositional environment of an ancient basin. Ripples have been used in facies analysis and determination of the location of the beach, but also for calculating several hydrological parameters (e.g. morphology, length and height of waves) and motion of sediments (Shulyak 1961; Harms 1969; Tanner 1970; Komar 1974; Allen 1984; Baas 1999). The study of ripple marks is based mainly on recent siliciclastic deposits, using also experimental data and formulas comprising empirical coefficients and parameters. The methods applied are difficult to use in case of fossil ripple marks that have developed in carbonate deposits. Ancient ripple marks are often poorly preserved due to post-sedimentation erosion (Romanovski 1977; Allen 1984). Furthermore, similar ripple marks could have been formed at highly variable depths (Kindle & Bucher 1926; Shulyak 1961; Romanovski 1977; Gradzinski et al. 1980; Allen 1984). Ewans (1942) stated that even the size of fossil ripple marks is not sufficient to elucidate the exact depth of the water in which they were formed.

In Estonia fossil ripple marks have been identified in Cambrian and Devonian siliciclastics as well as in Ordovician and Silurian carbonate rocks. Ripple marks are mostly exposed in relatively restricted areas (outcrops). They have been studied in detail in Lower Cambrian sandstones of the Lükati and Tiskre formations at Kunda, Türisalu, Suurupi and some other localities (Pirrus 1971, 1978). Besides the Vasalemma area (Hints & Miidel 2004), Upper Ordovician ripple marks have been observed in siliciclastic carbonate rocks of the Oandu Stage in the Saku old quarry section in NW Estonia and in the reef complex of the Porkuni Stage in NE Estonia (Männil 1960; Põlma 1982). Silurian ripple marks are exposed on Saaremaa Island, in the old Eikla quarry (central part of the island) and at Kaugatuma (southwestern coast), where, respectively, rocks of the Rootsiküla and Kaugatuma stages crop out (Einasto 1965, 1970, 1990). Devonian ripple marks are exposed on the coast of Ruhnu Island and in the Vardja (SW Estonia) outcrop in the boundary interval between the Narva and Aruküla stages (Orviku 1948; Kurik 1958), and in the Narva quarry (NE Estonia) in the lowermost part of the Narva Stage just above the Ordovician–Devonian contact (Heinsalu et al. 2003).

## MATERIAL AND METHODS

An extensive quarry in Vasalemma settlement in north-western Estonia (Fig. 1), west of the Keila–Riisipere railway, has provided an opportunity for detailed study of ripple marks in the Upper Ordovician section. Limestones of the quarry are extracted by Nordkalk AS down to the rippled upper surface of the Pääsküla Member in the upper half of the Kahula Formation. The relatively well preserved ripple marks are exposed in an area of more than 1000 m<sup>2</sup> in the northern part of the quarry floor (Fig. 2A). This surface has been exposed for several years. However, in June 2007 most of the area with ripple marks was covered by piles of crushed rock or loose material and the ripples were visible only in some places.

In the Vasalemma (Nordkalk) quarry a variety of mud-supported carbonate rocks with a notably high content of peloids (Põlma 1982; Fig. 3H, I), mud mounds and reefs with the oldest tabulate corals (Mõtus 1997) crop out. In comparison with several other quarries in Vasalemma, this quarry exposes the most complete section of the Keila–Oandu transition comprising the Pääsküla and Saue members of the Kahula Formation and the Vasalemma Formation, including its upper contact with the overlying Rägavere Formation (Fig. 4C). The up to 4 cm thick conglomeratic layer in the base of the last formation possibly corresponds to the Tõrremägi Member of the Oandu Stage.

Preliminary study and measurements of ripples were conducted in 2004 in an area of about 8 m<sup>2</sup> (coordinates 59.2449N and 24.3353E) in the northern part of the

Vasalemma quarry (Fig. 2B). In the next year about 120 m<sup>2</sup> was cleaned with the help of a fire-brigade who removed loose material with water. Ripple marks are oriented roughly in the north–south direction (NE 10°, SW 190°). Their parameters were measured along west–east oriented profiles with a spacing of 1.0 m. Ripple marks outside the test area did not show essential differences and the obtained data evidently give a reliable overview of the rippled surface in the quarry.

The rippled surface or the respective horizon has in modern topography a small southward dip (about 3.4 m km<sup>-1</sup> between drillings Nos 792 and 789; Fig. 4A, B), which corresponds roughly to the average dip (2.5–3.5 m km<sup>-1</sup>; Männil 1990) of the Ordovician strata. The total inclination of the upper surface of the Pääsküla Member is about 6 m in the quarry, from the level of about 17 m above sea level in the north up to the 11-m level in the south (between drill cores Nos 36 and 789; Fig. 4B). In the west–east direction this surface is uneven and undulates between 0.5 and 2.5 m within a 100-m distance (Fig. 4B), possibly reflecting in some aspect the topography of an ancient sea bottom.

The configuration of the ripples described below was determined only by main parameters such as the wavelength (L), ripple height (H), and horizontal distance from the top of the ripple crest to the deepest point in the trough on both (western and eastern) slopes of the ripple (W-L, E-L) (Fig. 5). The wavelength was measured between the highest points on ripple crests as has been done in several studies of waves (Potter & Pettijohn 1963; Collinson & Thompson 1989, pp. 19–36; Einsele 2000). The ripple height was measured perpendicular to wavelength in the deepest part of the trough between the crests. However, some authors have used more characteristics and different terms for the description of ripples (Allen 1968, 1984; Reineck & Singh 1973). The measurements and corresponding statistical analysis revealed only the main characteristics of ripples exposed in the Vasalemma quarry. Several other data on the lithological composition of rocks (e.g. polished surfaces, thin sections), distribution of fossils and comparative data from drill core sections were used for the interpretation of sedimentary environments.

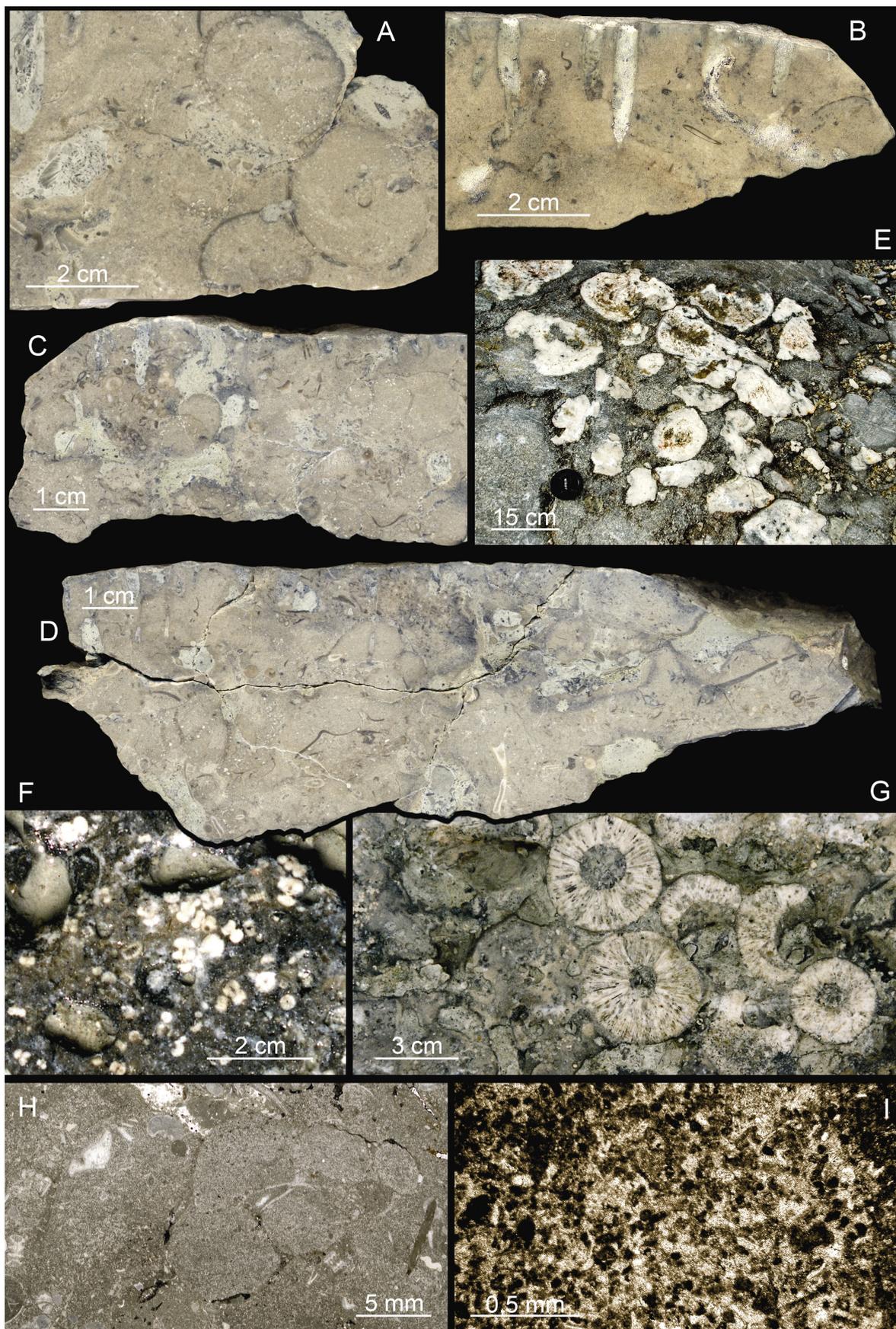
Several wavy surfaces marked by clayey films in the quarry walls possibly indicate the levels with ripple marks.

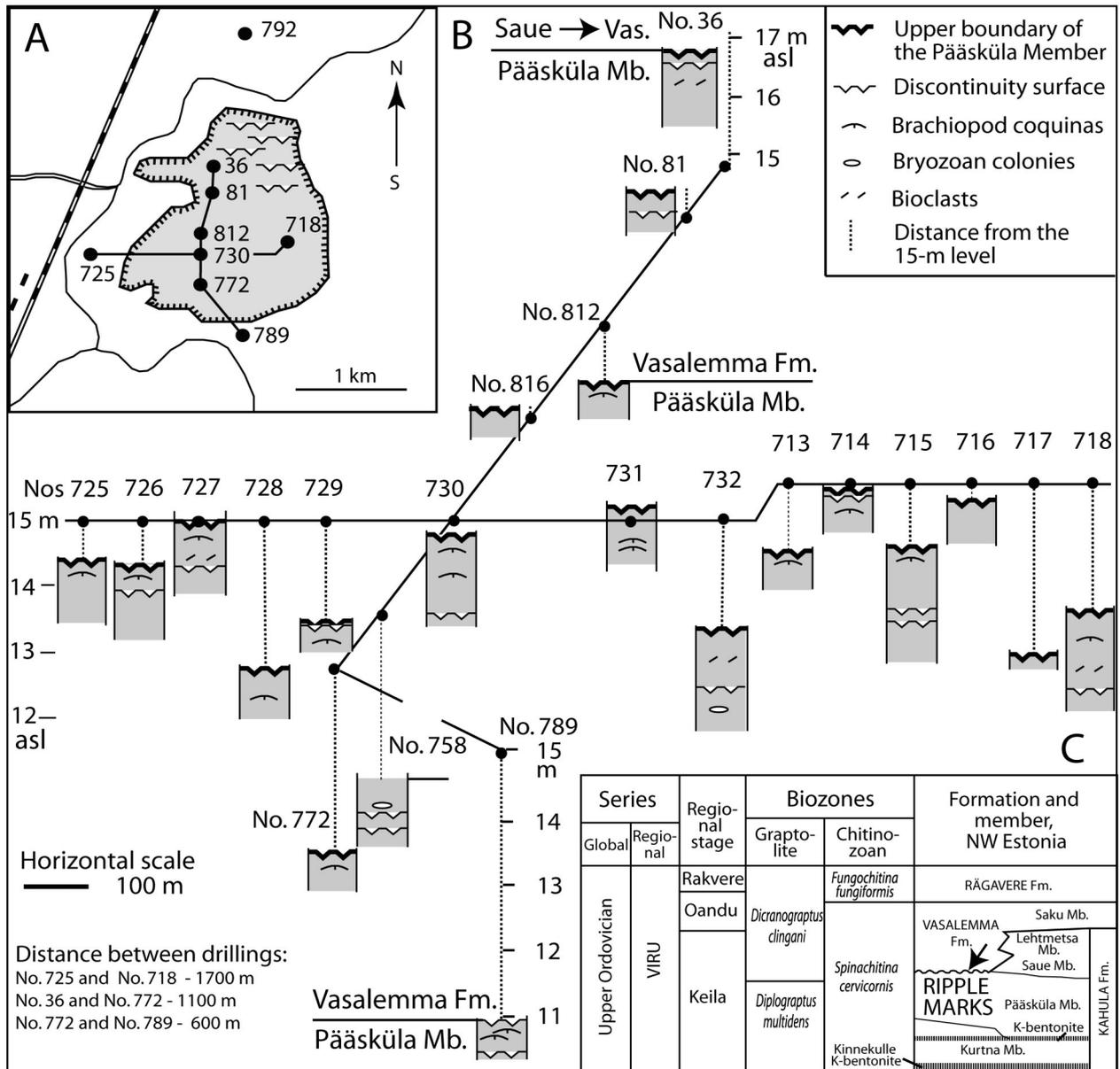


**Fig. 1.** Sketch map of the locality: shoal belt (1), area of non-deposition or erosion of late Keila (2) and Oandu (3) time (after Ainsaar & Meidla 2001).

**Fig. 2.** **A**, rippled surface in the northern part of the Vasalemma quarry. **B**, rippled surface with numerous burrows cleaned of loose material during preliminary study. **C**, pyritized surface of a ripple mark with *Trypanites*-type burrows. **D**, rippled surface with the fragmentary theca of the edrioasteroid echinoderm *Cyathocystis*.

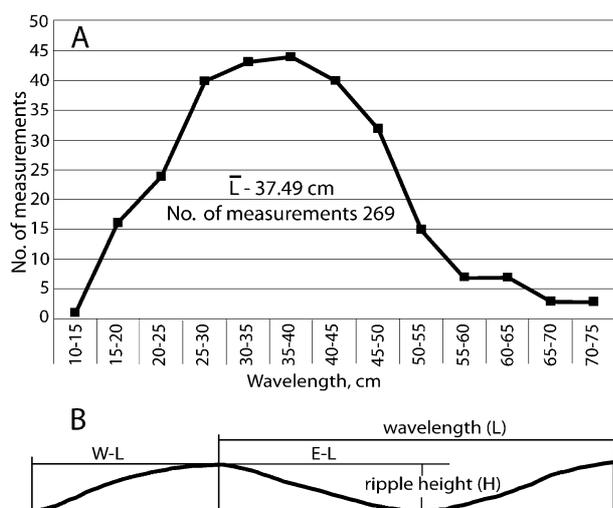






**Fig. 4.** Sketch map of the Vasalemma quarry (A), correlation of the uppermost beds of the Pääsküla Member (B) and of stratigraphical units (C). Saue→Vas. – lithologically transitional beds between the Saue Member of the Kahula Formation and lowermost Vasalemma Formation (B).

**Fig. 3.** A, cross-section of the uppermost bed of the Pääsküla Member with several algae *Cyclocrinites*. B, cross-section of the uppermost bed of the Pääsküla Member with *Trypanites*-type borings. C, D, cross-sections of the uppermost bed of the Pääsküla Member with burrows filled with argillaceous material. E, eroded upper surface of the Vasalemma Formation with tabulate corals surrounded by the relict of the bed with numerous pyritic lithoclasts. F, G, upper surface of ripple marks with eroded stem ossicles and bryozoan colonies. H, thin section with a gastropod shell partly filled with peloids; uppermost bed of the Pääsküla Member. I, thin section showing the peloidal tecture of the rock; uppermost bed of the Pääsküla Member.



**Fig. 5.** (A) Frequency curve of the wavelength (L) and (B) scheme for measurements: the westernmost (W-L) and easternmost (E-L) projections of the wavelength (below).

However, ripple marks that could be measured were only observed on two levels – on the upper surface of the Pääsküla Member, described in detail below, and in a restricted area in the lower part of the Saue Member of the Kahula Formation.

## GEOLOGICAL SETTING

The Baltic sedimentary basin underwent essential changes during the Keila–Oandu transition in the early Late Ordovician. However, the crisis in the evolution of Ordovician faunas in the same stratigraphical interval is expressed more clearly in shallow shelf facies of variably argillaceous carbonate deposits (Hints et al. 1989; Meidla et al. 1999; Ainsaar et al. 2004). Changes in the ecosystem of the Baltic palaeobasin were initiated by the warming of climate due to shift of Baltica towards the equator (Cocks & Torsvik 2002, 2005), and also by the transformation of a carbonate ramp-type sedimentary basin of the earlier periods into a rimmed shelf basin with a different depositional regime (Dronov & Rozhnov 2007). The differentiation of the basin floor topography followed the development of shoals with the deposition of peloidal carbonates and development of mud mounds and reefs in northwestern Estonia. The belt with specific shoal deposits is about 40 km long in an about west–east direction and 2–5 km wide in the north–south direction (Põlma & Hints 1984). In the limits of the shoal, especially in its middle part where Vasalemma is

located, the micritic-peloidal (aphanitic) limestones of the Pääsküla Member form a comparatively homogeneous 4–7 m thick unit. In northwestern Estonia, outside the shoal belt, the Pääsküla-type micritic limestone occurs in an up to 10-m interval, forming a cyclic intercalation with more or less argillaceous limestones (Põlma et al. 1988; Ainsaar 1991, 1993). The member decreases in thickness to the east and thus its identification in Northeast Estonia is problematic (Põlma et al. 1988, fig. 32).

The Pääsküla Member is overlain by biotrital limestones of the Saue Member, which grade into grainstones of the lowermost Vasalemma Formation (Hints 1990, 1996). The formation is represented in its total extent in some places in the southern part of the Vasalemma quarry. Its upper surface has been sporadically eroded by Pleistocene ice (Fig. 3E), but in several places it is covered by an about 5 cm thick bed of conglomerate (Pl. VII, fig. 3 in Põlma 1982) and/or of 2–3 cm thick yellowish mud-supported limestone. These rocks represent relicts of younger strata, occurring continuously a few kilometres south of Vasalemma. For example, in the Laitse (No. 1043) drill core (Põlma et al. 1988, fig. 29) about 5 km south of Vasalemma, the uppermost Oandu Stage consists of 0.9 m thick limestone with numerous discontinuity surfaces and pyrite-impregnated pebbles, which are included into the Tõrremägi Member of the Rägavere Formation. The conglomerate bed on the top of the Vasalemma quarry section supposedly corresponds to some part of these late Oandu strata in the Laitse section. The exact age of this bed in Vasalemma can only be established by special palaeontological study, which is currently in progress. Similar to the succession of rocks in the Laitse core, the above-mentioned yellowish limestone likely belongs to the Rakvere Stage.

## RIPPLE MARKS ON THE TOP OF PELOIDAL LIMESTONE

In the Vasalemma (Nordkalk) quarry rippled bedding is developed on the top of the Pääsküla Member (Fig. 4B). However, ripples become unclear or disappear in the southern direction, where the quarry floor is slightly undulating and mud mounds and reefs of the Vasalemma Formation are developed. It is difficult to tell the real nature of the upper boundary of the Pääsküla Member on the basis of drill core data, but it is nearly always marked by a pyrite-impregnated discontinuity surface (Fig. 4B), often with *Trypanites*-type borings.

The limestones of the Pääsküla Member contain a small amount of fine siliciclastic material (mainly less than 10%) and up to 8–16% unevenly distributed

(Fig. 3H, I) peloids, 0.04–0.06 mm, rarely up to 1.5 mm in size (Põlma 1977; Põlma et al. 1988). These rocks have been considered (Põlma 1982) as possible ancient analogues of modern peloidal sands in Bahama and other regions (Bosence & Wilson 2003). The formation of Ordovician peloids was possibly initiated by physical-chemical processes (Põlma 1982). The occurrence of pellets cannot be excluded either. Numerous discontinuity surfaces, and horizontal and vertical burrows are found in the Pääsküla Member, especially in its middle and upper parts (Fig. 4B). In the quarry the uppermost bed of the member with ripple marks consists of yellowish-grey seminodular micritic limestones with bioclasts of bryozoans, brachiopods, echinoderm columnals, algae (Fig. 3A), and trilobites. The structure of rocks is seminodular, composed of nodules or about 5 cm thick discontinuous layers. The initial texture of sediments has seemingly been destroyed by bioturbation of different burrowing organisms.

In Vasalemma the rippled bedding plane displays up to three different types of burrows (Figs 2B, C; 3B–D). The *Thalassinoides*-type horizontal and branching burrows probably belong to the *Skolithos* ichnofacies, which is characteristic of sandy shores (Brenchley & Harper 1998; Pemberton & MacEachern 2005). The subvertical burrows are indicative of the *Glossifungites* ichnofacies characteristic of semi-consolidated surfaces (Brenchley & Harper 1998; Pemberton & MacEachern 2005). The *Trypanites* ichnofacies, which is known to develop in fully lithified substrates (Benton & Harper 1997; Pemberton & MacEachern 2005), should have inhabited the rippled surface last. The entire surface of ripples is pierced by unevenly distributed *Trypanites*-type borings, 1.5–3 mm in diameter and up to 15 mm deep (Figs 2C, 3B), with up to 12 burrows on 1 cm<sup>2</sup>. The surface with ripple marks has pyritic impregnation and has been partly eroded before the formation of younger deposits. The burrows on the crests of ripples are more strongly eroded than those in the troughs. The upper parts of the hemispherical bryozoan colonies, seemingly lying in the life position, have been cut off and stem ossicles of the crinoids *Ristmacrinus* or *Babanicrinus* are eroded on the pyritized surface (Fig. 3F, G). The uppermost 5 cm of the Pääsküla Member contains spherical specimens of the dasycladacean algae *Cyclocrinites*, sometimes several specimens piled together (Fig. 3A), large almost flat valves of the brachiopod *Keilamena occidens* (Oraspöld), valves or shells of *Clinambon anomalus* (Schlotheim), and colonies of the bryozoan *Monotrypa*. These are the most common fossils identified earlier in the uppermost 2–3 m of the Pääsküla Member in several core sections. *Keilamena occidens* forms on some levels coquinas of horizontally packed valves (Fig. 4B),

presumably as a result of storm wave activity. On some bedding planes bryozoans are represented by numerous colonies in life position, indicating relatively low sedimentation rates. The formation of ripple marks and lithification of deposits were followed by a period of nondeposition and erosion of the basin floor, at least in the areas surrounding the central part of the shoal where mounds and reefs started to develop.

Ripple marks in the Vasalemma quarry have flat-topped, sometimes rounded, straight or sinuous crests. The crests are rather broad, the troughs are broad and flat (Fig. 2A, B). The troughs and crests lie subparallel to each other. The longitudinal axes tend to be nearly straight and parallel over long distances. If the axes are curved, the bends are mainly gradual. A series of such ripples are nearly parallel and show a quite uniform pattern over a wide area (Fig. 2A). Ripple marks form a bifurcating and intercalating pattern in plan view. The predominant wavelength of ripples is 20–40 cm (ranges from 14 to 75 cm, on average 37.49 cm) (Fig. 5), the height is 0.2–3.9 cm, on average 2.10 cm. The mean value of the ripple index (wavelength/height ratio; RI) is 19.8 by 292 measurements. In about 62% of cases the RI was 10–20. The symmetry indexes 1.28 (by 165 ratios of W-L to E-W) and 1.30 (by 133 ratios of E-L to W-L) do not show very clear asymmetry of ripples. However, the predominance (in 62% cases) of ripples with a longer western slope allows us to speculate about some asymmetry and wave-current origin of ripples.

Ripples in the Vasalemma quarry differ from those on other stratigraphic levels of Estonia in the wavelength and RI. The clearly asymmetric ripple marks occurring in siltstones of the Lower Cambrian Lükati and Tiskre formations have the wavelength of 10–20 cm and RI 3–32 and 5–16, respectively (Pirrus 1971, 1978). Rippled beddings in these units have supposedly developed in the shallow sea, whereas ripples of the Lükati Formation have formed in the conditions of undulating bottom relief, in a shallower part of the basin than those of the Tiskre Formation.

Short wavelengths of ripples and possible occurrence of cross ripple marks have been reported from the Saku Member (L = 10 cm) of the uppermost Vasalemma Formation and from the topmost Ordovician Porkuni Stage (L = 2–4 cm) (Põlma 1982). Ripple marks with the wavelength of 3–14 cm and height of 0.5–1.8 cm (RI 8) are found in the Silurian Rootsiküla Stage and are assumed to have formed in extremely shallow-water environments, at water depths less than 1 m (Einasto 1965, 1970). The average wavelength (4.5 cm) of ripples in the Devonian sandstones of the Aruküla Stage (Orviku 1948) is also much smaller than in Vasalemma.

Ripples in Vasalemma have some similarity with well-preserved large ( $L = 40\text{--}60$  cm,  $H = 10$  cm) Silurian ripples, which are exposed on the seashore close to the Kaugatuma cliff on Saaremaa Island (Einasto 1990; Märss et al. 2007). The latter ripples occur in the regressive succession of rocks (Einasto 1990) of the Kaugatuma Stage, which are characterized by abundant shallow-water shelly fauna of corals, stromatoporoids, and crinoids (Klaamann 1970). However, the ripples at Kaugatuma seem to be more linear, while those in the study area are sinusoidal. The ripples at Kaugatuma occur on top of bioclastic limestones, which have probably been formed in a deeper part of the shoal than the ripples in Vasalemma.

## DISCUSSION

The formation of ripples due to the oscillation of waves and their morphology have been studied mainly in cases of silty or sandy bottoms (Baas 2003). Ripple marks obviously never appear in sands coarser than 0.6 mm (no more than 0.7 mm by Leeder 1988) and finer than about 0.01 mm (Gradzinski et al. 1980; McLane 1995). The same grain sizes should be expected for the formation of ripples in carbonate sediments. It has also been established that for the motion of sandy deposits near the bottom water velocities of  $15\text{--}50$  cm  $s^{-1}$  were required (Bucher 1919; Kindle & Bucher 1926; Harms 1969; Romanovski 1977; Reineck & Singh 1973).

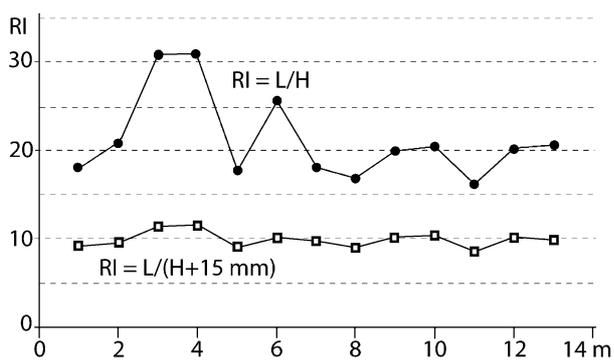
The average size of peloids (0.04 mm) and fine-grained (0.05–0.1 mm) organodetrital material predominating in the rocks of the Pääsküla Member (Põlma 1977) fit in the limits of the grain size suitable for the formation of ripple marks. However, the amount of peloids in initial deposit was probably much greater but decreased during diagenetic processes (Põlma 1977). Bio-turbation in an about 5 cm thick bed on the top of the Pääsküla Member (Fig. 3C, D) has seemingly destroyed the internal cross-lamination structures characteristic of beds with ripples (Allen 1968; Broadhurst 1968; Newton 1968; Dixon 1970; Reineck & Singh 1973; McLane 1995). As suggested by the almost spherical forms of the algae *Cyclocrinites* in the bed with ripple marks (Fig. 2A), the sediment forming the Vasalemma ripples should have been lithified fast. The occurrence of these dasycladacean algae is considered to be an indicator of shallow-water environments (Mørk & Worsley 1980). The recent dasycladaceans are distributed in firm carbonate substrates in less than 10 m deep water.

Ripple-forming deposits are commonly sorted by grain size and density – the material of the largest size and least density is commonly found on ripple crests

(Bucher 1919; Reineck & Singh 1973; Allen 1984). In our case no clear trend was observed in grain size distribution. For example, no orientation or concentration of fossil debris in relation to ripples was established. The pelmatozoan skeletons were disarticulated and the debris dropped down irregularly on the bottom. The hard-ground that was formed on ripple marks served later as the substrate for the colonization of new organisms, for example, the edrioasteroid echinoderm *Cyathocystis* occurring abundantly in reefs (Fig. 2D).

An important question is how much of the initial morphology of ripples has been preserved. It is very likely that the above statistical data do not characterize their original form. The shape of the crests is rather variable – the tops have been levelled off and the crests are very wide and flat. In some places eroded colonies of bryozoans are found. Their size and the depth of erosion indicate that the ripples were originally at least 10–15 mm higher. It is possible that even the initial width of troughs was greater because during burial and compaction the material from crests could be squeezed towards troughs. The RI 19.8 seems also too large, as the typical index of wave and wave-current ripples usually ranges from 3 to 16, and often is about 10 (Pettijohn 1949; Davies 1965; Tanner 1967; Harms 1969; Reineck & Singh 1973; Allen 1984). According to Tanner (1960, 1967), the RI 17 or more indicates swash (or wind) origin. However, very little is known about the distribution and morphology of ripples that have formed in the swash zone (Komar 1976). Studying nearshore bedforms along the south coast of Oregon, Clifton et al. (1971) found no ripples within the swash zone where the bed was planar. Flat-topped ripples are frequent in modern and ancient shallow-water basins (Wulf 1962, 1963; Davies 1965). Still, Tanner (1960, 1967) states that morphological features are useless and no real RI can be obtained for flat-topped ripple marks.

Compaction of rippled sediments or decrease in ripple height increases the RI (Tanner 1967; McLane 1995). Tanner (1967), for example, described ripples with the height of 0.2 cm and RI 20 in sandstones. When the original surface was established, the height became 0.4 cm and the RI became 10. Considering that the ripples in the Vasalemma quarry were originally at least 10–15 mm higher, the mean RI would be only about 10 (Fig. 6). Unfortunately, it is impossible to estimate supposed changes in the width of troughs. Both the supposed RI 10 and ripple symmetry index (RSI) 1.28–1.3 of the ripple marks in Vasalemma show similarity with the wave-current ripples (Tanner 1967; Reineck & Singh 1973). Such ripples are usually distributed in the nearshore shallow-water zone (Ewans 1941; Tanner 1967; Newton 1968; Allen 1984; Leeder 1988), but are sometimes found offshore from the breakers (Clifton et al. 1971).



**Fig. 6.** Variation of the average ripple indexes (RI) by 209 measurements on the 1 m network (1–14 m). Black circles – average RI by measurements of 17 ripples on the line of 14 m in the N–S direction; rectangles – supposed RI if the wave was 15 mm higher.

The fetch of wind and wave size are important factors in the formation of ripples (Davies 1965; Tanner 1970). According to Tanner (1970), an average ripple spacing smaller than 5 cm indicates highly restricted fetch (ponds, small lakes, etc.), whereas the spacing larger than 5 cm refers to a greater fetch. The ripple spacing in the Vasalemma quarry is much more ( $L = 37.4$ ), which may show that the rippled area had a great fetch.

The possible asymmetry of ripples in Vasalemma suggests that the wind was from the open sea in the west. The same can be supposed for early Keila time, considering the eastward decrease in the thickness of the Kinnekulle K-bentonite (Bergström et al. 1995). However, the direction of winds from the west does not mean that the shoreline was oriented meridionally, from north to south, because the waves could approach the shore obliquely. The position of the Baltica palaeocontinent in mid- to low latitudes during the first half of the Late Ordovician (in the Caradoc) (Cocks & Fortý 1998; Cocks & Torsvik 2002, 2005) and the preserved shallow sea deposits (Männil 1966) indicate an almost latitudinal in modern coordinates shoreline.

Besides the rippled bedding on the top of the Pääsküla Member, another one occurs 65 cm higher in the section, in the Saue Member. These ripples have the wavelength of 90–110 cm (direction 345°). Although the surface is strongly eroded, the asymmetric configuration of ripples can be supposed. The occurrence of that and other possible rippled beddings and hardgrounds in the intercalation of more or less argillaceous limestones and grainstones of the Saue Member indicates fast changes in environments, probably caused mainly by fast sea level oscillations. Episodes of rising sea level are marked also in the Vasalemma Formation by marly interlayers in

crinoidal limestones and mud mounds (Hints et al. 2004, fig. 2). The development of the Vasalemma Formation, and growth of mud mounds and reefs influenced the entire surrounding ecosystem. The sea bottom relief evidently became very differentiated, which caused variation in water flow and the direction of ripple marks. Successions of late Keila and Oandu deposits in the Vasalemma and surrounding shoal areas reveal a great variety of deposits associated with the Middle Caradoc facies turnover (Ainsaar et al. 2004, fig. 4) in the Baltic region. The gap on the Keila–Oandu boundary has been recognized in large areas in Estonia (Fig. 1) and also on the Island of Gotland.

## CONCLUSIONS

Ripple marks in the Lower Palaeozoic (Cambrian to Devonian) of Estonia have been described rather briefly on the basis of the wavelength and height. Our study revealed that the occurrence of ripple marks in carbonate rocks depends essentially, as in siliciclastic rocks, on the grain size. The high content of peloids (0.04–0.06 mm in size) together with skeletal debris in the deposits forming the Pääsküla Member of the Kahula Formation is a precondition for the formation of ripple marks. The values of ripple indexes ( $RI = 10.7$  and  $RSI = 1.3$ ) suggest the wave-current origin. The large wavelength (on average about 38 cm) differentiates the studied ripples from the others identified in the Lower Palaeozoic of Estonia. Still, the highest wavelength values (above 40 cm) characterize the ripples that developed in the shoal of the latest Silurian. Possible asymmetry of ripples and their relatively large spacing give evidence of a fetch from the open sea in the west. The internal structure of the bed with ripple marks has not been preserved due to intense bioturbation by organisms of different ichnofacies. The occurrence of *Trypanites* ichnofacies and erosion of the upper surfaces of ripples indicate a period of non-deposition before mud mounds started to develop. This erosional surface marks the boundary of a small-scale carbonate cycle (parasequence) of the depositional sequence comprising the deposits of the Kurna Regional Subseries (Haljala and Keila stages; Dronov & Rozhnov 2007) and corresponding to the boundary interval between the Sandbian and Katian global stages.

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## Lainevired kui Hilis-Ordoviitsiumi keskkonnatingimuste indikaatorid Loode-Eestis

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On kirjeldatud Vasalemma (Nordkalk AS) murrus ulatuslikul alal paljandunud Hilis-Ordoviitsiumi Keila lademes esinevaid laineviresid. Need on moodustunud rohkesti tombulist materjali sisaldavates karbonaatsetes setendites, mille valdav terasuurus (alla 0,6 mm) vastab setendite terasuurusele, millel on eeldus lainevired moodustamiseks. Uuritud vired pind markeerib geoloogilises läbilõikes Kahula kihistu Pääsküla kihistiku ülemist pinda. Vired on eeldatavasti moodustunud paleobasseini madalaveelises osas vahetult enne Ordoviitsiumi vanimate riffide teket. Viimased on esindatud Vasalemma murru lõunapoolses osas, kus rifikompleks lasub Pääsküla kihistiku kivimitel.

Vired iseloomustamiseks kasutatud statistilised andmed ja võrdlus erineva tekkega laineviredega lubab oletada, et Vasalemmas esinevad lainevired on moodustunud madalaveelistes tingimustes tugeva lainetuse ning ilmselt läänetuultel mõjul. Kiiresti litifitseerunud vired setendid on hiljem, enne uute setendite moodustumist, allunud kulutusele, mistõttu vired algne kuju on mõnevõrra muutunud, eelkõige madaldunud. Vasalemmas uuritud lainevired erinevad teistest Eesti aluspõhjas esinevatest lainetuse mõjul moodustunud viredest suhteliselt suure lainepikkuse ja vire indeksiga. Pääsküla kihistiku ülemisel pinnal ja teistel stratigraafilistel tasemetel oletatavad vired ning sedimentatsiooni lüngad osutavad merepõhja topograafilisele diferentseeritusele ja meretaseme muutustele. See on kooskõlas kogu Balti paleobasseinis toimunud oluliste muutustega Keila-Oandu intervallis.