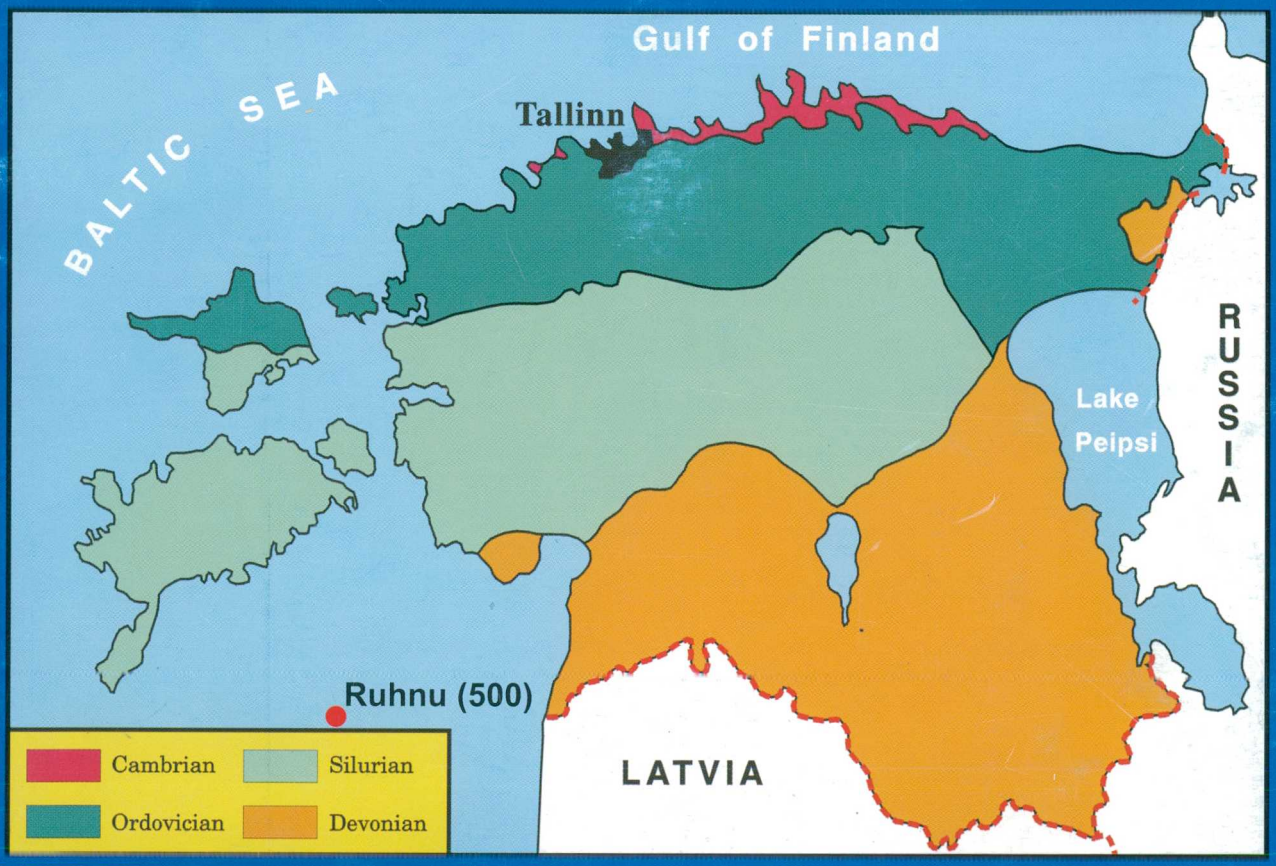
EESTI GEOLOOGIAKESKUS
GEOLOGICAL SURVEY OF ESTONIA

ESTONIAN GEOLOGICAL SECTIONS

BULLETIN 5

RUHNU (500) DRILL CORE



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PREFACE

The present issue of the journal *Estonian Geological Sections* deals with the Ruhnu (500) drill core from the central part of Ruhnu Island in Liivi Bay, southwestern Estonia (Fig. 1). The Ruhnu drill hole was made in the course of geological mapping of Saaremaa Island in 1972 (Kala *et al.* 1973). One purpose of drilling a 787.4 m deep hole reaching the crystalline basement was prospecting for oil and natural gas in this area, but only Cl–Ca–Na type groundwater from Lower and Middle Cambrian sediments with total mineralization of 17 g/l was found.

The core is housed in the depository of the Geological Survey of Estonia in the town of Keila, North Estonia. The source material for this study is available in mapping reports (Kala *et al.* 1973) and in an unpublished report (Põldvere *et al.* 2001) held in the Depository of Manuscript Reports, Kadaka tee 82, Tallinn. The results of detailed investigations and descriptions of stable isotope stratigraphy, micropalaeontology, mineralogy, chemical composition and petrophysical properties of sediments have been published in numerous papers (Nõlvak 1980; Jürgenson 1982; Nõlvak & Grahn 1993; Nestor 1994, 1997; Brenchley *et al.* 1997; Hints & Meidla 1997a; Kleesment & Mark-Kurik 1997; Mens & Pirrus 1997a; Puura *et al.* 1997; Heath *et al.* 1998; Kaljo *et al.* 1998, 2001; Hints *et al.* 2000; Kaljo & Martma 2000; Shogenova *et al.* 2003) and are used in the present work together with recently obtained data.

INTRODUCTION

The Ruhnu (500) drill hole (57° 48,200' N, 23° 14,609' E), one of the deepest in Estonia, penetrates the upper 3.2 m of the Estonian Mesoproterozoic crystalline basement. Cambrian (41.4 m), Ordovician (105.8 m), Silurian (454.9 m) and Devonian (138.3 m) sedimentary rocks are covered by 7.8 m thick loose Quaternary deposits (Fig. 2).

Macrolithological characterization of the drill core was completed through joint efforts of many specialists. Mati Niin (Geological Survey of Estonia) described the crystalline basement, Kaisa Mens (Institute of Geology at Tallinn Technical University) the Cambrian sediments. Anne Põldvere (Geological Survey of Estonia) compiled the Ordovician, Silurian and Quaternary parts using the description by Elmar Kala (Kala *et al.* 1973) and as a supplementary material for the interval of 267.4–558.5 m, field notes of Rein Einasto (Institute of Geology at Tallinn Technical University). Anne Kleesment (Institute of Geology at Tallinn Technical University) provided the lithology of the Devonian strata (description, 28 mineralogical, grain-size and X-ray diffractometry (XRD) analyses). All descriptions were supplemented with the results of thin-section studies and various chemical, mineralogical and grain-size analyses.

To improve the stratigraphic subdivision of the Ruhnu (500) section, its Ordovician and Silurian parts were additionally sampled for microfossils. All previous samples were used and restudied. Jaak Nõlvak identified Ordovician chitinozoans (109 samples), Viiu Nestor the Silurian ones (323 samples). Ordovician and Silurian conodonts (292 samples) were identified by Peep Männik, graptolites (69 samples) by Dimitri Kaljo, Silurian agnathan and fish microremains (53 samples) by Tiiu Märss (all from the Institute of Geology at Tallinn Technical University). Ordovician ostracods (69 samples) were identified by Tõnu Meidla (Institute of Geology, University of Tartu). Data on upper Ashgill–lower Wenlock brachiopods (83 samples) were derived from the research of Rachel J. Heath (Heath *et al.* 1998) into carbon ($\delta^{13}C$) and oxygen ($\delta^{18}O$) stable-isotope stratigraphy. Juozas Valiukevičius (Institute

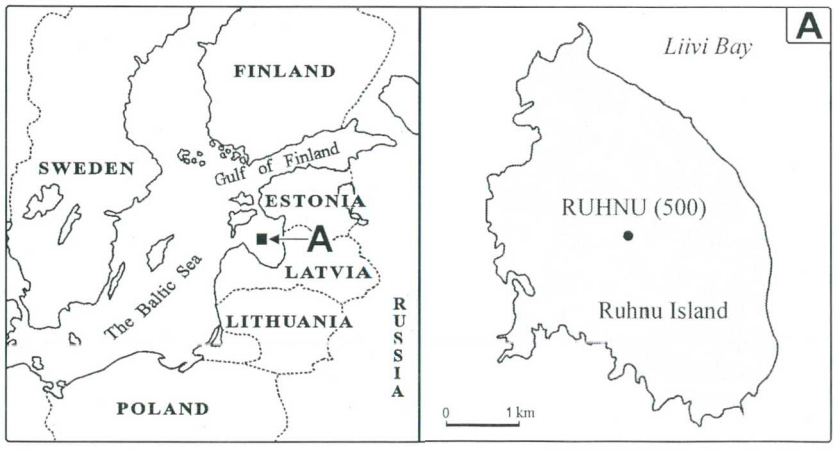


Fig. 1. Location of the Ruhnu (500) drill hole.

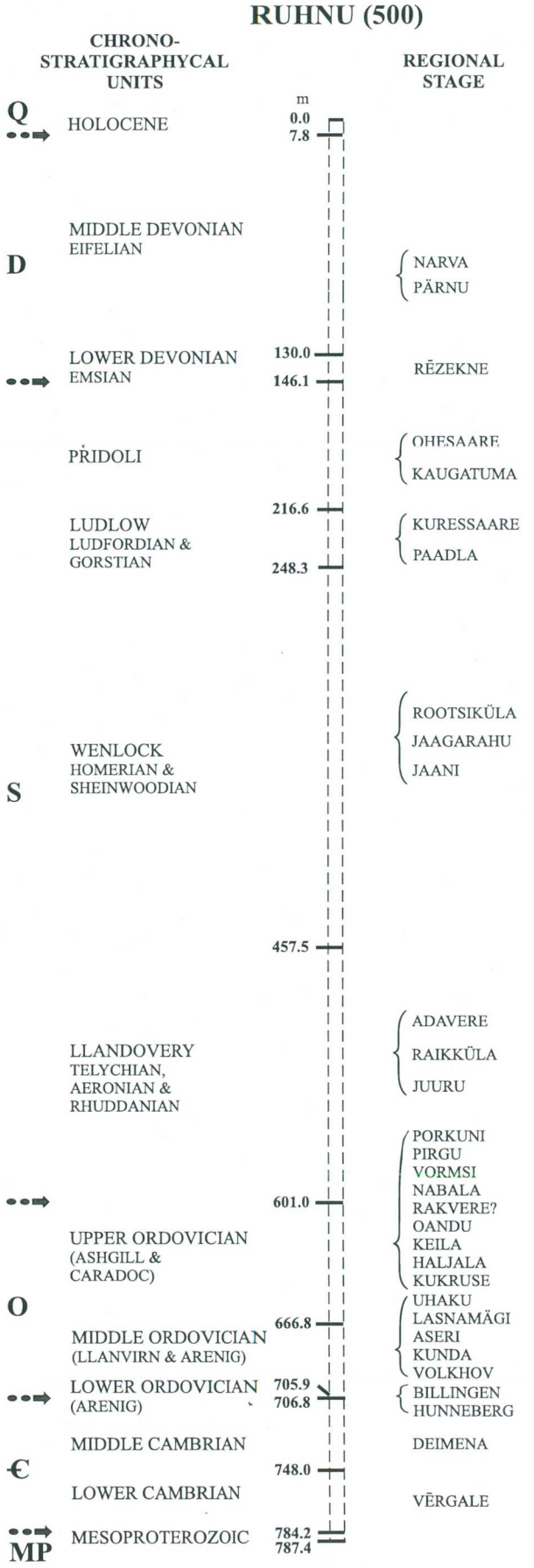


Fig. 2. Generalized stratigraphy of the Ruhnu (500) core. MP – Mesoproterozoic; Є – Cambrian; O – Ordovician; S – Silurian; D –Devonian; Q – Quaternary.

of Geology and Geography of Lithuania) identified Devonian acanthodians.

Alla Shogenova (Institute of Geology at Tallinn Technical University) and Argo Jõeleht (Institute of Geology, University of Tartu) provided wet silicate chemical analyses, X-ray fluorescence (XRF) spectrometry and physical measurements of the core (114 samples from the whole section, except for the Mesoproterozoic). Fifty-four thin sections of Palaeozoic rocks made from these samples were described by Kaisa Mens, Asta Oraspõld and Anne Kleesment (all from the Institute of Geology at Tallinn Technical University). Mati Niin (Geological Survey of Estonia) provided Mesoproterozoic thin sections (3).

Carbon isotopes ($\delta^{13}C$) of 161 upper Ashgill–lower Wenlock whole-rock samples not containing brachiopod shells were analysed by Tõnu Martma (Institute of Geology at Tallinn Technical University).

Toivo Kallaste (Institute of Geology at Tallinn Technical University) and Kiira Orlova (Geological Survey of Estonia) provided the XRD and XRF data of 30 Ordovician and Silurian volcanic interbeds. Kalle Kirsimäe (Institute of Geology, University of Tartu) performed XRD analysis of six Lower Cambrian samples.

The contents of CaO, MgO, CO_2 and insoluble residue of the Silurian sediments were analysed in the course of geological mapping (Kala *et al.* 1973) and also by Erika Jürgenson (79 samples) in the 1970s and 1980s. Additionally, she investigated the mineralogical composition of 32 samples out of a total of 79. All these data are considered in the description of the core.

Photos of the core were taken by Gennadi Baranov, Tõnis Saadre and Anne Põldvere, and prepared for publication by Gennadi Baranov and Elar Põldvere (Institute of Geography, University of Tartu). Ene Pärn (Geological Survey of Estonia) provided various technical assistance.

Useful comments by Heldur Nestor, Asta Oraspõld (Institute of Geology at Tallinn Technical University), Juho Kirs, Tõnu Meidla (Institute of Geology, University of Tartu) and Jaan Kivisilla (Geological Survey of Estonia) were of great help in finalizing the report.

The assistance of all these people at different stages of the work is gratefully acknowledged.

CORE DESCRIPTION AND TERMINOLOGY

The description of the Ruhnu (500) core is presented in the form of a table including main lithological features of the rock (Appendix 1). From the

Devonian terrigenous sediments 28 samples were studied for grain-size and mineral composition, 5 for chemical composition, and 3 thin sections were described. From the Silurian strata 171 chemical and 32 mineralogical samples (see also Appendix 2) and 26 thin sections were investigated. From the Ordovician sediments 32 chemical samples and 22 thin sections were analysed. Different groups of fauna were used for age specifications. Acanthodian scales were recovered from 3 samples of Devonian rocks as a by-product of mineralogical analyses. A total of 1013 samples from the Ordovician and Silurian strata were studied for brachiopods (Heath *et al.* 1998), co-nodonts, chitinozoans, graptolites, agnathan and fish microremains and ostracods. Six XRD samples (Appendix 3) and 3 thin sections of Cambrian sediments, and 3 thin sections of the Mesoproterozoic crystalline rocks were analysed.

To determine the degree of dolomitization of carbonate rocks, 3% hydrochloric acid was used during field work. The content of clay was estimated visually, and the rocks are traditionally referred to as slightly argillaceous (insoluble residue 10–15%), medium argillaceous (15–20%) and highly argillaceous (20–25%) (Oraspõld 1975). Marlstones with different contents of calcite are referred to as calcareous ($CaCO_3$ < 25%) or calcitic (> 25%).

The descriptions of the textures of carbonate rocks are based on the traditional Estonian classification of Vingisaar *et al.* (1965) and Loog & Oraspõld (1982), where the relative amounts of clastic and micritic components are crucial to identification of the textures. The content of carbonaceous clasts (including bioclasts) is given, if possible, in per cent.

The particles > 0.05 mm in diameter are described as grains. Skeletal remnants of organisms or their fragments (bioclasts), mainly < 1 mm in diameter, were systematically recorded. The size of chemogenic or biochemogenic ooliths is usually < 1 mm, while the size of carbonate intraclasts exceeds 1 mm. For the major part of the section, the amount of grains was determined with the magnifying glass on slabbed surfaces of the core. The micritic component consists of particles < 0.05 mm in diameter. The terms used for textures are explained in Appendix 1. Depending upon the degree of recrystallization, several transitional textures can be observed (secondary textures occur as patches or spots). In case of mixed texture, the word marking the dominant component is given last, while those marking less important components are placed before the basic word. The same principles were followed in descriptive terms for other characteristics of the rock as well. The comparision of the Estonian classification with Dunham's classification (Dunham 1962; Põldvere & Kleesment 1998) is given, if possible, at the end of the short description. The textures identified are illustrated on the photographs of thin sections of the core in Appendix 4 (on CD-ROM).

Several sedimentary structures are described in the way used in previous issues of the bulletin (see Põldvere 1999, 2001). The relationships between different parts of rock are given in Appendix 1. The variation of these structures in the Ruhnu (500) core is illustrated in Appendix 5 (on CD-ROM) and Pls 1–3.

The classification of sandstones is based on the generally used 5-fractional classification of Pettijohn *et al.* (1987), where the diameter of the finest sand particles is 0.05 mm. Fractions and terms for clay, silt and sand are described in Appendix 1. Gravel-sized fragments (diameter 2–10 mm) are larger than coarse sand and finer than pebbles. The term "terrigenous" is essentially synonymous with "non-carbonate" (e.g. *terrigenous sand* vs *carbonate sand*) and is applied to sediments originating from the land area and transported mechanically to the basin of deposition (Scholle 1978).

The terminology for igneous rocks was derived from their genesis and chemical and mineralogical composition.

GENERAL GEOLOGICAL SETTING AND STRATIGRAPHY

The bedrock succession in the Ruhnu (500) section can generally be divided into four parts: the Mesoproterozoic crystalline basement, Cambrian terrigenous sediments, Ordovician–Silurian carbonate strata and Devonian, predominantly terrigenous rocks. The Devonian sediments are overlain by the Quaternary cover (Fig. 2; Appendix 1).

The Ruhnu (500) drill hole on Ruhnu Island penetrates for 3.2 m (interval 784.2–787.4 m; Appendix 1, sheet 28) into weathered granite porphyry (Pl. 4, fig. 26) in the northeastern part of the huge Riga rapakivi batholith in Liivi Bay. The rapakivi-anorthosite pluton of the **Riga complex** embraces an area of about 40 000 km^2 under the southern part of Saaremaa Island, the Baltic Sea and Kura Peninsula. It is one of the largest rapakivi granite plutons of the world and belongs to the Riga–Åland 1600–1540 Ma rapakivi subprovince in the Fennoscandian Shield (Koistinen 1994; Puura & Floden 1996, 2000).

The eroded and weathered surface of the crystalline basement is overlain by 36.2 m thick **Lower Cambrian** sandstones (interval 748.0–784.2 m; Appendix 1, sheets 27, 28; Fig. 2). The sandstones be-

long to the Soela and Irbe formations, corresponding to the Vērgale Stage that represents the topmost Lower Cambrian in Estonia (Mens & Pirrus 1997a). Both formations occur on the islands of the West Estonian Archipelago and in the western part of mainland Estonia, and are known only from core sections. The lower boundary of the Irbe Formation is marked by the appearance of claystone interbeds; the upper boundary is erosional throughout the distribution area of the formation (Mens & Pirrus 1997 a). Sediments of the Vērgale Age were deposited during the transgression of the Aisčiai evolutionary stage, when the Baltic basin was submerged (Vidal & Moczydłowska 1996). The presence of ferruginous oolith interbeds, appearance of glauconite on bedding planes and noticeable bioturbation of argillaceous beds in the investigated core section indicate slow sedimentation or interformational breaks in this area (Mens & Pirrus 1997b).

Middle Cambrian sandstones (interval 706.8–748.0 m; Appendix 1, sheets 25–27) belong to the Ruhnu Formation (distributed in the southwestern part of Estonia), corresponding to the Deimena Stage (see Mens & Pirrus 1997a). These rocks are unfossiliferous and their age is determined according to the geological setting between palaeontologically characterized Lower and Upper Cambrian rocks (Mens & Pirrus 1997a). The Ruhnu (500) core has been selected as the type section for the Ruhnu Formation (Kala *et al.* 1984) which shows here the maximum registered thickness (41.2 m). The formation is underlain by the Irbe Formation containing chamosite-cemented sandstone with glauconite, quartz and feldspar grains in its uppermost part. Sediments of the Deimena Age have been deposited under high-energy conditions not far from the shoreline during the Deimena transgression of the westerly situated shallow-water basin (Mens & Pirrus 1997b).

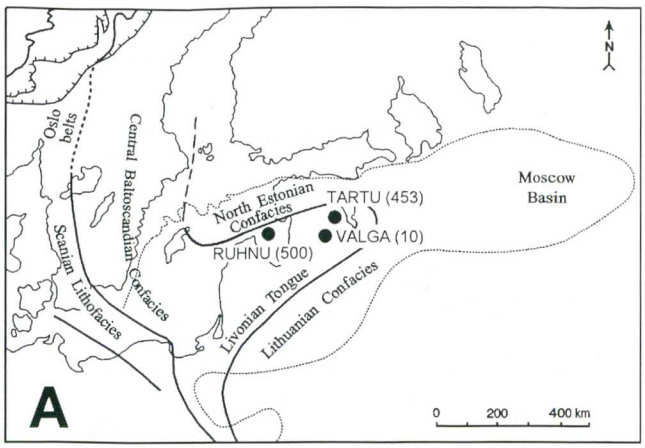
During the **Ordovician**, the present Baltoscandian area constituted the northern part of an epicontinental marine basin (Fig. 3A), surrounded by the Fennosarmatian land (Männil 1966; Põlma 1982; Jaanusson 1995; Nestor & Einasto 1997). Shallow-water sediments occur in the present-day outcrop area in the North Estonian Confacies Belt, while those formed in deeper-water environments are found in western Latvia and Sweden (Central Baltoscandian Confacies Belt). The Ruhnu (500) core log represents the transition between these two belts (Fig. 3A). The present paper makes use of the most recent correlation charts for the Ordovician of the East European Platform (Nõlvak 1997, p. 54; Table 7; Männil & Meidla 1994).

Lower Ordovician glauconitic sandstones and dolostones (interval 705.9–706.8 m; Appendix 1, sheets 25) are represented by the Leetse and Zebre formations, corresponding to the undivided Hunneberg–Billingen stages (Fig. 3B). The biostratigraphy of this interval is based mainly on conodonts studied by V. Viira (Mägi *et al.* 1989). The stages spread over the Estonian territory but are not documented from several sections of the West Estonian Archipelago (Meidla 1997). The thickness of the formations increases towards the east and south. In the Ruhnu (500) section the lower boundary of Ordovician rocks is marked by a 0.1 m thick dolomite-cemented interlayer with inarticulate brachiopods, dark green glauconite and well-rounded quartz grains. These sediments characterize the beginning of a worldwide Arenigian transgression in the Baltic basin (Nestor & Einasto 1997). Discontinuity of early carbonate sedimentation in the study area is reflected as impregnated discontinuity surfaces.

Middle Ordovician (interval 666.8–705.9 m; Appendix 1, sheets 24, 25) limestones (in the lower part dolostones) are represented by the Kriukai, Šakyna, Baldone, Segerstad, Stirnas and Taurupe formations, corresponding to the Volkhov, Kunda, Aseri, Lasnamägi and Uhaku stages (Fig. 3B). In southern Estonia these units are poor in fossils and thus the age relationships with northern sections are not clear. Contacts of the formations are more distinct. Therefore correlation of Middle Ordovician sections is based on main changes in the lithology of the formations (disposition of marlstone interbeds, bedding planes, content of grains (as well as bioclasts) and clay, variation of colours). The formations known from South Estonia are additionally analysed using the well-studied core material from northern Latvia (Ulst *et al.* 1982).

Dolostones and limestones of the lower and middle parts of the Middle Ordovician are reddish- or violetish-brown. The upper part comprises grey or greenish-grey ooliths-bearing limestones of the Stirnas and Taurupe formations. Thicknesses of the formations (except for the Segerstad Formation) increase towards the east and south. These sediments have formed at the boundary between the North Estonian and Central confacies belts (see Fig. 3A) in variable conditions between the sea level lowstand (Šakyna Formation) and highstand (Baldone Formation) (Nestor & Einasto 1997) in the open shelf environment (Segerstad, Stirnas and Taurupe formations).

Upper Ordovician limestones with marlstone interbeds (interval 601.0–666.8 m; Appendix 1, sheets 22–24) belong to the Dreimani, Adze, Blidene,



B

- Kuldiga and Saldus formations
- Jonstorp Formation
- Mõntu Formation
- Rägavere and Saunja formations
- boundaries:
  - S – Silurian
  - O_3 – Upper Ordovician
  - O_2 – Middle Ordovician
  - O_1 – Lower Ordovician
  - $Є_3$ – Upper Cambrian
  - $Є_2$ – Middle Cambrian
- (650.1) lower boundary of the Kinnekulle K-bentonite

Key to the boundaries (m) of regional stages:

	RUHNU (500)	VALGA (10)	TARTU (453)
Porkuni			
Pirgu	617.1–619.1	325.1	232.5 (249.0?)
Vormsi	631.1	363.4	280.0
Nabala	631.8	365.7	282.6
Rakvere	636.0 ?	373.5–376.9	286.5
Oandu	639.4*	383.0	288.4
Keila	642.0–647.1	384.9–389.2	296.6
Haljala	650.1	395.4	313.7
Kukruse	658.2	400.3	326.7
Uhaku	666.8	410.6	339.4
Lasnamägi	677.2	422.0	?
Aseri	682.5	–	355.9
Kunda	690.0	–	362.2
Volkhov	698.8	–	373.8
Billingen	705.9	–	381.0
Hunneberg	?	–	?
Varangu	706.8	–	?
Pakerort	–	–	382.2

* see Meidla in this volume

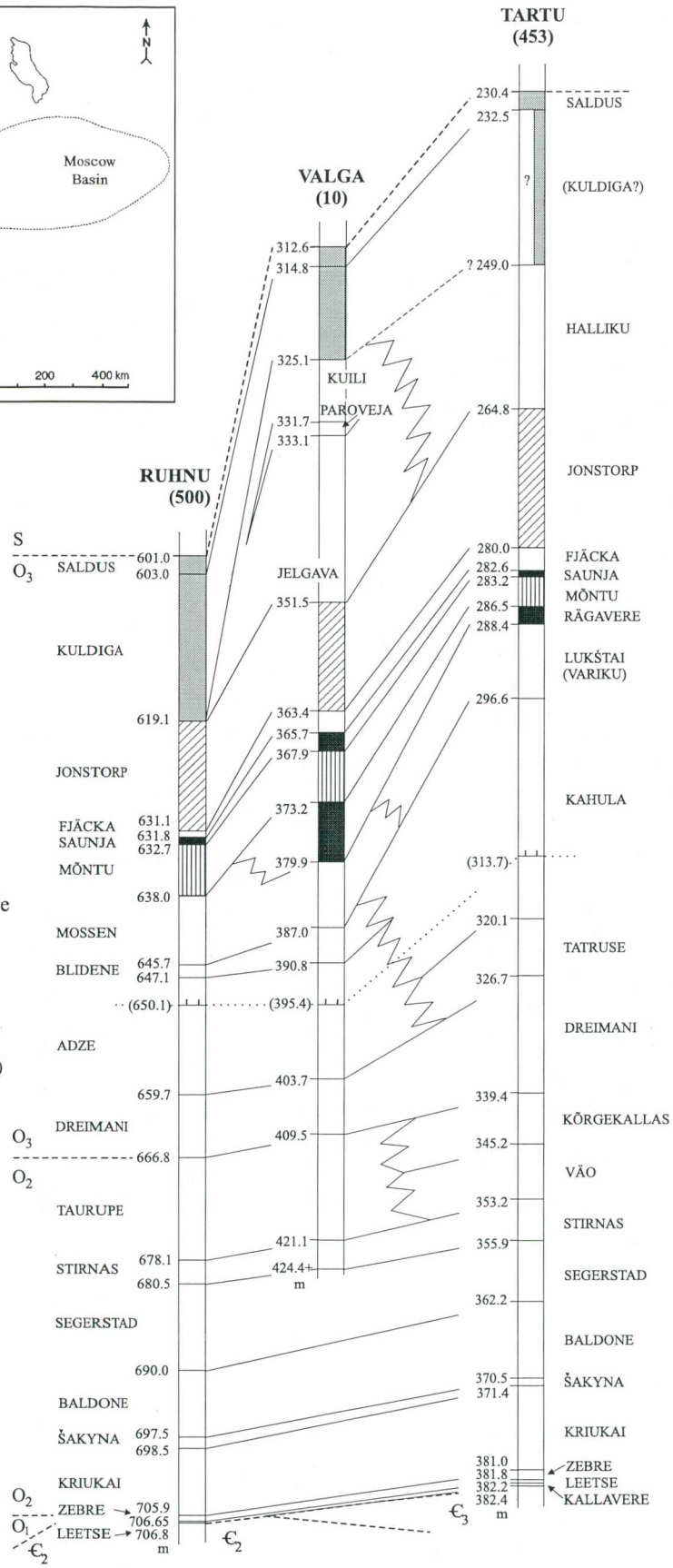


Fig. 3. (A) Baltic Ordovician confacies belts (after Jaanusson 1995, modified from Nõlvak 1997). (B) Correlation of Ordovician formations and regional stages in the Ruhnu (500), Valga (10) (after Põldvere 2001) and Tartu (453) (after Põldvere *et al.* 1998; Nõlvak in this volume) sections.

Mossen, Mõntu, Saunja, Fjäcka, Jonstorp, Kuldiga and Saldus formations, corresponding to the Kukruse, Haljala, Keila, Oandu, Rakvere(?), Nabala, Vormsi, Pirgu and Porkuni stages (Fig. 3B). There are no clear biostratigraphical criteria for determining the presence of the Rakvere Stage and defining the boundaries of the Keila and Oandu, and Oandu and (probable) Rakvere stages. The data provided by the distribution of chitinozoans and conodonts in this part of the section differ from ostracod data (see Nõlvak, Männik and Meidla in this volume). The problematic stage boundaries are marked with a dotted line in Appendix 1, sheet 23. A similar contradiction is observed also at the boundary of the Pirgu and Porkuni stages (Appendix 1, sheet 22).

K-bentonite at the lower boundary of the Keila Stage is a reliable marker level in Estonian sections. In the Ruhnu (500) section it lies in the interval of 649.9–650.1 m (observed thickness 20 cm, Appendix 1, sheet 23). X-ray diffractometry (see Kiipli & Kallaste in this volume) has revealed the identity of this bentonite bed with the widely distributed Kinnekulle bed, which is confirmed also by biostratigraphical data. Rich fauna of the Upper Ordovician units is well investigated and widely employed for biostratigraphical correlations. Systematic data available on brachiopods (see also Appendix 6), chitinozoans, conodonts and ostracods are used also for biostratigraphical subdivision of the Ruhnu (500) section (see Nõlvak and Männik in this volume).

The Upper Ordovician part of the Ruhnu (500) core differs from other sections of Estonia in many respects. The thickness and lithology of the South Estonian formations (Nõlvak 1997) indicate specific sedimentary conditions in the surroundings of Ruhnu. The thickness of the interval from the Dreimani to Mossen formations (28.8 m) increases essentially east- (52.9 m; see Fig. 3B) and southwards. Eastwards facies differentation is observed. Yellow and violet argillaceous limestone interbeds of the Adze Formation (interval 653.7–657.4 m, Appendix 1, sheets 23, 24; Pl. 4, figs 19, 20) contain iron ooliths. Marlstones of the Blidene and Mossen formations contain in places angular fine quartz grains. In the upper part of the Mossen Formation argillaceous limestones and marlstones of the Priekule Member contain glauconite grains (Appendix 1, sheet 23).

The thickness of the Mõntu Formation decreases towards the east (Fig. 3B) and south. Limestone with marlstone interbeds, rust-coloured discontinuity surfaces (Pl. 3, fig. 18) and glauconite-bearing interlayers are similar to the Mõntu level in the Valga (10) section (Põldvere 2001). Only the clay content of the formation increases eastwards.

The Saunja Formation in Estonian sections is represented by uniform micritic cryptocrystalline limestone with irregular distinct, up to 2 cm thick marlstone interbeds. In the Ruhnu (500) core a specific interbed (632.5–632.7 m, Appendix 1, sheet 23) of limestone with bioclasts (25–50%, packstone; mainly subrounded echinoderms, diameter > 1 mm), phosphatic ooliths, glauconite, pyrite aggregates and grains is documented between the discontinuity surfaces on the lower boundary of the formation (Appendix 4, T-33; Appendix 5, D-11). Limestone is lumpy and voids between rough particles are filled with sparry calcite. The lower part of the interbed contains pebbles from the lower complex. The sediments look like storm deposits or have possibly been exposed to vadose diagenesis. The total thickness of the Saunja Formation in the Ruhnu (500) section is 0.9 m, in northern and eastern sections its thickness may be over 10 m. In case of small thickness, distinct discontinuity surfaces and stromatolite crusts occur on the upper boundary of the Saunja Formation (see Tartu (453) core, Põldvere & Kleesment 1998; Appendix 1). On the Latvian territory towards the southwest, the Saunja level is documented by an erosional break (Ulst *et al.* 1982).

The thickness of the Fjäcka and Jonstorp formations increases towards the east (see Fig. 3B) and south. The lower boundary of the Fjäcka Formation is marked by a pyritized discontinuity surface with excavations, pyrite aggregates and burrows (Appendix 5, D-10). The contact between the limestones (Saunja) and shale-like marlstones (Fjäcka) is mostly sharp in Estonia, but less distinct in the Ruhnu (500) section (Appendix 5, D-11). The bituminous dark or brownish-grey shale-like marlstone (631.3–631.6 m; Appendix 1, sheet 23), mostly constituting the lower part of the Fjäcka Formation, occurs in the middle part of the formation in the Ruhnu (500) core.

Flat iron ooliths occur on the lower boundary of the Jonstorp Formation (Appendix 1, sheet 23). A complex of mainly goethitized, burrowed, inclined discontinuity surfaces is observed in its upper part (Appendix 1, sheet 22). The upper boundary of the formation is wavy, with pebbles from the lower complex (Appendix 5, D-9). On the Latvian territory towards the southwest the Jonstorp and Kuldiga boundary level is marked by an erosional break (Ulst *et al.* 1982).

The thickness of the Kuldiga Formation is notable in the Ruhnu (500) section – 16.1 m (Appendix 1, sheet 22). In southern Estonia, however, it is up to 10.3 m (Valga (10); see Põldvere 2001) and in northern Latvia up to 13 m. The distribution of the Kuldiga Formation and its lower boundary need further study. For example, the distribution of chitinozoans in the Tartu (453) core (Bauert & Bauert 1998;

Appendix 11) and lithological features suggest that this boundary lies lower in section (Fig. 3B; see also Nõlvak in this volume). The formation is represented by limestones containing interbeds with quartz sand, carbonate clasts and pellets (Pl. 3, fig. 16). The described rocks are overlain by cross-bedded limestones of the Saldus Formation, containing ooliths, pyrite aggregates, well-rounded carbonate and quartz sand interlayers (Appendix 5, D-8). An inclined pyritized discontinuity surface, serving as the Ordovician and Silurian boundary (Appendix 5, D-7), lies on the upper boundary of the formation.

The Upper Ordovician started in the Ruhnu area with a relative eustatic stillstand in the conditions of the open shelf. Sedimentation in deeper environments, in the transitional or even depression zones, took place in the Oandu and Vormsi ages. Volcanic ash beds formed in the Haljala and Keila ages give evidence of growing volcanic activity in the adjacent Iapetus Ocean (Nestor & Einasto 1997). Shallowing at the end of all Upper Ordovician ages (except for Haljala and Vormsi) is evidenced by the occurrence of clastic material, subrounded bioclasts, silt-bearing interlayers and discontinuity surfaces, often marking erosional sedimentation breaks. Briefly, the development of the Upper Ordovician basin began with a slow, gradual deepening of the basin and finished with recurrent shallowing (in Rakvere, Nabala and Porkuni times), in places with intensive erosion of the older deposits (Nestor & Einasto 1997). A major hiatus on the Ordovician–Silurian boundary resulted from the long-lasting Gondwana glaciation (Brenchley *et al.* 2003).

The **Silurian** sequence is fairly complete in the Ruhnu (500) core. The correlation chart for the Silurian is based on the latest version of the regional stratigraphic scheme (Nestor 1997, p. 90; Table 8). The limestones, marlstones and dolostones present in the section (interval 146.1–601.0 m; Appendix 1, sheets 6–21) belong to the Õhne, Saarde, Rumba, Velise, Riga, Jaani, Jamaja, Sõrve, Rootsiküla, Torgu, Kuressaare, Kaugatuma and Ohesaare formations, corresponding to the Juuru, Raikküla, Adavere, Jaani, Jaagarahu, Rootsiküla, Paadla, Kuressaare, Kaugatuma and Ohesaare stages (Fig. 2). The biostratigraphy of sediments is based mainly on brachiopods (see also Appendix 6), conodonts, chitinozoans and graptolites, in the upper part also on agnathans and fishes (see Männik, Nestor, Kaljo and Märss in this volume). Several Silurian bioevents (Kaljo *et al.* 1995) can be identified according to the distribution of microfossils and lithological changes (Kaljo *et al.* 1998).

The present distribution areas of the Silurian stages Estonia decrease throughout the period and shift southwestwards. The specific South Estonian formations (Nestor 1997) are represented in the Ruhnu (500) core and the Silurian sequence here is the most complete for Estonia. Still, the discontinuity of sedimentation is evident from the changes in the reduced thickness of some lithological units, and discontinuity surfaces or sharp lithological contacts. Precise information on the extent of gaps is obtained from the distribution of microfossils (see Nestor, Kaljo, Märss and Männik in this volume). Variability of sedimentation conditions is revealed by different structures and textures, especially disposition, shape and combination of grains.

The thickness of the Õhne and Saarde formations increases rapidly towards the northeast and east of Ruhnu. The boundary between these formations is marked by a pyritized discontinuity surface in the Ruhnu (500) section. It is underlain by violet-brown marlstones and overlain by the complex of Saarde marlstones, followed by interlayers of pyritized pebbly sub-angular to rounded limestone in the interval of 583.0–585.0 m (Appendix 1, sheet 21; Pl. 3, fig. 15). Alternating limestones and marlstones of the Saarde Formation (Pl. 3, figs 13–15) are bituminous (interval 557.0–563.5 m; Appendix 1, sheet 20) and contain concretions of silica (516.8–521.7 m; Appendix 1, sheet 19). A distinct pyritized discontinuity surface with pyrite crystals occurs on the upper boundary of the Saarde Formation (possible Sandvika Event level, Kaljo *et al.* 1998).

The thickness of the Rumba and Velise formations increases towards the north and south. The contact of the formations is sharp in the Ruhnu (500) section, between limestone and bituminous marlstone. The marlstones of the Velise Formation contain volcanic interbeds (Appendix 1, sheets 17, 18).

The thickness of the Riga, Jaani and Jamaja formations increases towards the northwest. At Ruhnu this interval represents a thick marlstone complex (Appendix 1, sheets 13–16) with rare limestones interbeds (Pl. 3, figs 10–12). Some volcanic interbeds occur in the Jaani and Jamaja formations. The boundaries of the formations are transitional, except for the upper boundary of the Jamaja Formation, which is marked by the sharp contact of marlstone and overlying limestone of the Sõrve Formation.

The thickness of the Sõrve Formation increases towards the northwest. In the Ruhnu (500) section the formation is represented by uniform nodular limestones and dolostones with marlstone (Pl. 2, fig. 9) interbeds. The rock contains up to 50% bioclasts (often unsorted), in the upper half with stromatoporoids and tabulate coral fragments and bioherms (Pl. 2, fig. 8; Appendix 1, sheets 10–13). Dolostone containing carbonaceous clasts and bioclasts (mainly

crinoids) over 50% (rudstone)occurs in the interval of 285.8–287.6 m between two discontinuity surfaces (influence of the Mulde Event, see also Kaljo *et al.* 1998, and Männik in this volume). The same interval includes also well-rounded, calcareous clastic material with pyritized surfaces, crusts of ooliths and quartz silt. A 3 cm thick conglomerate bed lies on the rugged lower boundary of the interval (Appendix 5, D-5).

The Rootsiküla Formation (Appendix 1, sheets 9, 10) composed of eurypterid-dolostone in its lower part and of bioclast-rich dolostone (boundstone) in its upper part. In places stromatolite, tabulate co-rals, oncolites, calcareous clasts and glauconite-bearing interlayers are found. Numerous pyritized discontinuity surfaces are present (Pl. 2, fig. 7). Determination of lithological contacts of beds is problematic due to dolomitization.

The present narrow distribution area of the upper Silurian (Ludlow and Přidoli) sediments on the Estonian territory is documented on the Sõrve Peninsula (southwestern Saaremaa) and Ruhnu Island. The thickness of the upper Silurian part increases to the southwest of Ruhnu Island. Because of dolomitization, it is hard to distinguish the formations and members in the Ruhnu (500) core.

Dolostones of the Torgu Formation contain tabulate corals, stromatolite and stromatoporoid fragments (Appendix 1, sheets 9). In places poorly sorted clasts make up to 50% of sediment. Pyritized discontinuity surfaces and pyritic mottles which generally are typical of the formation are indistinct because of dolomitization.

A volcanic bed with biotite flakes, identical to the Grötlingbo Bentonite (see Kiipli & Kallaste, and Männik in this volume) occurs at 221.8–222.0 m (Appendix 1, sheet 8) in the dolomitized limestones of the Kuressaare Formation. This bed is overlain by the limestone containing pyritized excavated discontinuity surfaces.

The limestones (Pl. 2, figs 3, 4), dolostones (Pl. 2, fig. 5), marlstones (Pl. 2, fig. 6) and dolomitic marlstones of the Kaugatuma Formation (Appendix 1, sheets 7, 8) include some distinct pyritized surfaces with pyritized limestone pebbles and bituminous interlayers. Dolostone (in places bituminous) and dolomitic marlstone microbeds (Appendix 5, D-2) at 175.0–177.0 m contain quartz silt and sand (possible level of the middle Přidoli Event, Kaljo *et al.* 1998).

The dolostones and dolomitic marlstones (Appendix 5, D-1; Pl. 2, fig. 2) of the Ohesaare Formation contain grains of quartz silt and sand. In the upper part (Appendix 1, sheet 6) glauconite grains and a siltstone interval (core yield 40%) with muscovite flakes are present. The Silurian sediments are overlain by Devonian sandstones.

Early Silurian sedimentation began with a glacio-eustatic rise of the sea level, followed by basin shallowing in the Middle Llandovery. Like in other Central and West Estonian sections, a local break in sedimentation and partial denudation are documented. The Silurian Baltic basin transformed into a gulf-like epicontinental sea, cutting into the presumable land in the north, east and south (Nestor & Einasto 1997). In the new, deepening phase (from Adavere to mid-Jaani ages) sedimentation took place in open shelf conditions (Rumba time). Deepening of the basin continued in Velise, Riga and Jaani times. The increase in volcanic activity in neighbouring areas is evidenced by numerous bentonite interlayers.

As determined from the northern sections, new shallowing of the basin started in the middle of the Jaani Age and continued gradually through the Jaagarahu Age. It ended with a sedimentation break and erosion in the marginal part of the sedimentation basin.

Sedimentation in the Rootsiküla and Paadla ages continued in wide shoal areas. The presumable regression maximum in Vesiku time turned gradually into transgression. In the southwestern part of the present distribution area of Rootsiküla–Paadla sediments, the deeper-water sedimentation was more continuous (Nestor & Einasto 1997).

The Kuressaare Age began with a transgression, which reached a maximum in the early Kaugatuma Age. The following shallowing of the basin in Ohesaare time corresponds to the shoal environment. The supply of terrigenous material from the Scandinavian Caledonides increased (Nestor & Einasto 1997).

In the **Devonian** the Estonian territory was covered by an epicontinental shallow sea, characterized by extensive sedimentation of terrigenous material transported from the northward mainland. The small sedimentary basin, which formed in the central Baltic area at the end of the early Devonian, expanded gradually during the middle–late Devonian (Kleesment 1997). In the Ruhnu (500) section (Fig. 2) the Devonian sediment sequence (Emsian, Eifelian) is 138.3 m thick (interval 7.8–146.1 m; Appendix 1, sheets 1–6) and lies unconformably on the Silurian. The Devonian part of the section is described in a special chapter (see Kleesment in this volume).

The **Quaternary** cover is 7.8 m thick but only 2.3 m of the core is available (Appendix 1, sheet 1). The fragmentary core and gamma-logging data show that the Devonian rocks are covered by sandy loam, predominantly overlain by sand with few siltstone pebbles (Holocene deposits).

DEVONIAN

The Rēzekne, Pärnu and Narva regional stages represent the Devonian sequence in western Estonia. The stratigraphical units in the Ruhnu (500) core (Appendix 1, sheets 1–6) were determined mainly on the basis of lithological-mineralogical criteria (see Appendixes 7–11). Only the Leivu Formation of the Narva Stage is confidently defined by palaeontological data – the occurrence of the scales of the acanthodian *Ptychodictyon rimosum* at a depth of 72.2 m (Appendix 12). From the Gorodenka Formation scales of long-ranging species were identified, which did not determine the exact stratigraphical position of this unit (Valiukevičius 1998).

The **Rēzekne Regional Stage** (130.0–146.1 m, Appendix 1, sheets 5, 6) lies unconformably on the siltstone complex of the upper Silurian Ohesaare Formation. The Rēzekne Stage is represented by the Lemsi Formation (stratotype in the Kihnu drill core, interval 69.8–85.8 m; Kleesment, 1981), which is rather similar and well correlatable in the Kihnu (core yield 32%) and Ruhnu (core yield 28%) cores. The basal layer of the formation contains redeposited fish scales of the Early Devonian Tilže Formation (unpublished data of Valentina Karatajūte-Talimaa). This refers to the possibility that in Tilže time the deposition area spread up to Ruhnu district, where deposition took place during the extensive Early Devonian break in sedimentation.

The succession of the Lemsi Formation is mainly represented by brownish-grey, weakly cemented fine- to medium-grained sandstone (Appendixes 7–11). According to the mineralogical composition after Folk (1974) the sandstones qualify as subarkoses and arkoses. The content of micas is notable only in the siltstone layer (sample 500–39 at 130.0–130.6 m) in the basal part of the succession (Appendixes 8, 9). Garnet is clearly dominating among transparent heavy minerals, also zircon is found in considerable amounts (Appendix 10; Kleesment & Mark-Kurik 1997).

The **Pärnu Regional Stage** (104.8–130.0 m, Appendix 1, sheets 4, 5) is represented by the Tori and Tamme members of the Pärnu Formation containing grey fine- to medium-grained sandstone (Appendix 7). The core yield is 36.5%. The sandstone of the Tori Member is weakly cemented. In the Tamme Member medium- and strongly cemented layers intercalate. According to the mineralogical composition the sandstone is mainly subarkose (Appendixes 8–11). The heavy transparent mineral spectrum is dominated by garnet and zircon. Tourmaline, apatite and staurolite occur in minor quantities (Appendixes 9, 10).

The **Narva Regional Stage** (7.8–104.8 m, Appendix 1, sheets 1–4) is represented by the Vadja, Leivu and Gorodenka formations. These formations can be traced in the whole territory of Estonia, also in the South East Baltic and western Belarus (Valiukevičius *et al.* 1986).

The lowermost, Vadja Formation (93.0–104.8 m; Appendix 1, sheet 4; core yield 78%) is characterized by intercalating of light grey dolostone, grey dolomitic marlstone and dark grey dolomitic claystone (Appendixes 7, 11). The breccia layer, commonly present in the basal part of this unit, is absent in the Ruhnu (500) core.

The detrital rocks belong, according to the mineralogical composition, to mica-rich quartzarenite (Appendix 8). Heavy minerals are dominated by pyrite and iron-hydroxide (Appendix 9), transparent heavy minerals by garnet and zircon. Some levels contain corundum in notable amounts (Appendix 10).

The middle of the stage is represented by dolomitic marlstones of the Leivu Formation (38.6–93.0 m, Appendix 1, sheets 2–4; core yield 57%). In the lower part of the formation rocks are predominantly grey, higher multicoloured, mainly reddish-brown, with grey partings and spots. The dolomitic marlstone contains abundantly thin interlayers of dolomitic claystone, dolostone and siltstone (Appendixes 7, 11). Dolostone interlayers occur in the lower part, siltstone interbeds in the upper part of the section. According to the mineralogical composition the detrital part of the rocks is mica-rich quartzarenite (Appendixes 8, 9). Iron hydroxides are dominating among heavy minerals (Appendix 9). Garnet is the main transparent heavy mineral, accompanied by zircon and titanite, also apatite and amphibole (Appendix 10).

The uppermost, Gorodenka Formation (7.8–38.6 m, Appendix 1, sheets 1, 2; core yield 67%) is represented by thinly intercalated reddish-brown and grey sand- and siltstone, with rare interbeds of multicoloured dolomitic marlstone (Appendixes 7, 11). The sandstone is mostly very fine-grained. According to the mineralogical composition detrital rocks belong to quartzarenites. Micas occur commonly in notable quantities (Appendix 8). Heavy minerals are dominated by micas (Appendix 9), transparent heavy minerals by apatite and garnet (Appendix 10). The content of zircon and tourmaline is lower in the Ruhnu (500) section than usually in rocks of the Gorodenka Formation (Kleesment & Mark-Kurik 1997).

The diagenetic alternation processes in the thinly laminated section of sand- and siltstone, dolostone, dolomitic marlstone and claystone have been described by the study of authigenic overgrowths on detrital feldspar grains (Kleesment 1998).

DISTRIBUTION OF SILURIAN CHITINOZOANS

From the Silurian part of the Ruhnu (500) core, 322 samples weighing between 0.3 and 0.5 kg were collected, processed and studied, of which 45 appeared to be barren of chitinozoans (Appendix 1, sheets 6–21; Appendix 13). Barren samples come mostly from the Rootsiküla, Paadla and Ohesaare stages (see Appendix, sheets 1–4). The sampling density was higher in the Adavere and lowermost Jaani stages. The samples, collected from there by Peep Männik for conodonts, were studied also for chitinozoans. The collection is stored at the Institute of Geology at Tallinn Technical University.

The biozonation of Silurian (mostly of Llandovery and/or Wenlock sequences) chitinozoans of Estonia and North Latvia has been discussed in several papers (Nestor 1982, 1994; Nestor & Nestor 2002; Nestor *et al.* 2003). The whole succession of Silurian chitinozoan biozones for these regions including 31 zones is presented in Nestor (1990). A global chitinozoan biozonation for the Silurian, with 17 biozones, was proposed in 1995 (Verniers *et al.* 1995).

In the Silurian of the Ruhnu (500) core, 26 chitinozoan biozones along with 3 interzones were established (Appendix 14, sheets 1–4). Three biozones (*Rhabdochitina* sp. 2, *Conochitina rara, Conochitina acuminata*) are provisionally distinguished for the first time. Because of the scarcity of chitinozoans and many barren samples in the upper Silurian, some biozones were missing or identified tentatively.

The distribution of 125 species is given in Appendix 14 (sheets 1–4). All previous samples (residues) were restudied and new ones were examined in the light of recently obtained data (Verniers 1999; Mullins & Loydell 2001). This caused some changes in species identification and biozonation, compared with Nestor (1990, 1994).

The occurrence of *Spinachitina fragilis* in the Puikule Member at 600.8 m defines the lowermost chitinozoan zone in the Silurian of the Ruhnu (500) core (Appendix 14, sheet 4), followed by an almost barren interzone. A single finding of *Belonechitina postrobusta* at 577.6 m in the lowermost beds of the Raikküla Stage indicates that the upper part of the Juuru Stage, characterized usually by abundant occurrence of this species, may be missing in this section. The lower boundary of the *Euconochitina electa* Zone is defined by the disappearance of *B. postrobusta* and abundant appearance of the zonal species. The *Ancyrochitina convexa* Zone is established in the interval of 557.2–560.6 m. The differentiation and use of the next two biozones, *Conochitina alargada* (541.2–557.2 m) and *C. malleus* (529.4–541.2 m) in the middle of the Raikküla Stage are discussed in Nestor *et al.* (2003). The *Rhabdochitina* sp. 2 Zone is provisionally distinguished in the Ruhnu (500) core in the interval of 500.7–529.4 m. The species occurs also in the other studied Llandovery sections, where this part of the Raikküla Stage is represented (Nestor *et al.*, 2003). The *Conochitina rara* Zone is also provisionally distinguished, corresponding to the Staicele Member. *C. rara* occurs in the interval of 492.3–500.0 m in the Ruhnu (500) core. It should be noted that this species has not yet been found in other sections and usually an interzone is distinguished in the corresponding part of the Staicele Member (Nestor *et al.* 2003).

The *Eisenackitina dolioliformis* Zone is restricted to the lowermost layer of the Velise Formation (488.7–489.2 m). The Rumba Formation, usually characterized by the rich assemblage of the *E. dolioliformis* Zone (Nestor 1994), in the Ruhnu (500) core contains only overcomers from the Raikküla Stage.

Angochitina longicollis appears at Ruhnu at a depth of 488.6 m (see Appendix 14, sheet 4), indicating a stratigraphical gap of about six graptolite zones in the lower part of the Velise Formation (see Loydell *et al.* 2003). *Conochitina proboscifera* appears at 485.7 m (see Appendix 14, sheet 3), also indicating condensed thickness of the *A. longicollis* Zone. Above the *C. proboscifera* Zone, the *Conochitina acuminata* Zone was distinguished in the interval of 459.1–465.6 m. *C. acuminata* is widely represented in the uppermost Llandovery of many East Baltic sections (Nestor 1994), but as a separate zone between the *A. longicollis* and *M. margaritana* zones it was first described by Mullins & Loydell (2001) in the Banwy River section, Wales. It should be noted that five species of chitinozoans, recently described in the Banwy River section and in the Builth Wells district (Verniers 1999), were established also in the Ruhnu (500) core.

The boundary of the *Margachitina margaritana* Zone is defined by the appearance of the zonal species at a depth of 459.0 m. Earlier (Nestor 1990, 1994), this level was considered to coincide with the Llandovery–Wenlock boundary. Later investigations (Mullins 2000; Mullins & Loydell 2001) established that the level of the appearance of *M. margaritana* fell in the upper Llandovery, corresponding to the *C. insectus* graptolite Zone. The changes in the chitinozoan succession in the stratotype for the base of the Wenlock were recently described in detail by Mullins & Aldridge *(in press)*.

The disappearance level of *A. longicollis* (at 451.0 m) indicates the boundary between the *M. margaritana* Zone and succeeding interzone.

It is worth mentioning that 23 chitinozoan taxa became extinct in the Tõlla Member of the Riga Formation in the Ruhnu (500) core (see Appendix 14, sheet 3), 12 of them in the interval of 451.0–456.0 m that corresponds to the main part of the Ireviken Event (Nestor *et al.* 2002).

Successive appearance of *Conochitina mamilla* (at 437.75 m), *Conochitina tuba* (429.7 m), *Cingulochitina cingulata* (413.2 m), *Eisenackitina lagena* (383.45 m), *Conochitina pachycephala* (356.0 m), *Conochitina cribrosa* (325.7 m) and *Sphaerochitina indecora* (315.2 m) determine the chitinozoan zonal succession (see Appendix 14, sheets 2, 3) in the Jaani, Jamaja and Sõrve formations of the Ruhnu (500) core as well as in the other studied Wenlock sections (Nestor 1994). In addition, many other stratigraphically important species (e.g. *Ancyrochitina paulaspina, Clathrochitina clathrata, Ramochitina martinssoni, Conochitina subcyatha, Cingulochitina baltica, Cingulochitina crassa*, etc.) have been recorded in this interval, demonstrating completeness of the lower–middle Wenlock sequence in this section.

Most chitinozoan species occurring in the Wenlock disappear in the topmost part of the Sõrve Formation (see Appendix 14, sheet 2), only a few last species range over into the Viita Beds of the Rootsiküla Stage. The rest part of this stage (Kuusnõmme, Vesiku and Soeginina beds) and lower portion of the Torgu Formation of the Paadla Stage (Appendix 14, sheet 1) were barren of chitinozoans. Probably alternation of lagoonal and agitated-water conditions inhibited preservation of thin-walled, fragile vesicles of chitinozoans.

Scarce occurrence of chitinozoans is characteristic of the entire upper Silurian sequence of the Ruhnu (500) core. The barren samples did not allow identification of the lowermost Ludlow biozones (see Nestor 1990). The first zonal species *Eisenackitina lagenomorpha* appears in the upper part of the Torgu Formation (at 233.2 m; Appendix 14, sheet 1), being the best represented species in the upper Silurian sequence.

A single occurrence of *Pterochitina perivelata* at 226.75–226.85 m might indicate the *P. perivelata* Zone with an unfixed upper boundary. A questionable occurrence of *Eisenackitina barrandei* in the basal part of the Lower Äigu Beds of the Kaugatuma Stage (214.0–214.1 m) is, according to Verniers *et al.* (1995), an element of the Ludlow fauna. Only rare *E. lagenomorpha* were found in the middle and upper parts of the Lower Äigu Beds.

Chitinozoans are lacking in the lower and middle parts of the Upper Äigu Beds in the Ruhnu (500) core. The assemblage of chitinozoans including the zonal species *Salopochitina filifera* (from 190.80 m) appears in the topmost part of the Upper Äigu Beds and ranges into the Lõo Beds (Appendix 14, sheet 1).

The Ohesaare Stage of the Ruhnu (500) core does not practically contain chitinozoans.

It is not quite understandable why the assemblage of chitinozoans is so poor in the upper Silurian sequence of the Ruhnu (500) core, compared with the Ohesaare core (Nestor 1990 and unpublished data). Probably more isolated, restricted shelf conditions prevailed in the surroundings of Ruhnu during late Silurian time. Six biozones have been distinguished and only some barren samples found in the Ohesaare core. Nevertheless, it should be noted that both biozones, distinguished in the Ruhnu (500) core, seem to correlate well with those in Ohesaare: *E. lagenomorpha* appears there at 98.95 m (upper part of the Torgu Formation) and *S. filifera* at 40.10 m (upper part of the Upper Äigu Beds).

DISTRIBUTION OF SILURIAN AGNATHAN AND FISH MICROREMAINS

In Estonia, agnathan and fish microremains appear in the Lower Silurian (Llandovery) Raikküla Stage. Their findings are extremely rare in the whole Llandovery and lower Wenlock (Jaani Stage). Higher, from the middle of the Jaagarahu Stage (Maasi Beds) up to the end of the Silurian, they become more and more frequent and abundant, with several bonebed levels (Märss 1986, 1990). Data on the distribution of vertebrate microremains in the Ruhnu (500) section are published in Märss (1986, fig. 40). Since this monograph, more scale material has become available and several taxa have been revised. In addition to the 66 earlier samples, 14 new ones have been studied. Because of very dense sampling in the upper part of the Ruhnu (500) section, only selected samples are included in the present issue (Appendixes 15, 16).

In the interval from 388.15–388.30 to 305.45–305.60 m, *Loganellia* sp. scales are found in small numbers, 1–3 in each sample. The scales are tiny, with very narrow crowns bearing longitudinal ridges. Some shorter scales in the lower beds resemble *L. scotica*, the index-species of the Upper Telychian (Llandovery). At the present stage of study these are not identified on the species level.

Rare scales of *Loganellia einari* were identified in a short interval between 333.65–333.80 and 329.65–329.80 m. It is the index-species of the Tagavere Beds (the lowermost part excluded) of the Jaagarahu Stage (Märss 1996), and the corresponding

biozone has been established in the Riksu, Kipi, Vesiku, Paadla and Sakla drill cores. ?*Thelodus* sp. appears at 307.00–307.15 m and ranges up to 291.65–291.80 m, while *Thelodus carinatus*? starts at 298.10–298.15 m and *Paralogania martinssoni* a few metres higher, at 293.30–293.45 m. The last three species were also identified at 291.65–291.80 m where an anaspid *Birkenia* sp. and an osteostracan *Trematapsis* sp. ind. joined the assemblage. The whole range of the thelodont *Par. martinssoni* is from the base of the Viita Beds of the Rootsiküla Stage up to the middle of the Uduvere Beds of the Paadla Stage (Märss 1986). Other taxa in the studied samples, especially ?*Thelodus* sp. with specific ultrasculpture of the crown, are indicative of the Rootsiküla Stage, particularly of the Vesiku Beds of the stage where this taxon is rather common (T. Märss pers. obs. 2003). Also the taxon identified as *T. carinatus*?, having distinct downstepped margins but lacking parallel fine ridgelets on the crown, supports this age of these beds (for example, in the Vesiku outcrop); the real *T. carinatus* is a taxon characteristic of the Paadla Stage. Thus, the whole assemblage refers to the Rootsiküla Stage.

The association of agnathans and fishes between 190.8 and 175.0 m is represented mainly by acanthodians of *Nostolepis striata* type, *N. gracilis*, recently described *N. linleyensis* (see Miller & Märss 1999), of *Gomphonchus sandelensis* type and *Poracanthodes* sp. The listed acanthodians are accompanied by rare thelodonts *Katoporodus tricavus* appearing at a depth of 187.6 m and *Loganellia cuneata* appearing at 177.4 m. The first evidence of the heterostracans *Tolypelepis undulata* is at 179.0 m and *Strosipherus indentatus* at 177.4 m, while *Cyathaspididae* gen. et sp. ind. appear in slightly lower beds. In Estonia and northern Latvia the entire Kaugatuma Stage is characterized by two to three acanthodians. The index-species *Nostolepis gracilis* usually appears in the upper part of the Äigu Beds. *Nostolepis linleyensis* is described from the Downton Castle Sandstone Formation (Přidoli) of Linley Brook near Much Wenlock (Shropshire, Britain) (Miller & Märss 1999). The above-listed thelodonts may appear already in the Tahula Beds of the Kuressaare Stage (Ludlow).

The upper Přidoli portion of the Ruhnu (500) core is very rich in vertebrate microremains. On the basis of their assemblages, the strata between 174.5 and 148.1 m can be divided into two parts. In the lower part (174.5–161.8 m), in addition to the taxa that continue their distribution from the underlying beds, several new species and genera are recorded for the first time, such as the acanthodian *Gomphonchus hoppei* and osteichthyan *Lophosteus superbus* at 174.5 m, the anaspid *Liivilepis curvata* and acanthodian *Poracanthodes punctatus* at 172.6 m, the osteichthyan *Lophosteus ohesaarensis* at 170.0 m, and the thelodont *Goniporus alatus* and anaspid *Ruhnulepis longicostata* at 163.2 m. *Thelodus parvidens* starts at 174.5 m and *T. traquairi* at 163.2 m in the Ruhnu (500) section. The levels do not show the earliest occurrence of these two thelodant species because their probable appearance is not documented here. Elsewhere they are known to appear already in the Uduvere Beds of the Paadla Stage and in the Tahula Beds of the Kuressaare Stage, respectively (Märss 1986). Small fragments of cephalaspidid osteostracans are distributed both in the lower and upper beds. Biostratigraphically important species characteristic of the Ohesaare Stage are *G. hoppei, L. superbus, L. ohesaarensis* (see Schultze & Märss submitted), *P. punctatus* and recently described anaspids *Liivilepis curvata* and *Ruhnulepis longicostata* (Blom *et al.* 2002).

In the upper part (157.2–148.1 m) *Nostolepis alta, Tylodus deltoides*, rare scales of *Paralogania*? *tarranti* and *Paralogania* sp. nov. have been identified. *N. alta* occurs above the beds that crop out in the Ohesaare cliff (for example, in the Kaavi (568), Kaavi (571), Kolka (54), and Ventspils sections). The true *Par. tarranti* has been described from the upper Přidoli at Man Brook locality (Britain), below the range of *Paralogania kummerowi* (Märss & Miller in press). The latter is a characteristic species of the uppermost Silurian.

DISTRIBUTION AND BIOSTRATIGRAPHICAL VALUE OF GRAPTOLITES

Silurian graptolite-bearing rocks occur mainly in three intervals in the Ruhnu (500) drill core – in the lower part of the Saarde Formation of the Raikküla Stage, in the Velise Formation of the Adavere Stage (both Llandovery) and in the Riga (Tõlla Member) and Jaani formations of the Jaani Stage (Wenlock). Only a few occurrences are known slightly higher than the Jaagarahu Stage, but the uppermost Wenlock, Ludlow and Přidoli, as well as the very beginning of the Llandovery, are devoid of graptolites. The Ordovician is also practically barren in the Ruhnu (500) core (only two occurrences recorded). This general distribution pattern is well known from the earlier studied cores (Ohesaare, Ikla, etc., summarized by Kaljo 1997) and is determined by regressive-transgressive changes in the location of the shelf and basin facies belts in the East Baltic.

The studied collection holds 69 samples (Appendix 17) containing graptolite remains (marked Gr in Appendix 1, sheets 12–23), but most of these

are too fragmentary for correct species- or even genus-level identifications. The most reliable data (including sp., cf., ex gr.) are listed in Appendix 18. The study was financially supported by the Estonian Science Foundation (grant No. 5042).

Upper Ordovician graptolites are represented by two samples. The sample (depth 650.2 m) from the Haljala Stage contains fragments of *Climacograptus* sp. and that (615.6 m) from the Porkuni Stage a benthic dendroid *Estoniocaulis* sp. Obut & Rytzk (1958) described the latter inocaulid genus from the Juuru Stage of North Estonia; the specimen from the Ruhnu (500) core is the second record of the genus here. These graptolites are of little biostratigraphical value, but occurring at the levels where graptolites, especially dendroids are found most frequently in mainland Estonia, they seem to have an environmental meaning.

The above-mentioned Silurian intervals contain more abundant graptolites, allowing us to date lithostratigraphical units like members and beds in terms of graptolite biostratigraphy or even to define more or less exactly some biozonal boundaries in the core section.

The lowermost two Silurian samples (586.2 and 585.6 m, Appendix 18) come from a marlstone packet, the Heinaste Member (Nestor *et al.* 2003), in the bottom of the Saarde Formation. *Neodiplograptus* ex gr. modestus (perhaps cf. *diminutus* Elles & Wood) and *Raphidograptus toernquisti* occurring here are not decisive for the identification of a biozone, but most likely they fit into the assemblage of the *Coronograptus cyphus* Biozone. A firmer conclusion about the late Rhuddanian age is suggested by the occurrence of *Huttagraptus acinaces* slightly higher in the Slitere (cf. Appendix 18) and Kolka members. This graptolite species, earlier known only in the *cyphus* Biozone, was reported for the first time in the Baltic from the middle of the Saarde Formation of the Ohesaare core (Loydell *et al.* 1998) and later from the Remte Formation of the Aizpute-41 core (Loydell *et al.* 2003). The occurrence of *C. cyphus* itself in the Ruhnu (500) core is doubtful (Appendix 18), but *Atavograptus atavus* and *Glyptograptus* cf. *sinuatus* are most typical of the upper *cyphus* Biozone in the Baltic (Kaljo *et al.* 1984) even if continuing in the lower *Demirastrites triangulatus* Biozone.

The beginning of the latter zone, marked usually by the appearance of the eponymous species and/or *Coronograptus gregarius*, coincides in the Ruhnu (500) core more or less exactly with the bottom of the Ikla Member of the Saarde Formation. The lower boundary of the member is placed (see Appendix 1, sheet 20) at a depth of 558.5 m; a specimen of *C. gregarius* with a rather short sicula (4.1 mm) occurs only 30 cm higher. Hutt (1975), Štorch (1988) and some others have shown that short siculae are indicative of earlier representatives of the species beginning with rare occurrences in the uppermost *cyphus* Biozone (Loydell *et al.* 1998). Co-occurrences of the last specimens of *C. cyphus* and first *C. gregarius* have been recorded also in the Baltic (Kaljo *et al.* 1984, table 3; Ulst 1973, Staicele core). Paškevičius (1979) noted a *C.* cf. *gregarius* having a short sicula in the uppermost *cyphus* Biozone in the Kunkoiai core. An aff. *gregarius* was identified by Kaljo & Vingisaar (1969) in the Ikla core (three specimens found, the earliest with a 4.5 mm long sicula, higher ones with 5.0 and 6.0 mm siculae) below the base of the Ikla Member. The first record of *Demirastrites triangulatus* in the Ruhnu (500) core is at 557.8 m, i.e. 70 cm above the base of the Ikla Member (in the Ikla core 190 cm above this level, Kaljo & Vingisaar 1969). R. Ulst (Gailite *et al.* 1987) identified it in the Ventspils core 50 cm, but Loydell *et al.* (2003) in the Aizpute-41 core 1.32 m above the lower boundary of the Dobele Formation.

In different correlation charts the lower boundary of the Ikla Member has been placed (Kaljo 1990; Nestor 1997) at the same level with the base of the *triangulatus* Biozone (Aeronian) and also with that of the Dobele Formation. Here this view is retained, but the above data from the Ruhnu and Ikla cores suggest that the lowermost beds of the member (less than 70 cm), as well as a small part of the Dobele rocks, might be correlated with the *cyphus* Biozone (Rhuddanian).

The graptolite assemblage identified in the lower 16.5 m of the Ikla Member is listed in Appendix 18. Higher in the Saarde Formation and in the thin Rumba Formation (see Appendix 1, sheet 18), no graptolites were found, i.e. there is a 53 m gap in the corresponding information. Judging from the assemblage content, the graptolitic part of the Ikla Member belongs without doubt to the *triangulatus Biozone* (Aeronian), represented mainly by the lower (*triangulatus* s. str.) and perhaps middle (*magnus*) subzones. The latter subzone is indicated by the occurrence of *Campograptus millepeda*. For the interpretation of the overlying 53 m of non-graptolitic rocks some useful data might be obtained from other cores.

Several core sections in the neighbourhood of the Ruhnu (500) core show besides the information gap also a real hiatus. Loydell *et al.* (1998) identified in the Ohesaare core a gap embracing the biozones beginning with the *magnus* Subzone until the middle of the *Spirograptus turriculatus* Biozone (represented by the *proteus* Subzone). The gap began 9 m

above the occurrence of an early *C. gregarius*. In the Aizpute-41 core, the Dobele Formation is richly graptolitic and all Aeronian graptolite biozones are well represented, but the Telychian begins as in Ohesaare with the *proteus* Subzone (Loydell *et al.* 2003), i.e. after a gap embracing one and a half zones or a little more, depending on how complete the *Stimulograptus sedgwickii* Biozone is. In the Ventspils core, located closer to the Ruhnu and Ohesaare ones, the Dobele Formation includes much more limestone intercalations and the graptolite record is less full. Nevertheless, Gailite *et al.* (1987) list *Campograptus lobiferus* (McCoy), *Demirastrites decipiens* (Törnquist), *Stimulograptus sedgwickii* (Portlock), etc. in the upper part of the formation, indicating that both the *Demirastrites convolutus* and *S. sedgwickii* biozones are represented at least in some part. Above the latter biozone occur *Pristiograptus* ex gr. *nudus* and *Monograptus parapriodon*, which do not give any clear biostratigraphic information, but it seems that at least the *turriculatus* s. lato Biozone is missing. *Stimulograptus* ex gr. *sedgwickii* was reported by Ulst (1973) from a dolostone underlying the marlstones with *Streptograptus exiguus* (Lapworth) and *S. crispus* (Lapworth) in the Burtnieki core (North Latvia). The sense of this ex gr. is obscure, but Ulst (1973) places the dolostone into the Aeronian, allowing us to conclude that the gap at the Aeronian–Telychian boundary embraces the whole *turriculatus* s. lato Biozone and perhaps a little more.

Proceeding from the logic of the above information, the author is sure that the gap in the upper part of the Raikküla Stage (Aeronian) in the Ruhnu (500) core should be much smaller than defined by Loydell *et al.* (2003) in the Ohesaare core. For specification of limits of the hiatus besides graptolite distribution also different micropalaeontological data are needed.

The Telychian part of the Ruhnu (500) section begins with the Velise marlstones at 489.2 m. The list of graptolites identified (Appendix 18) from the lower 1 m comprises mostly species appearing usually in the *crispus* Biozone and occurring also higher (e.g. *Stimulograptus* cf. *clintonensis*, *Oktavites* cf. *spiralis*, etc.). Judging from these occurrences, the *Spirograptus guerichi* and *turriculatus* biozones are missing in the Ruhnu (500) core. Here it should be noted that Kaljo & Martma (2000) reported *Rastrites linnaei*? from the first Velise sample at 489.2 m, but revising the collection for this paper the author decided to drop the identification due to very poor preservation of the specimen. At 488.0 m *Monograptus parapriodon* marks the *Monoclimacis griestoniensis* Biozone, represented here rather unconvincingly. At 487.6 m *Streptograptus* cf. *kaljoi* refers to the lower *Oktavites spiralis* Biozone, at 482.5 m *Diversograptus ramosus* to the middle *spiralis* Biozone and at 477.65 m *"Monograptus" vesiculosus* to the upper *spiralis* Biozone. Some additional refinements are possible through the discussed interval, but surely no firm markers for the topmost two Telychian biozones are found. The only possible representative of the lower *Cyrtograptus lapworthi* Biozone assemblage is *Monoclimacis* aff. *linnarssoni*.

The bottom of the Tõlla Member, and of the Wenlock Series, is drawn (Appendix 1, sheet 16) at 457.5 m. The first *Cyrtograptus* cf. *murchisoni* is recorded (Appendix 18) at 453.9 m, i.e. a 3.6 m interval is left without graptolite dating. Which part of it is missing information and which part belongs to a gap at the Llandovery–Wenlock boundary cannot be decided on the basis of the available data. The *Cyrtograptus murchisoni* Biozone is easily identifiable up to 447.8 m thanks to frequent occurrences of the eponymous species, also *Monoclimacis vomerina, M. hemipristis*, etc. and *with a Monograptus firmus* band in the very top of the zone. It is surprising that *Retiolites* is missing in the Wenlock of the Ruhnu (500) core.

The first *Monograptus riccartonensis* appears at 447.2 m, i.e. the boundary of the biozones should be at some level within a 60 cm interval. Typically of the Ruhnu area, the *riccartonensis* Biozone assemblage is rather poor. Characteristic is also the *Pristiograptus dubius* group in the upper part of the biozone and above it. In this sense the *riccartonensis* Biozone assemblage in the Ruhnu (500) core (even its thickness of 6.5 m) is very much the same as in the Ohesaare core.

From the Sõrve Formation a doubtful occurrence of *Gothograptus pseudospinosus* was recorded. It may indicate the *Cyrtograptus lundgreni* Biozone in the upper Wenlock.

DISTRIBUTION OF ORDOVICIAN AND SILURIAN CONODONTS

In total, 292 samples from the interval from the Lasnamägi (middle Llanvirn) to Rootsiküla (?) stages (Homerian) were studied for conodonts (Appendixes 19–21). The size of the samples varied from 180 to 940 grams, and the number of conodont specimens per sample from less than 10 to many hundreds. All samples but three – two from the Ēdole Member of the Kuldiga Formation (615.45–615.55 and 610.95–611.05 m) yielded conodonts. Conodonts are amber in colour (CAI=1 sensu Epstein *et al.* 1977). The number of taxa and specimens in samples varies greatly. Two intervals with particu-

larly rich faunas were recognized, one corresponding to the Lasnamägi–lower Haljala stages (upper Llanvirn–lower Caradoc) and the other to the Adavere–lower Jaani stages (Telychian–lower Sheinwoodian). Both high-diversity episodes were terminated by an extinction event (see below).

The study of conodonts was supported by the Estonian Science Foundation grants Nos 5088 and 5406. The studied collection is stored at the Institute of Geology at Tallinn Technical University.

Ordovician

Pygodus serra to *Amorphognathus tvaerensis* zones. The lower part of the studied Ordovician interval is characterized by rich faunas (high number of specimens and taxa in samples). The *Pygodus serra* and *P. anserinus* zones are well represented by their nominal taxa (Appendix 20). In the *P. serra* Zone, the *Baltoplacognathus reclinatus, Eoplacognathus robustus, Yangtzeplacognathus protoramosus* and *E. lindstroemi* subzones were recognized. The lower boundary of the *P. serra* Zone probably lies further down in the Lasnamägi Stage, below the interval sampled for conodonts.

The lower boundary of the *P. anserinus* Zone coincides with the level where *P. serra* is replaced by *P. anserinus*, and its upper boundary is marked by the appearance of *Amorphognathus tvaerensis*. Two subzones, Lower Subzone and Upper Subzone *sensu* Bergström (1971), can be recognized in the *P. anserinus* Zone. According to Bergström (1971), the boundary between these subzones corresponds to the level of appearance of *Baltoniodus variabilis*. Later, Dzik (1978) pointed out that primitive specimens of *B. variabilis* had amorphognathiform (Pa) element hardly distinguishable from that of its ancestor *B. prevariabilis*. Data from the Ruhnu (500) core agree with Dzik's conclusions and the level of appearance of *B. variabilis* (and the position of the boundary between the Lower and Upper subzones) in the studied section (Appendix 20) is quite problematic. In the Upper Subzone of the *P. anserinus* Zone, *A. inaequalis* was found (samples from 664.8 and 663.8 m). The occurrence of *A. inaequalis* in this interval probably indicates that it corresponds to the *A. inaequalis* Zone *sensu* Dzik (1978).

The appearance of *A. tvaerensis* in the middle of the Dreimani Formation (sample from 662.80 m; middle part of the Kukruse Stage) marks the lower boundary of the *A. tvaerensis* Zone. The upper boundary of the zone corresponds to the level of disappearance of *A. tvaerensis* and lies in the uppermost Idavere Formation. As in several other Estonian sections (e.g. Viira & Männik 1999; Männik 2001a), three subzones, *Baltoniodus variabilis*, *B. gerdae* and *B. alobatus* can be recognized in the *A. tvaerensis* Zone also in the Ruhnu (500) core (Appendix 20).

The Mid-Caradoc Event. An episode of biotic, climatic, sea-level and facies changes, called the Mid-Caradoc Event, has been recognized in the upper Caradoc sequence (Keila and Oandu stages) in the Baltoscandian area (see Ainsaar 2001 and references therein). A distinct positive $\delta^{13}C$ excursion was described in the upper Keila Stage and a notable change within various groups of fauna documented in the Keila–Oandu transition interval. The record of a coeval isotopic event in North America suggests that the Mid-Caradoc Event recognized in Baltoscandia is a result of a global oceanographic and/or climatic event (Ainsaar 2001 and references therein). Now, from the conodont data of the Ruhnu (500) core and the results of recent studies (Viira & Männik 1999; Männik 2001a) it is evident that the event started already in Haljala time.

One of the most distinct changes in conodont succession in the Ruhnu (500) core occurs in the upper Haljala Stage. Here, *A. tvaerensis* and *B. alobatus* disappear, the number of conodont specimens in samples decreases considerably and long-ranging simple-cone taxa start to dominate in the fauna. *Panderodus* and *Decoriconus* are the most abundant taxa in the uppermost Haljala Stage and in the overlying Keila Stage. Similar changes in the conodont faunas were noticed earlier in the Taga-Roostoja (25A) and Valga (10) core sections (Viira & Männik 1999; Männik 2001a). The order of changes in conodont faunas is the same in all three sections: (1) *A. tvaerensis* disappears, (2) *B. alobatus* disappears and (3) simple-cones (mainly *Panderodus* ex. gr. *equicostatus* and *Decoriconus pesequus–Decoriconus* sp.) start to dominate in the fauna. Morphological changes take place in the *Scabbardella* ex gr. *altipes* lineage in the Ruhnu (500) and Valga (10) cores at (or close to) the level of disappearance of *A. tvaerensis*: high slender equally curved elements are replaced by strongly curved ones with a wide base and relatively narrow cusp. The levels of disappearance of *A. tvaerensis* and *B. alobatus* can be considered as Datum 1 and Datum 2 of the Mid-Caradoc Event.

The interval dominated by simple-cones is about 7 m thick in the Ruhnu (500) core. It corresponds to the upper Adze Formation, Blidene Formation and the lowermost Mossen Formation (to the upper Haljala, Keila and lowermost Oandu stages) (Appendix 20). Ramiforms, including *Amorphognathus*, are very rare or missing in samples from this interval. Due to the lack of diagnostic taxa this in-

terval cannot be assigned to any known condont zone.

The recovery of the event-affected conodont faunas evidently started already in early Oandu time. *Amorphognathus* (*A. ventilatus*) re-appeared in large numbers in the lowermost Mossen Formation (Appendix 20). The last specimen of *Semiacontiodus* ex gr. *cornuformis*, probably marking the uppermost extinction level of the Mid-Caradoc Event in the conodont succession, was found from the same level.

The uppermost *Baltoniodus alobatus* range. As noted above, *B. alobatus* disappears higher in the section than *A. tvaerensis* and indicates Datum 2 of the Mid-Caradoc Event in the conodont sequence. The datums of global events, particularly the levels of extinction of taxa, have proved extremely valuable in high-resolution stratigraphy (e.g. Jeppsson 1997). It has not been checked yet if the succession of events in conodont faunas recognized in the Mid-Caradoc Event interval in Estonia can be followed also in other regions of the world, but, based on isotope studies (Ainsaar 2001 and references therein), it seems most probable. Anyhow, at least in Estonia the datums of the Mid-Caradoc Event provide an excellent tool for detailed correlation of sections. The interval between Datum 1 (the level of extinction of *A. tvaerensis*) and Datum 2 (level of disappearance of *B. alobatus*) of the Mid-Caradoc Event is here considered as a distinct stratigraphic unit and provisionally named as the "Uppermost *B. alobatus* range" (Appendix 20). Precise thickness of this unit is not known yet (sections have not been sampled in enough detail) but it might be about 1 m in the Ruhnu (500) core. The "Uppermost *B. alobatus* range" is identified in the Valga (10) core section where it may be also about 1 m thick (Männik 2001a) and in the Taga-Roostoja (25A) core section in a possible thickness of more than 2 m (Viira & Männik 1999).

Amorphognathus ventilatus to *A. ordovicicus* zones. Starting from the lowermost Mossen Formation (lowermost Oandu Stage), *Amorphognathus*, stratigraphically one of the most important genera in Upper Ordovician strata, is again well represented. The Ruhnu (500) core section is the only one known so far in Estonia where *Amorphognathus* occurs almost continuously (and in relatively large numbers) in the upper Caradoc strata. Judging from the occurrence of *A. ventilatus*, the main part of the Mossen Formation (=Oandu Stage) in the Ruhnu (500) core corresponds to the *A. ventilatus* Zone. The lower boundary of the zone is marked by the appearance of *A. ventilatus*. However, as the strata between the top of the *A. tvaerensis* Zone and this level contain only rare unidentifiable fragments of *Amorphognathus*, it cannot be excluded that in reality *A. ventilatus* appears already further down in the section. Anyhow, as noted above, at the moment the strata between the levels of disappearance of *A. tvaerensis* and appearance (of identifiable specimens) of *A. ventilatus* cannot be assigned to any conodont zone.

In the upper Mossen Formation, *A. ventilatus* is replaced by *A. superbus*. The occurrence of *A. superbus* indicates that the strata from this level up to the top of the Mõntu Formation correspond to the *A. superbus* Zone. *A. superbus* was found in all samples from this interval. In the lower and middle parts of the interval, *A. complicatus* was identified together with *A. superbus* (Appendix 20). Earlier in Estonia, extremely rare specimens of *A. superbus* have been found only in the cryptocrystalline limestones of the Rägavere Formation (Männik 1992, 2001a).

The uppermost identifiable specimens of *A. superbus* in the Ruhnu (500) section come from the uppermost Mõntu Formation (Nabala Stage). The overlying Saunja Formation (upper Nabala Stage) has not been studied for conodonts.

The single sample (from 631.35–631.45 m) from the Fjäcka Formation (Vormsi Stage) contains *A. ordovicicus*, which indicates that the lower boundary of the *A. ordovicicus* Zone lies below that level. This agrees with earlier data showing that *A. ordovicicus* in Estonia appears in the lowermost Vormsi Stage (Männik 1992). Restudy of the collection from the Valga (10) core revealed that identifiable specimens of *A. ordovicicus* appeared there in the lowermost Jonstorp Formation. Specimens of *Amorphognathus* below that level, and identified in Männik (2001a) as *A. ordovicicus*, are too poorly preserved to tell surely to which species they belong.

Icriodella sp. n. L was identified from the upper part of the Jonstorp Formation (Pirgu Stage), in the sample from 620.90–621.00 m. The Ruhnu (500) core is the fourth section in Estonia where this taxon has been found. Earlier, it has been reported from the Halliku Formation in the Seliste (Viira 1974; identified as *Icriodina* sp., illustrated in Pl. 13, fig. 43) and Laeva (18) (Männik 1992) cores, and from the Jelgava Formation in the Valga (10) core (Männik 2001a; identified as *Icriodella* sp. n.). In all sections the taxon has very short range in the Pirgu Stage. Comparison of the intervals of occurrences of *Icriodella* sp. n. L at Ruhnu (Appendix 20) and Valga (Männik 2001a, Appendix 10) shows that the upper part of the Jonstorp Formation in the Ruhnu (500) core corresponds to the Jelgava Formation in the Valga (10) core, and that the upper part of the strata of Pirgu age present at Valga is missing at Ruhnu.

The uppermost Ordovician strata. *A. ordo-*

vicicus occurs in all samples from the Fjäcka Formation to the lowermost Kuldiga Formation (Bernati Member, =lowermost Porkuni Stage) (Appendix 20). As in the Valga (10) section (Männik 2001a), also in the Ruhnu (500) core most of the taxa characteristic of the *A. ordovicicus* Zone disappear in the Bernati Member. Most common, although rare, are poorly preserved specimens identified as *Noixidontus girardeauensis* in the Ēdole Member of the Kuldiga Formation at Ruhnu. It is evident that the Kuldiga Formation is of the same age in the Ruhnu and Valga cores. The comparison of the distribution of *Noixodontus* in these two sections indicates that the upper part of the Kuldiga Formation is either highly condensed in the Ruhnu (500) core or some strata are missing.

The Ordovician–Silurian boundary. As known earlier (e.g. Männik 1992, 2001a), the Ordovician–Silurian boundary interval in Estonia is poorly represented by conodonts. As a rule, only some genera of simple-cone conodonts survived the end-Ordovician extinction event. In the Ruhnu (500) core, the last ramiform taxa, surely identifiable as Ordovician conodonts (N. *girardeauensis*, fragments of *Amorphognathus*), come from the uppermost Kuldiga Formation (sample from 604.50–604.60 m; Appendix 20). The oolithic limestones (Appendix 5, D-7, D-8) of the uppermost Ordovician Saldus Formation were not sampled at Ruhnu. The lowermost Silurian sample (600.00–600.15 m) in the Ruhnu (500) core contains several simple-cone taxa, which seem to be different from their relatives in the Ashgill (Appendix 20). Further detailed taxonomical studies of these simple-cone genera are needed to tell real differences between their latest Ordovician and earliest Silurian representatives. Often this is very difficult, particularly if there are too few specimens in samples (e.g. in the Valga (10) core).

Silurian

Distomodus kentuckyensis to *D. staurognathoides zones.* This interval corresponds to the Juuru, Raikküla and lowermost Adavere stages (Appendix 21, sheet 3). The conodont faunas of this interval in the Ruhnu (500) core, as also in several other sections in Estonia (Männik 1992; Nestor *et al.* 2003), are dominated by long-ranging simple-cone taxa, which are still too poorly studied to be effectively used in biostratigraphy. The appearance of *Aspelundia expansa* in the middle of the Slitere Member (sample from 575.10–575.25 m), below the Rhuddanian–Aeronian boundary (Kaljo in this volume), indicates that this level corresponds already to the *A. expansa* Zone. The Silurian strata below this level are assigned to the *Distomodus kentuckyensis* Zone although the zonal species has not been identified.

Considering the data from other sections, the *A. expansa* Zone is followed by the *A. fluegeli* Zone, with the boundary between these units in Estonia in the Ikla Member (Nestor *et al.* 2003). In the Ruhnu (500) core, no specimens of *A. fluegeli* were found below the sample from 494.60–494.75 m, already well in the *D. staurognathoides* Zone (Appendix 21, sheet 3). Most probably, the lack of any indication of the *A. fluegeli* Zone at Ruhnu results from too rare occurrence of conodonts and not from a gap in the section.

The first identifiable specimens of *D. staurognathoides* come from the lowermost Staicele Member of the Saarde Formation (Appendix 21, sheet 3). The specimens of *Distomodus* found below that level are too poorly preserved and cannot be identified at the species level. Data from the Aizpute-41 core (Latvia) indicate that the base of the *D. staurognathoides* Zone lies within the *Demirastrites convolutus* graptolite Zone (Loydell *et al.* 2003). Comparison of these data with the chitinozoan zonation in Loydell *et al.* (2003) and Nestor *et al.* (2003) suggests that in the Saarde Formation this base lies somewhere in the Lemme Member. Most probably also in the Ruhnu (500) core the real lower boundary of the *D. staurognathoides* Zone should be looked for below the level with the lowermost identifiable specimen of *D. staurognathoides*, and we cannot define it just due to too poor preservation of specimens. The scarcity of fauna in the discussed interval in the Ruhnu (500) core is also confirmed by the fact that *Oulodus*? *panuarensis* and *Ozarkodina* ex gr. *excavata*, appearing in many sections in Estonia already in the uppermost Juuru Stage (e.g. Nestor *et al.* 2003), are here not found below the Lemme Member (Appendix 21, sheet 3).

The upper boundary of the *D. staurognathoides* Zone is marked by the appearance of *Pterospathodus eopennatus*. It probably correlates with the boundary between the Rumba and Velise formations (Appendix 21, sheet 3).

Pterospathodus eopennatus ssp. n. 1 to *P. amorphognathoides amorphognathoides zones.* The lowermost part of this interval is highly condensed: the *P. eopennatus* ssp. n. 1 Zone fauna has been identified only in one sample (489.10–489.20 m) and the *P. eopennatus* ssp. n. 2 Zone fauna in two samples (488.60–488.70 and 488.10–488.20 m) (Appendix 21, sheet 3). The next sample (487.70–487.80 m) contains already fauna characteristic of the *P. amorphognathoides angulatus* Zone (the

lowermost zone in the *P. celloni* Superzone; Männik 2001b). The upper boundary of this zone lies between 484.00–484.10 and 483.20–483.30 m (Appendix 21, sheet 2). From the sample at 483.20–483.30 m the lowermost specimens of *P. a. lennarti*, indicating the *P. a. lennarti* Zone, were identified. The uppermost specimen of this taxon in the Ruhnu (500) core come from the sample at 480.80–480.90 m. It is possible that the boundary between the *P. a. lennarti* and *P. a. lithuanicus* zones lies just above this sample. However, as the only specimen of *P. a. lithuanicus* comes from the sample at 472.20–472.30 m (just below the upper boundary of the *P. celloni* Superzone), the interval between the *P. a. angulatus* Zone below and the *P. a. amorphognathoides* Zone above is indicated here as corresponding to the *P. a. lennarti–P. a. lithuanicus* zones (Appendix 21, sheet 2).

The lower boundary of the *P. a. amorphognathoides* Zone is defined by the first appearance of the nominal species in the sample from 471.40–471.50 m. The upper boundary of the zone most probably lies just above the sample from 454.30–454.40 m. According to Jeppsson (1997), the upper boundary of the *P. a. amorphognathoides* Zone corresponds to Datum 1 of the Ireviken Event, which is defined by the extinction of *Nudibelodina sensitiva* and by considerable decline in the occurrence frequency of *Pseudooneotodus tricornis*. In the Ruhnu (500) core, *Ps. tricornis* is continuously present up to the level of 454.30–454.40 m, but has not been found above this level (Appendix 21, sheet 2). *N. sensitiva* has not been identified in the Ruhnu (500) section.

The Ireviken Event. Jeppsson (1997) proposed a very detailed conodont zonation for the uppermost Telychian–lowermost Sheinwoodian strata. He described five zones in this interval (Lower *Ps. bicornis*, Upper *Ps. bicornis*, Lower *P. pennatus procerus*, Upper *P. p. procerus* and Lower *K. ranuliformis*), with the boundaries between them corresponding to the datums of the Ireviken Event. However, later (e.g. Männik *et al.* 2002; Loydell *et al.* 2003) some of these zonal boundaries (datums of the Ireviken Event) appeared to be very complicated (if not impossible) to identify in strata formed in offshore environments. Foreseeing possible problems with the identification of some datums in a particular section, Jeppsson (1997) grouped his new zones into superzones, and even into wider units – zonal groups.

In the Ruhnu (500) core section, only three datums of the Ireviken Event can be identified: Datum 1 (see above), Datum 3 (the level of disappearance of *P. a. amorphognathoides*) and Datum 6 (the level of disappearance of *P. p. procerus*) (Appendix 21, sheet 2). Datum 1 (between samples from 454.30–454.40 and 453.70–453.80 m) marks the boundary between the *P. a. amorphognathoides* Zone and the overlying *Ps. bicornis* Superzone, Datum 3 (between samples from 448.70–448.80 and 447.00 m) corresponds to the boundary between the *Ps. bicornis* and *P. pennatus procerus* superzones and Datum 6 (between samples from 447.00 and 444.00 m) to the boundary between the *P. p. procerus* and *Kockelella ranuliformis* superzones. As no specimens of *Distomodus staurognathoides* were found above Datum 6 in the Ruhnu (500) core, it is possible that also Datum 8 occurs between samples from 447.00 and 444.00 m. This datum corresponds to the level of disappearance of *D. staurognathoides* and defines the boundary between the Lower and Upper *K. ranuliformis* zones (Jeppsson 1997). However, as *D. staurognathoides* is known to be very rare above Datum 7 of the Ireviken Event (Jeppsson & Männik 1993), additional sampling is needed to check its real distribution in the Ruhnu (500) core. For the time being, the interval above Datum 6 is assigned to the *K. ranuliformis* Superzone.

The Llandovery–Wenlock boundary. The Llandovery–Wenlock boundary was defined in Hughly Brook near Leasows Farm, Welsh Borderland. Comparative analysis of conodont successions through the Ireviken Event interval from Gotland (Sweden) and from the Leasows shows that the Llandovery–Wenlock boundary in its type section most probably lies very close to (or coincides with) Datum 2 of the Ireviken Event (Aldridge *et al.* 1993; Jeppsson 1997). The data presently available for the Ruhnu (500) core section do not allow precise identification of the position of the Datum 2 of the Ireviken Event, and thus also the position of the Llandovery–Wenlock boundary. However, clearly it should be looked for in the interval between the levels of 454.30–454.40 and 447.00 m (Appendix 21, sheet 2). In the graptolite sequence (Kaljo in this volume, Appendix 18), this interval lies in the *Cyrtograptus murchisoni* Zone, well above the lower boundary of the *C. centrifugus* Zone, above the traditional Llandovery–Wenlock boundary level in the graptolite succession. This fits well with the earlier data that the Llandovery–Wenlock boundary as defined in its type section at Leasows does not coincide with the base of the *C. centrifugus* graptolite Zone but correlates with a level in the *C. murchisoni* graptolite Zone (Männik *et al.* 2002; Loydell *et al.* 2003).

Kockelella ranuliformis Superzone to *Ozarkodina sagitta sagitta* Zone. The lower boundary of the *K. ranuliformis* Superzone corresponds to the level of disappearance of *P. p. procerus* and its up-

per boundary to the level of appearance of *Ozarkodina sagitta rhenana* (Jeppsson 1997). In the Ruhnu (500) core, *O. s. rhenana* was found only in one sample: 386.40–386.55 m (Appendix 21, sheet 2). *Kockelella walliseri* appears higher, in the next sample (384.70–384.85 m) and occurs sporadically up to the level of 358.35–358.60 m. Jeppsson (1997) described five zones (grouped into two superzones) in the interval of total ranges of *O. s. rhenana* and *K. walliseri*. Due to rare occurrence of these and the lack of several other diagnostic taxa important for identification of some of his zones, it seems proper to refer to this interval at Ruhnu as corresponding to the *O. s. rhenana*–Upper *K. walliseri* superzones. The lowermost part of this interval where *O. s. rhenana* was identified evidently corresponds to the *O. s. rhenana* Zone (Appendix 21, sheet 2). However, as the number and size of the studied samples are limited, and as *O. s. rhenana* is known to be rare and occur sporadically in Estonian sections (e.g. Jeppsson *et al.* 1994), most probably the real level of its appearance lies further down in the Ruhnu (500) core. The recorded level of appearance of this taxon does not mark the real lower boundary of the *O. s. rhenana* Zone at Ruhnu.

The upper boundary of the Upper *K. walliseri* Superzone (level of disappearance of *K. walliseri*) lies between 358.35–358.50 and 356.30–356.45 m. The strata above this level, up to Datum 1 of the Mulde Event, are considered to correspond to the *Kockelella ortus ortus* Superzone *sensu* Jeppsson (1997). Probable specimens of *K. ortus* (identified as *K.* cf. *ortus*) were found in the upper part of the superzone which, on the basis of the occurrence of *O. s. sagitta* and *Pseudooneotodus linguicornis*, is correlated with the *O. s. sagitta* Zone (Appendix 21, sheet 2). The lower boundary of the zone lies between 327.95–328.10 and 325.65–325.80 m, below the appearance level of *O. s. sagitta* and *Ps. linguicornis*. The specimen of *O. s. sagitta* in the sample from 325.65–325.80 m is the only one so far found in Estonia.

The Mulde Event. This event has recently been discussed in detail by Calner & Jeppsson (2003) and Jeppsson & Calner (2003). The Mulde Event includes at least three extinction steps: Datum 1 at the beginning of the event had a strong effect on all major taxa, including graptolites and conodonts; at Datum 1.5 some conodonts became extinct; Datum 2 caused a near total extinction of graptoloids but had a lesser effect on conodonts and "shelly faunas" (Jeppsson & Calner 2003). At Datum 1 the rich and diverse fauna of the *O. s. sagitta* Zone disppears. According to Jeppsson (in Jeppsson & Calner 2003, p. 139): "The succeeding fauna lacks zonal taxa but otherwise is closely related to the first fauna with *O. bohemica longa*. Both are markedly less diverse and strongly dominated by ramiforms, in most collections *O. excavata*. They are therefore separated as Subzone 0 (zero) and Subzone 1 of the *O. b. longa* Zone". The most characteristic event in the conodont sequence at Datum 2 of the Mulde Event, at the boundary between subzones 1 and 2 of the *O. b. longa* Zone, is the change of the dominating taxon: the faunas between datums 1 and 2 were dominated by *O. excavata*, which at Datum 2 was replaced by *Panderodus equicostatus* (Jeppsson & Calner 2003). In Subzone 3, ramiforms, particularly *O. excavata*, regained dominance. Subzone 4 has a more balanced conodont fauna.

In Estonia, the Mulde Event interval has earlier been recognized only in the Ohesaare core section (see Jeppsson & Calner 2003 and references therein). In the Ruhnu (500) core, Datum 1 of the Mulde Event is marked by the disappearance of *Panderodus* ex gr. *greenlandensis*. The uppermost specimens of this taxon were found in the sample at 298.10–298.15 m, indicating that Datum 1 of the event, and accordingly the lower boundary of Subzone 0 of the *O. b. longa* Zone, lies above this level (between 298.10–298.15 and 297.15–297.30 m; Appendix 21, sheet 1). Datum 2 of the Mulde Event (the boundary between subzones 1 and 2 of the *O. b. longa* Zone) lies between the levels of 287.85–288.00 and 285.55–285.70 m, and probably corresponds to the erosional surface at 287.60 m (see Appendix 1, sheet 11). The fauna in the sample at 287.85–288.00 m is still strongly dominated by *O. excavata* (as in all samples from the silty marlstones in the interval from 287.6 to 293.9 m; Appendix 21, sheet 1). In the next sample (at 285.55–285.70 m), and in all samples studied higher above this level, *P.* ex gr. *equicostatus* dominates. The sample at 287.20–287.30 m yielded only two conodont specimens, one of them belonging to *O. excavata* and the other to *Ps. beckmanni*.

Due to the lack of critical taxa (*Ps. linguicornis* and *Walliserodus* sp. n. V do not reach the Mulde Event interval in the Ruhnu (500) core; Appendix 21, sheet 1), Datum 1.5 cannot be recognized in the studied section. As the lowermost specimens of *O. b. longa* were found only in Subzone 2, probably due to too small size of the samples (*O. b. longa* is known to be relatively rare and occur sporadically in sections), also subzones 0 and 1 of the *O. b. longa* Zone cannot be distinguished at Ruhnu.

The conodont sequence recognized in the Ruhnu (500) core indicates that the interval between the levels of 298.10–298.15 and 287.20–287.30 m

correlates with the Fröjel Formation (Calner & Jeppsson 2003) on Gotland. A high content of fine quartz sand in the residues of samples from 287.6–293.9 m agrees with this conclusion and suggests that this interval corresponds to the upper part of the formation, the Gannarve Member ("Slite Siltstone"). The occurrence of oolithic grains in the dolostone (interval 285.8–287.6 m, see Appendix 1, sheet 11) above the silty marlstones evidently indicates that these strata correspond to the Bara Oolite Member of the Halla Formation on Gotland (=lower part of Subzone 2 on Gotland; Jeppsson & Calner 2003). This conclusion is in accordance with the conodont data (see above), as is also the suggestion that the bentonite in the Ruhnu (500) core (interval 283.65–283.90 m) is identical with the Grötlingbo Bentonite (Kiipli in this volume), recognized in the lower part of the Mulde Brick-clay Member of the Halla Formation (Calner & Jeppsson 2003).

DISTRIBUTION OF ORDOVICIAN CHITINOZOANS

A total of 109 samples from the middle–upper Ordovician part of the Ruhnu (500) core were processed and studied for chitinozoans (Appendix 22). The work was carried out at the Institute of Geology at Tallinn Technical University, where the collection is stored, and financially supported by the Estonian Science Foundation (grant No. 4674). The samples varied from 0.3 to 0.5 kg in size and were commonly not more than 5 cm in vertical range. Fifteen samples were barren, or yielded only some indeterminable fragments. In almost all cases the unproductiveness of samples was mainly due to the distribution of marine redbeds in the intervals of 618.9–631.1, 632.7–634.2 and 680.5–706.8 m. The most probable reason is microscopic recrystallization (changes in Fe-compounds) during which the walls of chitinozoan specimens were crushed into very small pieces or powder, so that they cannot be found using standard preparation techniques (Nõlvak 2002). Another reason is secondary dolomitization, which also destroyed, or influenced strongly the preservation of organic-walled microfossils. The uppermost Ordovician ooliths containing (10–50%, in some layers > 50%) limestones in the Ruhnu (500) section (see Brenchley *et al.* 2003, fig. 6) were barren as they were formed in the grain-supported facies, in the active water environment unfavourable for the setting of chitinozoans.

The Ordovician chitinozoan zonation of Baltoscandia was introduced by Nõlvak & Grahn (1993) and revised by Nõlvak (1999a). In the Ruhnu (500) section, 14 zones and subzones were established. Altogether, 79 chitinozoan taxa were distinguished, the distribution of which is presented in Appendix 23. The number of specimens in samples was highly variable. The richest samples came from the lower part of the section (Lasnamägi–Kukruse stages), where chitinozoans of particularly good preservation and relatively high species diversity were found.

The lowermost samples represent the *Conochitina clavaherculi* Subzone of the *Laufeldochitina striata* Zone, which corresponds to most of Lasnamägi and early Uhaku times (Nõlvak & Grahn 1993). Despite the absence of some clear criteria among chitinozoans marking the level of the lower boundary of the Uhaku Stage, their association in the lowermost samples suits well with the uppermost portion of the beds belonging to the Lasnamägi Stage in other sections.

The boundary of the *Laufeldochitina striata* and *L. stentor* zones lies within the uppermost part of the Uhaku Stage as, for example, in the Taga-Roostoja (25A) and Valga (10) cores (Nõlvak 1999b, 2001). The middle portion of the Uhaku beds is represented by the *Conochitina tuberculata* Subzone. The appearance level of this species and the frequency of all chitinozoans are probably influenced by the occurrence of red spots in the rocks of that interval (672.0–673.5 m). The succeeding higher *Eisenackitina rhenana* Subzone is followed clearly, and its range coincides roughly with the *Laufeldochitina stentor* Zone. In general, both of these species occur during Kukruse time. The lower boundary of the Kukruse Stage can be defined by the appearance of the former species. Most noteworthy is the appearance of *Conochitina* sp. 1 and *Conochitina* sp. 2 in the lower part of the Kukruse Stage (=*C. savalaensis* and *C. viruana* nom. nud. in Männil 1986, fig. 2.1.1; Bauert & Bauert 1998; Nõlvak 1999b, 2001). These species are characteristic of the lower and middle parts of the stage in the sections of the North Estonian Confacies (see Fig. 3A). At the same time, in the upper part of the stage there occurs an extensive break in the North Estonian sections, which at Ruhnu is fulfilled by beds containing, among others, *Conochitina tigrina*, *Lagenochitina* sp. A aff. *capax*, *Cyathochitina* sp. 2 and remarkable finds of stratigraphically very important *Nemagraptus gracilis* (Hall) at a depth of 662.8 m. The last species marks the global lower boundary of the Upper Ordovician Series (Bergström *et al.* 2000).

The base of the Haljala Stage (Idavere Substage) can be defined at the level of the lower boundary of the *Armoricochitina granulifera* Zone, supported by the disappearance of the index species *Laufeldochitina stentor* and *Eisenackitina rhenana*, and

by an abrupt increase in the number of the acritarch *Leiosphaeridia baltica* at an approximate depth of 658.8 m. Such a mass occurrence of acritarchs is widespread at the same level in North Estonian and Swedish sections (Nõlvak *et al.* 1999; Nõlvak 2001). These data suggest that the lower boundary of the Haljala Stage could most probably be traced at a depth of 659.0 m, and not at 658.2 m, where *A. granulifera* appears, encountered here only in one sample. However, this always small zone is missing in the Valga (10) section (Nõlvak 2001), but has been proposed as a possible criterion for the lower boundary of the Haljala Stage (Nõlvak & Grahn 1993; Hints *et al.* 1995). This level coincides broadly also with the boundary between the Dreimani and Adze formations.

The next stratigraphically important zones are the *Angochitina curvata* and *Lagenochitina dalbyensis* zones (Nõlvak & Grahn 1993) from the beds corresponding to the lowermost Idavere Substage of the Haljala Stage. The latter zone enables the correlation of sections over the whole Baltica palaeocontinent and with North Gondwana (Nõlvak 1999a; Paris *et al.* 1999). It is noteworthy that the Haljala Stage, having a restricted thickness of no more than 9 m, is partly represented by beds with almost barren samples in the Ruhnu (500) core (interval between 653.5–657.5 m). This interval belongs probably to the *L. dalbyensis* and *Belonechitina hirsuta* zones. The beds of the Jõhvi Substage lie about 2.3 m below the Kinnekulle K-bentonite bed at a depth of 650.1 m, however, their age is not proved by chitinozoans.

In general, the distribution and diversity of chitinozoans in the Uhaku, Kukruse, Haljala and to some extent also Keila stages in the Ruhnu (500) section agree well with earlier data (e.g. Taga-Roostoja (25A), Valga (10); see Nõlvak 1999b, 2001), although the thicknesses of the beds are smaller at Ruhnu than in the sections of the North Estonian Confacies Belt in central Estonia.

The lower boundary of the Keila Stage coincides with the base of the Kinnekulle K-bentonite bed (Hints & Nõlvak 1999) at a depth of 650.1 m in the Ruhnu (500) section. However, the stratigraphically valuable *Angochitina multiplex* Subzone, which usually lies just above the Kinnekulle bed (Hints & Nõlvak 1999, fig. 4), has not been found there. There is a possibility of some breaks in the lower–middle part of the very condensed portion (about 3 m) of the section. In the Keila beds the possible gap is indicated also by the distribution of a specific population (curved specimens) of *Euconochitina primitiva*, here referred to as cf. (see Appendix 23). The latter form is widely distributed only in the uppermost beds of the Keila Stage in the North Estonian sections, in the interval of substantial extinction of chitinozoans: e.g. in the Rapla section about 63% and in the Valga (10) section about 45% of the species disappeared (see Kaljo *et al.* 1996; Nõlvak 2001). Such a disappearance can be followed also in the Ruhnu (500) section. However, at Ruhnu the late Keila extinction and diversity minimum in Oandu time, and the considerable lithological change, obvious in the sections of the North Estonian Confacies Belt (Hints *et al.* 1989), are not connected with some certain level. Chitinozoans disappear more gradually. Gradual changes are observable also in lithology. The possible level of the upper stage boundary could be drawn according to the disappearance of *Euconochitina* cf. *primitiva* and/or acritarch *Leiosphaeridia baltica* at depths of 645.7 or 647.1 m. The appearance of *Ancyrochitina* sp. n. 1 at a depth of 646.8 m confirms the gradual or continuous character of that boundary in the South Estonian sections, including the Valga (10) section (Nõlvak 2001, appendix 8). For Ruhnu the level of 645.7 m is preferred. It is important to note that the interval of 645.7–647.1 m is by the distribution of chitinozoans much the same as the beds in the Viljandi section from the interval of 336–338 m assigned by microfossils to the Lehtmetsa beds of the Keila Stage (Kaljo *et al.* in press).

The data available provide no clear biostratigraphical criteria for the recognition of the beds corresponding to the Rakvere Stage in the Ruhnu (500) section. In the stratotype area this is a topostratigraphical unit with traditionally lithological boundaries, characterized by the continual distribution of *Cyathochitina angusta*. Often gaps and clear facies changes are observed on its boundaries. At Ruhnu, the very low appearance of *Cyathochitina angusta* and *Fungochitina fungiformis* (rare specimens) and the unusually high disappearance level of *Ancyrochitina* sp. n. 1, the zones of which have never been recorded as overlapping, fulfill the breaks well known in North Estonia. It is not excluded that the interval between the depths of 638.8 and 645.7 m in the Ruhnu (500) section is absent in the Valga (10) section, or is represented there only by the beds between the depths of 383.8 to 384.9 m (see Nõlvak 2001, appendix 8). At the same time, these very similar argillaceous rocks of the Ruhnu and Valga cores are interpreted as the lithological analogies of the Mossen Formation of the Central Baltoscandian Confacies. Should our interpretation by chitinozoans be proved by some other group of fossils, some more gaps, and more lenses with similar lithology but different in age might be revealed in this part of the section.

A somewhat indefinite boundary between the *Spinachitina cervicornis* and *Fungochitina fungiformis* zones is caused due to the original definition of these zones as the total ranges of both species (Nõlvak & Grahn 1993). For practical reasons, the definitions had to be revised and a supplementary notice – "continual distribution" added. More precisely, this was caused by the difficulties with the identification of the first or last, often single specimens, found in considerably lower or higher samples than the main part of the population. In the Ruhnu (500) section, for example, the total range of *F. fungiformis* begins at a depth 646.8 m, but continual range at a depth of 637.8 m (Appendix 23).

In the succession of chitinozoans the lower boundary of the *Armoricochitina reticulifera* Subzone at a depth of 635.5 m marks the beginning of the beds belonging to the Nabala Stage. However, most probably the underlying limestones (interval 635.5–638.6 m) can also be tied to that stage. Higher, the uppermost glauconite-bearing and condensed limestones with rare red spots (interval 632.7–634.2 m) of the Mõntu Formation are unusually barren, as is the specific 0.2 m coarse-grained bed (Appendix 4, T-33; Appendix 5, D-11) at the base of the Saunja Formation (632.5–632.7 m, see p. 9 in this volume). The upper boundary of this layer marks also the sequence boundary – a sharp facies transition from the underlying Mõntu Formation to the grain-supported facies with the overlying mud-supported facies of the Saunja Formation (Harris *et al.* in press).

Very condensed marlstones of the Fjäcka Formation (interval 631.1–631.8 m) are represented by the *Acanthochitina barbata* Subzone (Nõlvak 1980, fig. 2), which has been distinguished up to now only in the uppermost portion of the Vormsi Stage. The uppermost beds of the *Fungochitina fungiformis* Zone and the lowermost beds of the *Tanuchitina bergstroemi* Zone (Nõlvak & Grahn 1993) are absent. Contrary to the statement of some authors (e.g. Meidla in Hints & Meidla 1997b, p. 82), these data support the idea that the main part of the beds corresponding to the lower and middle Vormsi Stage in the North Estonian Confacies Belt is absent in the Ruhnu (500) core.

The barren redbeds are interpreted as the lower part of the Pirgu Stage (see also Männil *et al.* 1968) despite the well-known metachronous character of the boundaries of the redbed portions in different sections. However, it makes uncertain the beginning of the continual distribution of *Spinachitina taugourdeaui*, which is suggested as a relatively good criterion for the lower boundary of the Porkuni Stage (Nõlvak 1999a).

In the Ruhnu (500) section, the upper boundary of the S. taugourdeaui Zone coincides also with the disappearance of some other forms (see Appendix 23) similarly to some other sections of that facies belt, e.g. Valga (10), Ikla, Kardla, Taagepera, Riekstini (Nõlvak 2001, appendix 8; Brenchley *et al.* 2003, figs. 6, 7, 8, 10). A radical change takes place within the Bernati Member of the Kuldiga Formation in the interval of 617.6–618.2 m: mass extinction among chitinozoans, associated with a glaciation and mass extinction of biota in the latest Ordovician (Kaljo *et al.* 2001; Brenchley *et al.* 2003; see also Martma in this volume). The highest Ordovician *Conochitina scabra* chitinozoan Zone occurs just above that change level in the interval of 617.6–603.6 m. It is not excluded that this form is also present in the beds just above the Ordovician–Silurian boundary level at a depth of 601.0 m (Brenchley *et al.* 2003, fig. 6). As earlier data show, the beds of the Saldus Formation are barren also in the Ruhnu (500) section due to the active water environment.

DISTRIBUTION OF ORDOVICIAN OSTRACODS

The ostracod samples used in the current study belong to two different sample sets (Appendix 24). One series of samples throughout the Ordovician and Silurian was obtained and prepared in the course of the first investigation of the core right after the drilling. The Ordovician samples of that collection were re-examined by the author. Recently supplementary sampling of the Ordovician sequence was carried out, but only samples from the interval from the uppermost Pirgu Stage to the base of the Silurian are used in this work. New samples were processed according to standard methodology (see, e.g., Meidla 1996a). The samples were prepared at the Geological Survey of Estonia and studied at the Institute of Geology, University of Tartu. The study was financially supported by the Estonian Science Foundation (grant No. 4574). The collection is stored at the Institute of Geology, University of Tartu.

All recent samples are richly fossiliferous and contain a diverse fauna, although the topmost Ordovician shows mostly only moderate ostracod diversity. The micropreparates of the old sample series often contain only a limited number of large specimens, especially in the Middle Ordovician. Such a difference could apparently be explained with differences in the laboratory cycle or picking routine. Due to the changing quality of the material, mainly the absence/presence data are used and commented below.

The ostracod distribution data are interpreted

in the context of former investigations: Sarv (1959), Meidla (1996a), Meidla *et al.* (1998), Põldvere *et al.* (1998), Meidla (2001), Tinn & Meidla (2001), Ainsaar *et al.* (1999), Ainsaar & Meidla (2001).

The lowermost ostracod sample comes from a depth of 699.8 m (Appendix 25). It contains a few long-ranging species: *Aulacopsis simplex* and *Elliptocyprites nonumbonatus* make their first appearance in the upper part of the Volkhov Stage; *Conchoprimitia socialis* (=*Conchoprimitia gammae* Öpik) ranges throughout the Billingen–Kunda interval in Baltoscandia. Although such an ostracod assemblage could principally be referred to the Volkhov Stage, the occurrence of poorly preserved *Asteusloffia acuta*? suggests that it could also be younger. The occurrence of *Pinnatulites procerus*, *Asteusloffia acuta* and *Ogmoopsis variabilis* higher up in the sequence (698.75 m) unambiguously refers to the Kunda Stage. To sum up, the lower boundary of the Kunda Stage should be drawn at 698.8 m or deeper, thus deeper than the grey-coloured Šakyna Formation. This formation has been considered as equivalent to the basal Kunda Stage in one of the recent correlation charts (Männil & Meidla 1994, etc.) but both the ostracod and conodont evidence from the Tartu core (respectively after Meidla and Stouge in Põldvere *et al.* 1998) suggests that it is much younger, at least in Estonian sections.

The lower boundary of the Aseri Stage could be drawn between the disappearance level of *Pinnatulites procerus* (690.1 m) and the appearance of a new faunal assemblage at a depth of 688.1 m (Appendix 25). The ostracod fauna from the Aseri–Uhaku interval is relatively scarce. The appearance of *Sigmobolbina variolaris* in the Lasnamägi Stage is in agreement with the results from Latvia (see Gailite in Ulst *et al.* 1982). The position of the lower boundary of the Lasnamägi Stage in the upper part of the Segerstad Formation is noteworthy, as this formation is traditionally considered as the equivalent of the Aseri Stage in southern Estonia and western Latvia.

As a summary, the available integrated biostratigraphical evidence refers to certain discrepancies between the new results from the Ruhnu (500) core and the generally accepted correlation (Männil & Meidla 1994) of the Middle Ordovician rock units in the Livonian Tongue of the Central Baltoscandian Confacies Belt (see Fig. 3A).

The lower boundary of the Haljala Stage should definitely be drawn above the highest occurrence of *Tallinnella dimorpha* and *Longiscula loknensis*. This is also in agreement with the chitinozoan data (see Nõlvak in this volume).

The lower boundary of the Keila Stage in the Ruhnu (500) core is well defined by the Kinnekulle K-bentonite as a marker horizon, but there is no faunal evidence in the ostracod succession (see also Nõlvak in this volume). In the upper part of the Keila Stage, two distinct and widely distributed faunal assemblages can be recognized (Appendix 25). The assemblage with *Klimphores bimembris*, *Pedomphalella egregia*, *Pelecybolbina graesgardensis* and *Sigmoopsis rostrata* at a depth of 646.2 m is typically recorded in the topmost Keila Stage in the sections of the transitional zone (roughly Central Estonia: see Meidla 1996a, fig. 1). The assemblage has been recorded in the Laeva-18 (*ibid.*, fig. 13) and Pärnu (*ibid.*, fig. 14) sections, but also in the southern Estonian Abja-92 (*ibid.*, fig. 18) and Valga (10) (Meidla 2001) sections. The record of *Consonopsis consona*, *Tetrada pseudoiewica*? and *Vogdesella subovata* at a depth of 644.8 m at Ruhnu allows us to distinguish here the age equivalents of the Plunge (former "black shale") Member of the Mossen Formation (see Meidla 1996a, pp. 161, 166 and figs 17, 18). This interval is also correlated with the basal part (Keila age) of the Variku Formation (Ainsaar & Meidla 2001). In the Ruhnu (500) core the particular interval comprises the basal part of the relatively uniform marlstone unit (640.5–645.7 m). In the former publications (Ainsaar *et al.* 1996, 1999) the same biostratigraphical unit has informally been referred to as the *Tetrada* beds.

The lower boundary of the Oandu Stage is distinct in the section, being marked by the appearance of abundant *Klimphores minimus*, *Pelecybolbina illativis* and *Easchmidtella fragosa* (Appendix 25). The appearance of these typical members of the late Ordovician ostracod fauna (see Meidla 1996a, p. 11) marks the level of the most remarkable faunal change in the Middle–Upper Ordovician ostracod succession of Baltoscandia. The correlation of this event horizon has repeatedly been discussed in the literature (Meidla 1996a; Ainsaar *et al.* 1999; Ainsaar & Meidla 2001; Meidla 2001) and is therefore skipped here.

The lower boundary of the Rakvere Stage is mostly distinct in the sections of South Estonia (see Meidla 1996a and Ainsaar & Meidla 2001 for details), and this is the case with the Ruhnu (500) core as well (Appendix 25). The distinction of the stage is based on the successive appearance of two species of the genus *Pelecybolbina* (*P. illativis* and younger *P. pelecyoides*). The latter species appears in southern Estonian sections in the Priekule Member of the Mossen Formation (like in the Abja-92 core: Meidla 1996a, fig. 18 or in the Valga (10) core: Meidla 2001), in the upper part of the Variku (=Lukštai in Männil & Meidla 1994) Formation (Ristiküla-174

and Tartu (453) cores: Ainsaar & Meidla 2001) or in the Rägavere Formation (in northern sections: Meidla 1996a, figs 13, 14; Ainsaar *et al.* 1999). In the Ruhnu (500) core, the appearance level of *P. pelecyoides* lies within the Mossen Formation, at a depth of 638.5 m. The lower boundary of the Rakvere Stage could tentatively be drawn even deeper, where poorly preserved *Pullvillites* sp. was recorded (at 639.4 m). *P. pelecyoides* ranges up to a depth of 636.9 m, thus restricting the Rakvere Stage to the boundary interval of the Mossen and Mõntu formations. The Rakvere age of the Mõntu Formation is supported by the evidence from the Tartu (453) core where the ostracod data suggest the assignment of the basal Mõntu Formation to the Rakvere Stage (Meidla in Põldvere *et al.* 1998).

The lower boundary of the Nabala Stage should be drawn in the interval of 636.9–634.1 m, between the last occurrence of *P. pelecyoides* and the appearance level of *Hippula eddolensis* (Appendix 25). Unlike the Tartu (453) core, where the ostracod and chitinozoan evidence looks contradictory, in the Ruhnu (500) core both data sets seem to be in good agreement (see Nõlvak in this volume), which suggests that the boundary should be drawn approximately at a depth of 636.0 m.

As stated earlier (Meidla 1996a), the lower boundary of the Vormsi Stage represents a sharp lithofacies change throughout Estonia and is not very well reflected in the distribution of ostracods. Similarly to other South Estonian sections (Kaagvere-1, Otepää-2, Taagepera, Abja-92: see Meidla 1996a, figs 15–18), the corresponding strata of the Ruhnu (500) core are highly argillaceous and contain *Kinnekullea thorslundi*. However, this species seems to have a wider stratigraphic range in the sections of western Latvia (see Gailite in Ulst *et al.* 1982).

The red-coloured Jonstorp Formation has traditionally been considered the equivalent of the Lower Pirgu Substage (Männil & Meidla 1994) in southern Estonian and Latvian sections. This is based on the correlation of the *Acanthochitina barbata* Zone (Nõlvak 1980) along the facies profile. This correlation is reliable in the belt where the Vormsi–Pirgu boundary interval is grey-coloured and provides a continuous succession of acid-resistant microfossils. In south Estonia, the redbeds lacking acid-resistant microfossils almost directly overlie the Fjäcka Formation. Considering the probable metachronous character of the redbeds (see Meidla 1996a, p. 189, also Nõlvak in this volume), the traditional correlation of the Pirgu Stage in South Estonian and Latvian sections might need further biostratigraphical approval.

In the ostracod record, the appearance level of a new faunal assemblage (*Daleiella rotundata*, *Gryphiswaldensia plavinensis*, *Laevanotella nonsulcata* and several others) is usually a few metres above the lower boundary of the Jonstorp Formation. In the Ruhnu (500) core, the first appearance of *D. rotundata* was recorded at a depth of 629.0 m (Appendix 25). This fact principally leaves open the stratigraphical classification of the basal two-metre interval of the Jonstorp Formation, above the level of 631.2 m with an impoverished chitinozoan assemblage.

It is remarkable that the upper part of the Jonstorp Formation contains also *Steusloffina cuneata*, which is generally indicative of shallow water conditions and thus geographically generally restricted to the northern and Central Estonian sections. The record of this species in the Ruhnu (500) core is its southernmost occurrence in Estonia and most probably indicative of an extensive regression. This viewpoint is also supported by the high diversity values in the same level (17 ostracod species were recognized in that particular sample, which is also the highest value for the whole Ordovician succession in the Ruhnu (500) section). However, the ostracod diversity decreases again in the topmost part of the formation and higher up.

In the sections of the Central Baltoscandian Confacies Belt, the boundary of the Porkuni Stage is usually drawn by the appearance of the specific members of the Hirnantia fauna and by the increase in stable isotopic values in the section. The shift in the stable carbon isotopic composition is recognized both in the bulk rock samples and in the brachiopod (and perhaps also ostracod) shell material (see Kaljo *et al.* 2003 and references therein; Brenchley *et al.* 2003).

One of the components of the Hirnantia fauna *sensu lato* is a specific ostracod assemblage, the so-called *Harpabollia* fauna (see Meidla 1996b). This assemblage characterizes the Kuldiga and Saldus formations in South Estonia, Latvia and Lithuania but is also recorded in northeastern Poland and several parts of Sweden (Östergötland, Scania). It contains many genera which make their first appearance in the Baltoscandian area namely in this level. The Baltoscandian ostracod fauna is still considered relatively endemic, but the species of that particular association are recorded also from Bohemia and the Carnic Alps. Considering the wide distribution of the taxa, the appearance of the *Harpabollia* association in the Baltoscandian area could be interpreted as an immigration event, directly related to onset of the Hirnantian glaciation (Meidla 1996b).

In the Ruhnu (500) core, the marlstone interval overlying the Jonstorp Formation (617.1–619.1 m)

is attributed to the Bernati Member of the Kuldiga Formation (Appendix 1, sheet 22). Three ostracod samples from this interval do not display any changes in the faunal succession; the assemblage resembles that in the upper part of the Jonstorp Formation. The appearance of the first specific Porkuni/Hirnantia taxa (*Circulinella gailitae*, *Rectella composita*, *Harpabollia harparum* is recorded at a depth of 616.8–616.9 m only (Appendix 25). The faunal assemblage in the Ēdole Member of the Kuldiga Formation is more diverse in the Ruhnu (500) core than usual for the topmost Ordovician. Apart from the typical members of the *Harpabollia* association (species listed above and additionally *Aechmina groenwalli*, *Rectella sturiensis*, *Scanipisthia rectangularis*, *Drepanella*? *pauxilla* and *Pseudoancora confragosa*), the strata also contain some taxa which are specific to the Porkuni Stage in North Estonia (Ärina Formation, except for its basal part), such as *Medianella aequa* and *Duplicristatia asymmetrica* (Appendix 25).

Nõlvak (1997, 1999) has proposed the chitinozoan species *Spinachitina taugourdeaui* as a relatively good marker for the boundary of the Porkuni Stage. However, in the Tartu (453) core (Bauert & Bauert 1998) the same species is recorded in the upper part of the Pirgu Stage, in the interval for which preliminary ongoing measurements have given relatively low carbon isotopic values in the rock. The range of the same species in the Ruhnu (500) core is restricted to the Bernati Member.

The ostracod data suggest an alternative interpretation for the Pirgu–Porkuni boundary interval in the Ruhnu (500) core, where the lower boundary of the Porkuni Stage could be drawn in the interval of 616.9–618.25 m (Appendix 25), and preferably could be tied to the level of lithological change (617.1 m). This interpretation is not necessarily in conflict with the stable isotopic data. According to Martma (in this volume, Fig. 4), the stable carbon isotopic values in the Bernati Member are not substantially higher than those in the topmost part of the Jonstorp Formation, which supports indirectly such a re-interpretation of the stratigraphy in the Ruhnu (500) core.

The Saldus Formation was not sampled for ostracods. The basal Silurian strata (598.4 m) contain an impoverished and poorly preserved assemblage, including the species of the long-ranging genera *Longiscula*, *Rectella* and *Microcheilinella*, typical of the basal Silurian in the Ruhnu area.

CARBON AND OXYGEN ISOTOPES

The Ruhnu (500) drill core has twice been sampled and measured for stable isotope studies. Our analyses are based on the whole-rock sampling method. This method was chosen in spite of its shortcomings (see below) to characterize the entire studied sequence by samples from more or less regular intervals, not depending on the possibility of finding any bioclasts. However, the sampling strategy did consider the stratigraphic context (lithology, unit thickness, position of unit boundaries). Generalized data and some details on carbon isotopes in the Ruhnu (500) core have earlier been published in the following papers: the curve from the top of the Pirgu to the middle of the Jaagarahu stages in Kaljo *et al.* (1998), the curve from the Llandovery up to the lowest Wenlock in Kaljo & Martma (2000), the curve and data from the Porkuni Stage in Kaljo *et al.* (2001), the curve as in 1998 but with sampling points noted in Kaljo *et al.* (2003). A full set of analytical data on the carbon isotopes obtained from bulk samples of the Ruhnu (500) drill core is published here for the first time (Appendix 26). A total of 161 samples were analysed, with a mean sampling interval of 1.5 m, but the Porkuni and uppermost Pirgu stages were studied in more detail – nearly two samples per metre. The Liverpool University team analysed carbon and oxygen isotopes using calcite from bioclasts (different brachiopod shells). Their results were published and methods discussed in Heath *et al.* (1998) (their list of analyses embracing the interval from the Kuili Formation up to the Jamaja Formation is here included into Appendix 6). The Pirgu–Porkuni curves (whole-rock carbon isotopes (measured in Tallinn) and carbon and oxygen isotopes from bioclasts (measured in Liverpool) were presented also by Brenchley *et al.* (2003). The Ruhnu (500) core is the only section in Estonia that has provided a reliable set of brachiopod bioclasts from the uppermost Ordovician and lower Silurian, but even there bioclasts are sparse.

The methodology of carbon isotope analysis used in the isotope palaeoclimatology laboratory of the Institute of Geology at Tallinn Technical University is explained in detail by Kaljo *et al.* (1997, 1998); here only the most important aspects are noted. The whole-rock samples were powdered to a <10 μm grain size, reacted with 100% phosphoric acid at 100 °C for 15 min and analysed with a Finnigan MAT "Delta E" mass spectrometer. The results are presented in the usual δ notation, as per mil deviation from the VPDB standard. The reproducibility of the results is better than 0.1‰. Previous studies (Brenchley *et al.* 1994; Kaljo *et al.* 1997) show little diagenetic alteration of Baltic early Palaeozoic rocks, so we expect reliable carbon isotope analysis in whole-rock samples. Brenchley *et al.* (2003) discussed newly in detail the reliability of isotope signals in the late Ordovician rocks of Estonia and noted that the ma-

jor changes in isotope values reflect primary composition. The comparison of our whole-rock isotope data (Kaljo *et al.* 1998, 2001) with those obtained for brachiopod shells from the Baltic Ordovician and lower Silurian (Marshall *et al.* 1997; Heath *et al.* 1998; Brenchley *et al.* 2003) and from the Silurian of Gotland (Samtleben *et al.* 1996) shows only slight difference in $\delta^{13}C$ values but great similarity of the corresponding curves. The oxygen isotope ratios are more sensitive to diagenesis (Marshall 1992; Saltzman 2002) and therefore data from whole-rock analysis are not trustworthy. Another difficulty arises from the fact that Baltic carbonate rocks are mostly highly variable mixtures of calcite and dolomite that have different oxygen isotope fractionation factors. Marshall *et al.* (1997) and Brenchley *et al.* (2003) provide additional information about the Hirnantian and Heath *et al.* (1998) about the Silurian oxygen trend based on calcite from brachiopod shells.

Based on the studies quoted above and analyses included in Appendix 26, the following main carbon isotopic events and specific intervals of the $\delta^{13}C$ temporal variation through the uppermost Ordovician and lower Silurian of the Ruhnu (500) core could be listed (Fig. 4).

(1) The Porkuni (Hirnantian) major isotopic event. The carbon isotope profile is characterized by a relatively rapid rise in $\delta^{13}C$ values from 1‰ in the *taugourdeaui* chitinozoan Biozone to a peak value of 6‰ in the lower part of the *scabra* chitinozoan Biozone, 5 m above the start of the excursion. Values fall gradually until a small disconformity at the top of the Hirnantian sequence where there is a sharp drop of 1.6‰. Brenchley *et al.* (2003) have considered the 18 m long Porkuni bulk-rock $\delta^{13}C$ profile in the Ruhnu (500) core as typical of this global isotopic event, marking the Hirnantian glaciation and mass extinction of biota.

(2) The lowermost Juuru low or post-Hirnantian lessening of carbon isotope values. The shift is clearly indicated at Kirikuküla (–1.2‰), but not so well in the Ruhnu (500) core (1.0‰).

(3) The lowermost Raikküla negative shift, called also "Pusku" low (reaches –1.2‰ at Ruhnu), followed by a small positive excursion (~2‰). The negative shift is confined to the Heinaste Member (Nestor *et al.* 2003) and is very sharp and short.

(4) The next stratigraphical interval comprising the Slitere and Kolka members and the lower part of the Ikla Member of the Saarde Formation shows a rather smooth, slightly rising trend from 1.5‰ up to 2.2‰. However, it is interrupted by a couple of lows (1.1‰) in the Kolka Member.

(5) The positive shift (3.7‰) in the middle of the Raikküla Stage is well dated by graptolites (upper part of the *Demirastrites triangulatus* graptolite Biozone). After a short interval of steady decrease (until 0.8‰), a second positive shift is noted in the upper part of the Ikla Member, where the $\delta^{13}C$ values reach 2.5‰. This second shift was attributed by Kaljo & Martma (2000) to the Lemme Member.

(6) Higher in the Ruhnu (500) section, in the Lemme and Staicele members of the Saarde Formation and up to the uppermost part of the Velise Formation, the $\delta^{13}C$ values vary below 2‰. The negative excursion of $\delta^{13}C$ values characteristic of the Rumba Formation (reaching –1.3‰ at Kirikuküla; Kaljo & Martma 2000) is not observed in this trend because only a small part of the beds is represented at Ruhnu.

(7) The next major excursion occurs in the lower Wenlock (+4.6‰ at Ruhnu), beginning at the Llandovery–Wenlock boundary and reaching maximum values above the *Monograptus riccartonensis* graptolite Biozone. This peak is the well-known early Sheinwoodian carbon isotope event discussed by Kaljo *et al.* (1998, 2003).

The oxygen isotope values ($\delta^{18}O$), published by Heath *et al.* (1998), change in the same stratigraphic interval parallel to the carbon isotope values (Fig. 4). This typical pattern is well seen in two major, Porkuni and early Wenlock excursions, but the mid-Raikküla carbon isotope peak is not reflected in the oxygen curve or is even shown controversially.

It is generally accepted (Brenchley *et al.* 1994, 2003) that big positive shifts of the $\delta^{18}O$ values refer to conspicuous coolings of the climate, and both major excursions in the Ruhnu (500) core have been interpreted this way (Heath *et al.* 1998; Kaljo *et al.* 1998; Brenchley *et al.* 2003). Throughout the Llandovery the oxygen isotope curve shows only a very gradual change toward more negative $\delta^{18}O$ values from –4.2‰ as mean at the bottom to –5.3‰ at the top, indicating a slow rise in temperature. The character of the trend is in harmony with ideas about the early Silurian climate. The noted discrepancy with our carbon data in the Llandovery seems to be caused, at least partly, by gaps in the brachiopod sampling record.

In stratigraphy the carbon isotope data have served very well for correlation of sections, but reliable results could be achieved when used together with biostratigraphical data. Brenchley *et al.* (2003) suggested to use the chronostratigraphic "ruler" provided by the carbon isotope profiles as a scale against which the sequence of biotic changes may be related. The ruler also allows high-resolution correlation of biotic events at different locations.

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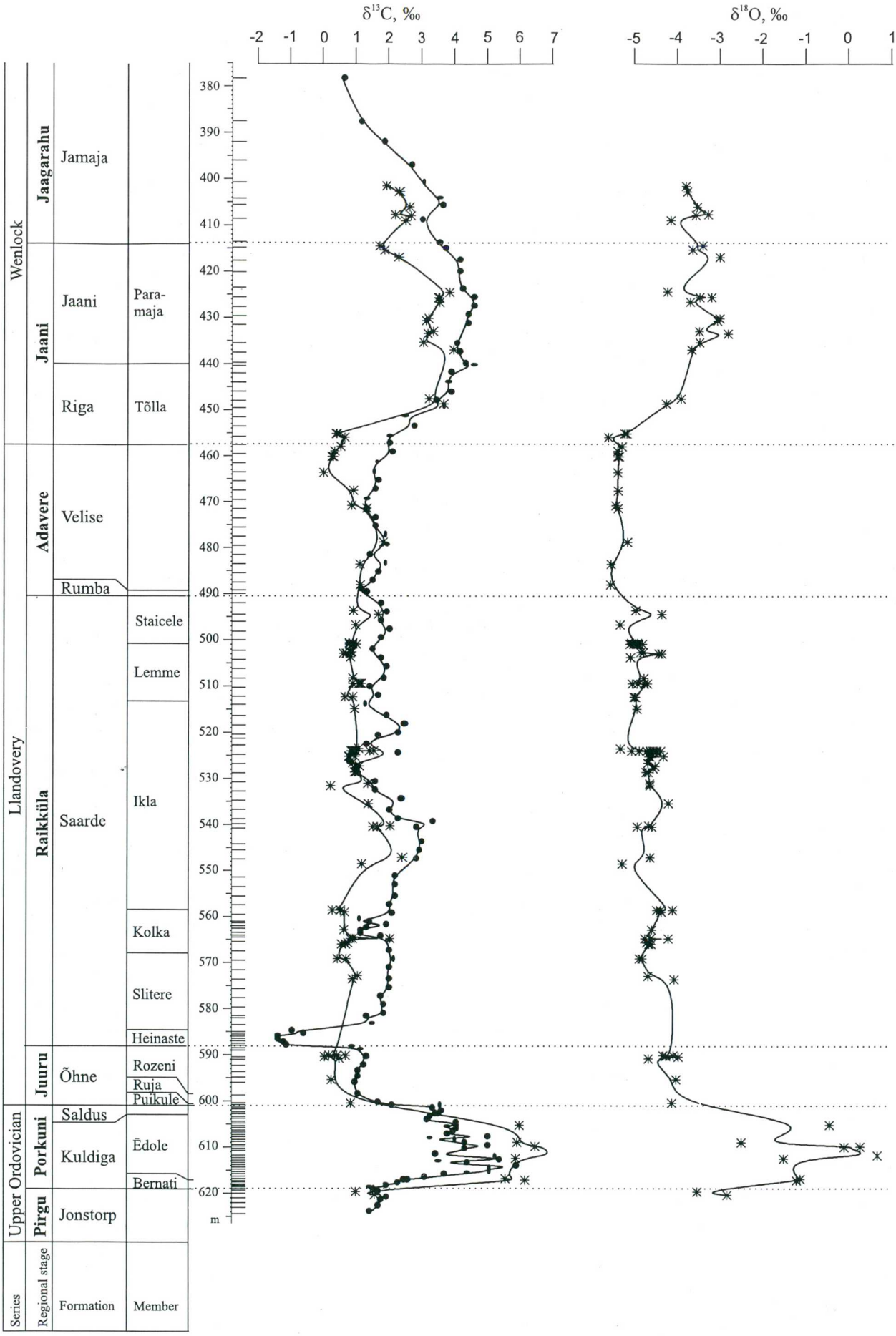


Fig. 4. Bulk carbonate carbon (filled circles), and brachiopod carbon and oxygen stable isotope (stars; after Heath *et al.* 1998) profiles of the Ruhnu (500) core.

ALTERED VOLCANIC ASH BEDS

A total of 30 samples were studied from the Ruhnu (500) drill core (Appendix 27). The suspected volcanic origin was proved for 26 samples by bulk sediment X-ray diffractometry (XRD) in randomly oriented specimens. The presence of illite-smectite and authigenic K-sanidine, and lack of carbonates and terrigenous quartz were considered as indicators of altered volcanic material. The bulk sediment chemical composition and trace elements were analysed by the X-ray fluorescence (XRF; Appendix 28) method (Kiipli *et al.* 2001). For correlation purposes, the content and composition of magmatic phenocrystals (quartz and K–Na sanidine) in coarse fractions (0.03–0.1 and > 0.1 mm; Appendix 29) were studied by the XRD method described in Kiipli & Kallaste (2002). The presence of idiomorphic and broken phenocrystals was checked under the binocular microscope.

Stratigraphically the identified volcanic beds range from Upper Ordovician to upper Silurian (see Appendix 1, sheets 8, 10, 12–18, 20, 22, 23).

Chemical and mineralogical composition of altered volcanic ash beds

The composition of volcanic beds in the Ruhnu (500) core is extremely variable. The Al_2O_3 content varies from 13.2% (K-feldspar with terrigenous admixture) and 18% (pure K-feldspar) to 31.7% (samples containing about 50% kaolinite). The K_2O content is even more variable – from 3.4% in kaolinite-rich samples to 12.94% in feldspar-rich samples. The volcanic beds dominated by illite-smectite revealed intermediate contents of Al_2O_3 (20–26%) and K_2O (6–8%). A specific feature, previously not recorded in Estonian sections, is the association of kaolinite and K-feldspar in some beds. Beds with a very different composition alternate frequently (often within few metres) in vertical section, which proves the idea that the composition of a particular volcanic bed is not determined by late diagenetic burial or fluid penetration processes. Quite evident is major influence of the chemistry of local environment (marine, volcanic ash and host sediment chemistry; Kiipli *et al.* 1997).

Sanidine and trace elements

Large variations in trace element content in volcanic beds refer to different volcanic sources (Kiipli *et al.* 2001). The source magma differentiation diagram by Winchester & Floyd (1977) indicates various source magmas. Most points of the diagram fall into the trachyandesite field (Fig. 5). This diagram has been used by many researchers (including

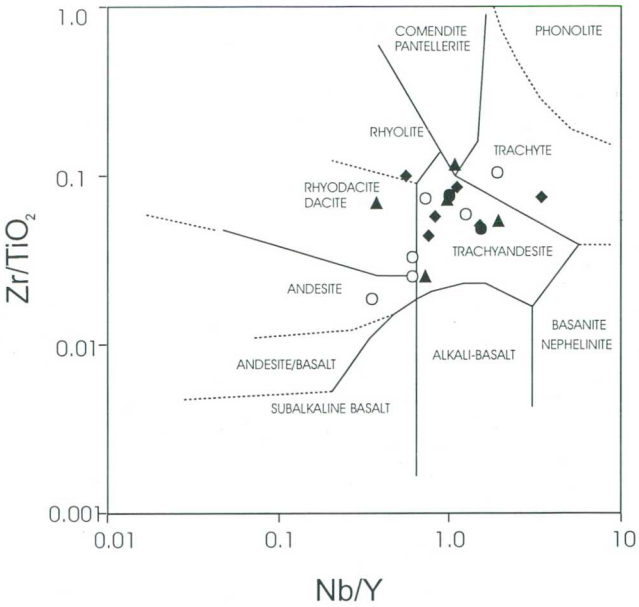


Fig. 5. Source magma discrimination diagram after Winchester & Floyd (1977). Filled rhombs – Wenlock and upper Silurian, open circles – upper Adavere, filled triangles – lower Adavere, filled circles – Ordovician.

the authors of the present study) and has revealed a similar distribution of trace elements in different regions and stratigraphical levels. In reality, such representation of trace element data poses the question: is such a wide occurrence of volcanoes erupting mildly alkaline ashes realistic? There are several circumstances contradicting this possibility. (1) Alkaline rocks are relatively rare in the earth's crust. (2) Alkaline magmas have a low SiO_2 content, which determines low viscosity of magmas and consequently domination of lava flows in eruptions of alkaline magmas. Violent explosive eruptions with extensive ash distribution are uncommon. (3) Quartz phenocrystals are very common in Estonian Palaeozoic altered volcanic ashes, evidencing about early crystallization of quartz. This is possible only in silica-rich magmas. (4) The niobium content of alkaline rocks is commonly much higher than that of Estonian altered volcanic ashes. The average values are 118 ppm for trachyandesite, 146 ppm for trachyte, 178 ppm for phonolite and 159 ppm for pantellerite (Winchester & Floyd 1977). The maximum niobium content of Estonian altered volcanic ashes is 60 ppm (Kiipli *et al.* 2001), which was probably originally about twice lower as ash loses approximately 50% of weight in glass crystallization (Kiipli *et al.* 2002).

High Nb/Y ratios in altered volcanic ashes are caused not by high Nb, but by low Y contents. This is not characteristic of alkaline rocks. What can be the cause of this uncertainty? There are three possible sources of error: (1) Y has been considered as an immobile element, but in reality it can dissolve

and move away to some extent, (2) the selection of volcanic rocks used by Winchester and Floyd does not cover the whole natural variability, (3) older Y determinations are systematically too high (Dulski 2001; Dulski & Longerich 2002).

Below, we give another version of source magma types proceeding from the XRD study of coarse fractions of volcanic ash represented partly by magmatic phenocrystals (Fig. 6). This version is based on the fact that altered volcanic ashes contain quartz phenocrystals and consequently must originate from acidic magmas. Volcanic ash beds containing quartz below the detection limit of the XRD are rare. Therefore it is probable that most of the altered volcanic ashes were formed from dacite and rhyolite, rarely from andesite. Volcanic beds containing sodium-rich sanidine (and being also relatively rich in Nb) originated probably from magma of trondhjemite (acidic magma with Na dominating over K) composition (Barker 1979). Trondhjemites are well known from the Norwegian Caledonides (Barker 1979). Field boundaries in Fig. 6 are only preliminary, as special comparative study of non-altered volcanic rocks was not performed. The suggestion about the dominance of silica-rich magmas in volcanic sources fits well with the distribution of ash clouds over 1000–2000 km (distance from Estonia to the plate margins), which

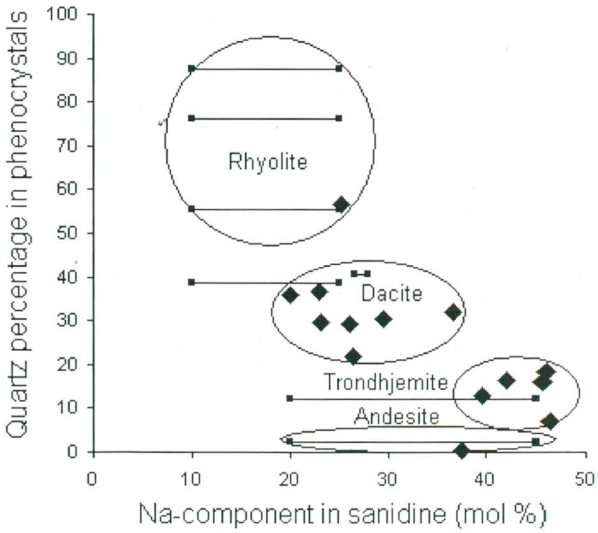


Fig. 6. The content and composition of magmatic phenocrystals in altered volcanic ashes of the Ruhnu (500) core. Oval contours represent hypothetical source magma fields. Horizontal lines represent data from volcanic beds with wide sanidine reflections.

is possible only in the case of huge explosive eruptions. Eruptions of this type are characteristic of volcanoes having silica-rich magmas with high viscosity. Both versions of source magma compositions are represented in Table 1.

Plagioclase problem

Table 1 presents the approximate quantity of magmatic phenocrystals, calculated on the basis of the quartz and K–Na sanidine contents of the coarse fraction. This method does not take into account the existence of biotite, apatite and some other accessory minerals and, therefore, the calculated contents can be substantially underestimated for some beds. The method leaves out also very fine phenocrystals. Although it gives first approximation, the content of phenocrystals is only a few per cent. This concentration is unusually low compared to fresh volcanic rocks in which the values of 10–25% are common (Ewart 1979, 1982). Another noteworthy feature is the absence (or rare traces) of plagioclase in altered volcanic ashes, and the dominance of plagioclase among phenocrystals in fresh volcanic rocks. There seems to be no doubt of dissolution of plagioclase in the process of recrystallization of volcanic ash in sedimentary environment.

Correlation with other sections

Correlation of the volcanic ash beds of the Ruhnu (500) core (Table 1; Kiipli & Kallaste 2002, table 1) with other sections is based on the properties of magmatic K–Na sanidine: its sodium content and width of the $20\bar{1}$ XRD reflection. Graphic correlation with the Ohesaare and Viki cores was used to check mineralogical correlations. Some beds containing no characteristic sanidine are correlated only on the basis of graphic correlations between sections. Correlations based on volcanogenic marker levels reveal that the lowermost part of the Velise Formation (interval 174.4–183.5 m in Viki, Kiipli *et al.* 2001) is absent in the Ruhnu (500) core. It is possible that much of the Rumba Formation is also in a hiatus as no "O" (Osmundsberg; Bergström *et al.* 1998) altered volcanic ash bed was found in the Ruhnu (500) core. The Kinnekulle bed was confirmed at a depth of 649.9–650.1 m (see Appendix 1, sheet 23). The volcanic bed at 653.06–653.1 m cannot be correlated by the composition. Several other beds can potentially be correlated, but these are not yet established in other sections.

Table 1. Interpretation of source magma composition of volcanic beds of the Ruhnu (500) core on the basis of geochemical and mineralogical analyses and correlation with the Ohesaare and Viki sections

Sample depth (m)	Interval (m)	Thickness (m)	Regional stage	Nb/Y	Zr/TiO_2	Hypothetical source magma according to Winchester & Floyd (1977)	Quartz percentage in phenocrystals	$NaAl\ Si_3O_8$ in sanidine (mol%)	Hypothetical source magma according to quartz and sanidine content	Depth of correlated volcanic ash beds (m)	
										Ohesaare	Viki
222.00	221.800–222.000	0.200	Kuressaare	0.751	0.044	Trachyandesite	35.8	20.0	Dacite	–	–
283.80	283.650–283.900	0.250	Jaagarahu–Rootsiküla	3.422	0.074	Trachyte	–	–	–	154.40	–
283.90	283.650–283.900	0.250	Jaagarahu–Rootsiküla	–	–	–	38.7	Weak reflection	Dacite	154.40	–
337.50	337.498–337.500	0.002	Jaagarahu	–	–	–	36.7	22.9	Dacite	215.70	–
374.00	373.970–374.000	0.030	Jaagarahu	1.109	0.085	Trachyandesite	30.4	29.6	Dacite	–	–
388.40	388.390–388.400	0.010	Jaagarahu	1.496	0.050	Trachyandesite	87.4	Weak reflection	Rhyolite	294.20	–
411.40	411.400–411.450	0.050	Jaagarahu	0.821	0.057	Trachyandesite	11.9	Wide reflection	Trondhjemite	–	–
430.50	430.498–430.500	0.002	Jaani	–	–	–	2.3	Wide reflection	Andesite	–	–
435.76	435.740–435.838	0.098	Jaani	–	–	–	–	Wide reflection	–	–	–
435.84	435.838–435.840	0.002	Jaani	0.547	0.099	Rhyolite	18.3	45.9	Trondhjemite	323.20	–
437.40	437.398–437.400	0.002	Jaani	–	–	–	0.2	37.5	Andesite	323.85	–
459.00	458.985–459.000	0.015	Adavere	1.241	0.059	Trachyandesite	32.0	36.7	Dacite	351.72	131.10
467.60	467.580–467.600	0.020	Adavere	0.599	0.033	Dacite	–	–	–	359.30	145.75
470.80	470.780–470.800	0.020	Adavere	0.996	0.075	Trachyandesite	16.0	45.4	Trondhjemite	361.30	147.50
471.80	471.790–471.800	0.010	Adavere	0.720	0.073	Trachyandesite	16.4	42.1	Trondhjemite	361.70	148.00
473.10	473.097–473.100	0.003	Adavere	0.347	0.019	Andesite	–	–	Andesite	362.23	148.80
473.70	473.650–473.700	0.050	Adavere	1.922	0.104	Trachyte	7.1	46.1	Trondhjemite	362.46	149.40
478.90	478.890–478.900	0.010	Adavere	0.603	0.025	Andesite	–	–	Andesite	–	–
488.24	488.238–488.240	0.002	Adavere	0.372	0.068	Rhyodacite	29.7	23.1	Dacite	369.75	169.60
488.30A	488.240–488.270	0.030	Adavere	0.971	0.072	Trachyandesite	76.3	Weak reflection	Rhyolite	–	171.95
488.30B	488.270–488.300	0.030	Adavere	1.078	0.115	Pantellerite	40.7	26.5–28.0	Dacite	–	–
488.40	488.390–488.400	0.010	Adavere	0.721	0.025	Trachyandesite	22.0	26.4	Dacite	–	–
489.05	489.040-489.050	0.010	Adavere	1.930	0.054	Trachyandesite	13.0	39.6	Trondhjemite	369.98	173.10
489.05	489.040–489.050	0.010	Adavere	–	–	–	29.4	26.0	Dacite	–	174.40
628.05	628.050–628.060	0.010	Pirgu	–	–	–	–	Wide reflection	–	–	–
650.00	649.900–650.100	0.200	Keila	0.989	0.076	Trachyandesite	56.7	25.2	Rhyolite	466.30	329.95
652.80	652.790–652.800	0.010	Haljala	–	–	–	55.4	Weak reflection	Rhyolite	–	–
653.00	653.060–653.100	0.040	Haljala	1.527	0.048	Trachyandesite	–	–	–	–	–

– data not available

CHEMICAL COMPOSITION AND PHYSICAL PROPERTIES OF THE ROCK

A total of 114 rock samples from the Cambrian, Ordovician, Silurian and Devonian parts of the Ruhnu (500) drill core were studied by petrophysical and geochemical methods and interpreted using correlation analysis (Appendixes 30, 31). Thin sections were made from 54 samples to study interrelationships between minerals, textures and composition of rocks (Appendix 4). The investigated core section is represented by primary sedimentary rocks (limestones, calcitic marlstones, sand-, silt- and claystones) and by dolomitized rocks (dolostones, dolomitic marlstones, dolomite-cemented sand- and siltstones).

Methods

Physical properties of the rock were measured at room temperature and pressure in the laboratories of the Geological Survey of Finland and Research Institute of Earth's Crust of St. Petersburg University. Thermal conductivity of all samples was measured in the Geological Survey of Finland on disks with 25–31 mm diameter and 5–7 mm length (54 samples), and on cubes with sides of length 2.2–2.4 mm (40 samples) using the divide bar technique. The measurements made in different laboratories are in good accordance, except for apparent resistivity. High-resistivity compact rocks show similar results, while more porous low-resistivity rocks show differences. This may be explained by different laboratory methods of water saturation of samples, resulting in a lower resistivity of the higher saturated rocks.

The bulk chemical composition of the rocks was measured by XRF spectrometry in the laboratories of the All-Union Geological Institute (VSEGEI), St. Petersburg, and the State Institute of Mineral Resources of Ukraine, Simferople. Most of the XRF results are in good accordance, except for Na_2O. This may be explained by a low Na_2O content in the studied rocks and by different sensitivity of the techniques used in these laboratories.

The insoluble residue (IR) and FeO contents were measured by wet chemical analysis in the Institute of Geology at Tallinn Technical University (IG TTU).

Thin sections used for interpretation were prepared in IG TTU. Physical and chemical parameters were interpreted together using correlation analysis.

Composition of rock samples

The IR measured by wet chemical analysis and data of XRF analysis were used for determination of the lithology of rocks (Appendix 30). The studied rocks were subdivided into six lithological groups based on the following limits of the calculated and measured chemical components (Fig. 7): (1) limestone (IR < 25%, $CaCO_3$ > 50%), (2) dolostone (IR < 25%, $CaMg(CO_3)_2$ > 50%), (3) calcitic marlstone (IR > 25%, SiO_2 < 35%, $CaCO_3$ > $CaMg(CO_3)_2$), (4) dolomitic marlstone (IR > 25%, SiO_2 < 35%, $CaCO_3$ < $CaMg(CO_3)_2$), (5) mixed carbonate-siliciclastic rock (IR< 75%, SiO_2 > 35%), (6) siliciclastic rock (IR > 75%). The first group (46 samples) includes pure (IR < 10%) and variously argillaceous (10 < IR< 25%) limestones. The second group (26 samples) of dolostones is interpreted in the same way. Calcitic marlstones are represented by 18 samples and dolomitic marlstones account for 6 samples. The fifth group (7 samples) includes highly argillaceous silt- or sand-containing marlstones, usually cemented by carbonates. Silt-, sand- and claystones (sixth group) are represented by 10 samples.

Dolostone together with dolomitic marlstones and siliciclastic rocks have a high negative MgO–IR correlation and positive MgO–CaO correlation.

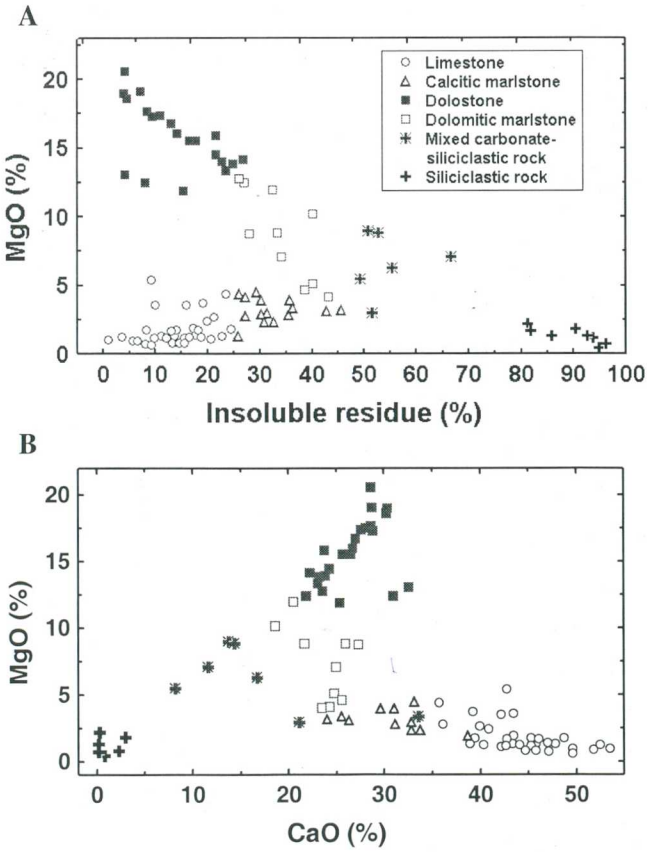


Fig. 7. (A) MgO content measured by XRF spectrometry versus insoluble residue content measured by wet chemical analysis. Correlation coefficient $R = -0.85$ for dolostones and dolomitic marlstones. For limestones and calcitic limestones $R = 0.55$. (B) MgO content versus CaO content measured by XRF spectrometry. Correlation coefficient $R = 0.43$ for dolostones and dolomitic marlstones. For limestones and calcitic limestones $R = -0.70$.

Limestones together with calcitic marlstones have a positive MgO–IR correlation and negative MgO–CaO correlation (Figs 7, 8).

Entering IR, the chemical constituents SiO_2, Al_2O_3, TiO_2 and K_2O have a high positive correlation with it (respectively 0.99, 0.93, 0.88 and 0.97) and with each other in carbonate rocks (Figs 8 and 9A, B). SiO_2 enters IR in the form of siliciclastic (quartz) and clay minerals. K_2O and Na_2O may enter also siliciclastic (feldspar) and clay minerals. The higher K_2O content in siliciclastic and mixed carbonate-siliciclastic rocks compared to carbonate rocks shows the abundance of K-feldspar in siliciclastic rocks (Fig. 9A). Na_2O is usually very low (< 0.3%) in the studied rocks and nearly absent (below the detection limit of XRF spectrometry) in some sandstones (see Appendixes 30, 1). Al_2O_3 and TiO_2 may serve as indexes of the clay content because they enter only clay minerals (Fig. 8).

The total iron (Fe_2O_3 total) content of most of the studied rocks (0.3–4.6%) correlates with the clay content. It is higher (5.5–5.6%) in hematite containing dolostone of the Sakyna (697.6 m) and Kriukai (701.4 m) formations, in Kriukai (705.9 m) glauconite-bearing dolostone, in glauconite-rich (9.9–19.9% of Fe_2O_3 total) marlstone of the Zebre Formation (706.2 m) (see Appendix 1, sheet 25) and in Cambrian rocks (7.1–9.5%) with siderite cementation ($FeCO_3$ content 5–8.1%; Figs 8, 10A, see also Appendix 1, sheets 25–28). The MnO content is generally higher in the rocks with a higher total iron content (Fig. 10B), but a high MnO content (up to 0.4%) was also measured in the Upper Ordovician limestones (Fig. 8) with a low total iron content (< 1%).

Porosity and density

Among the studied rocks, the Silurian (Saarde Formation, 490.3–588.1 m; see Appendix 1, sheets 18–21) and Ordovician limestones had the lowest porosity (Fig. 11). Limestone porosity changed from 0.83 to 10.9% with an increase in IR from 0.88 up to 24.9% (except for one strongly argillaceous Silurian sample with 14.2% porosity). The porosity of calcitic marlstones increased from 7.63 to 18.5% with an increase in IR from 25.2 to 41.8% (Figs 11, 12). The correlation coefficient of primary porosity with IR for these primary rocks was 0.89. The porosity of dolostones changed from 1.3 to 21%. It was higher than the porosity of limestones with a similar IR content. This is explained by secondary nature of porosity formed owing to leaching of rocks during dolomitization. The porosity of dolomitic marlstones (8.1–19.6%) was prevailingly higher than that of calcitic marlstones with the same IR content. The porosity of mixed carbonate-siliciclastic rocks was in the same limits (7.8–17.4%) as in marlstones, although mixed rocks had a higher IR content (Fig. 12). The porosity of siliciclastic rocks (Fig. 13) was the highest (15.3–28.8%) and wet density the lowest (2.06–2.45 g/cm^3). The average wet density of mixed carbonate-siliciclastic rocks was 2.5 g/cm^3, that is, a bit lower than that of marlstones (2.53 g/cm^3). The correlation coefficient (R) for limestones together with calcitic marlstones of the density–porosity plot was –0.97, for dolostones and dolomitic marlstones –0.86. Usually the density of dolostones is higher than that of limestones with the same porosity. This is explained by a higher grain density of dolomites (in average 2.79 g/cm^3) compared to limestones (2.72 g/cm^3).

P-wave velocity

The P-wave velocity of the studied rocks changes in a wide range 1.7–5.8 km/s and depends on porosity and mineralogy (Figs 11, 14). Among the studied dolostones, the highest velocity was determined in the Lower Ordovician and Silurian dolostones. High velocity was measured also in pure limestones, but the velocity of most dolostones was higher than that of limestones with the same porosity. Velocity (< 3 km/s) was the lowest in argillaceous limestones, dolostones and siliciclastic rocks with a porosity higher than 10%. Relatively low velocity (2.9–3.5 km/s) was determined in the Silurian argillaceous dolostones with a combination of primary and secondary porosity (interval 222.0–287.6 m). In average, velocity decreases in the following rock succession: dolostones, limestones, dolomitic and calcitic marlstones, mixed carbonate-siliciclastic and siliciclastic rocks.

Thermal conductivity

Thermal conductivity changed in the studied rock data set in the range 1.84–4.4 W m^{-1} K^{-1} (Fig. 15). The highest thermal conductivity was measured in the Silurian dolostones (interval 222.0–287.6 m; Fig. 11). Thermal conductivity was low in calcitic marlstones (mean 1.97 W m^{-1} K^{-1}) and limestones (mean 2.63 W m^{-1} K^{-1}), making one common correlation line with porosity (R = –0.85). The average thermal conductivity of dolostones (3.3 W m^{-1} K^{-1}) was the highest among the studied rock groups. The greatest variability in thermal conductivity in the whole range of measurements was determined in mixed carbonate-siliciclastic rocks. Statistically, thermal conductivity decreases in the following rock succession: dolostones, mixed carbonate-siliciclastic rocks, siliciclastic rocks, limestones, dolomitic marlstones and calcitic marlstones. The correlation between thermal conductivity and the total iron content

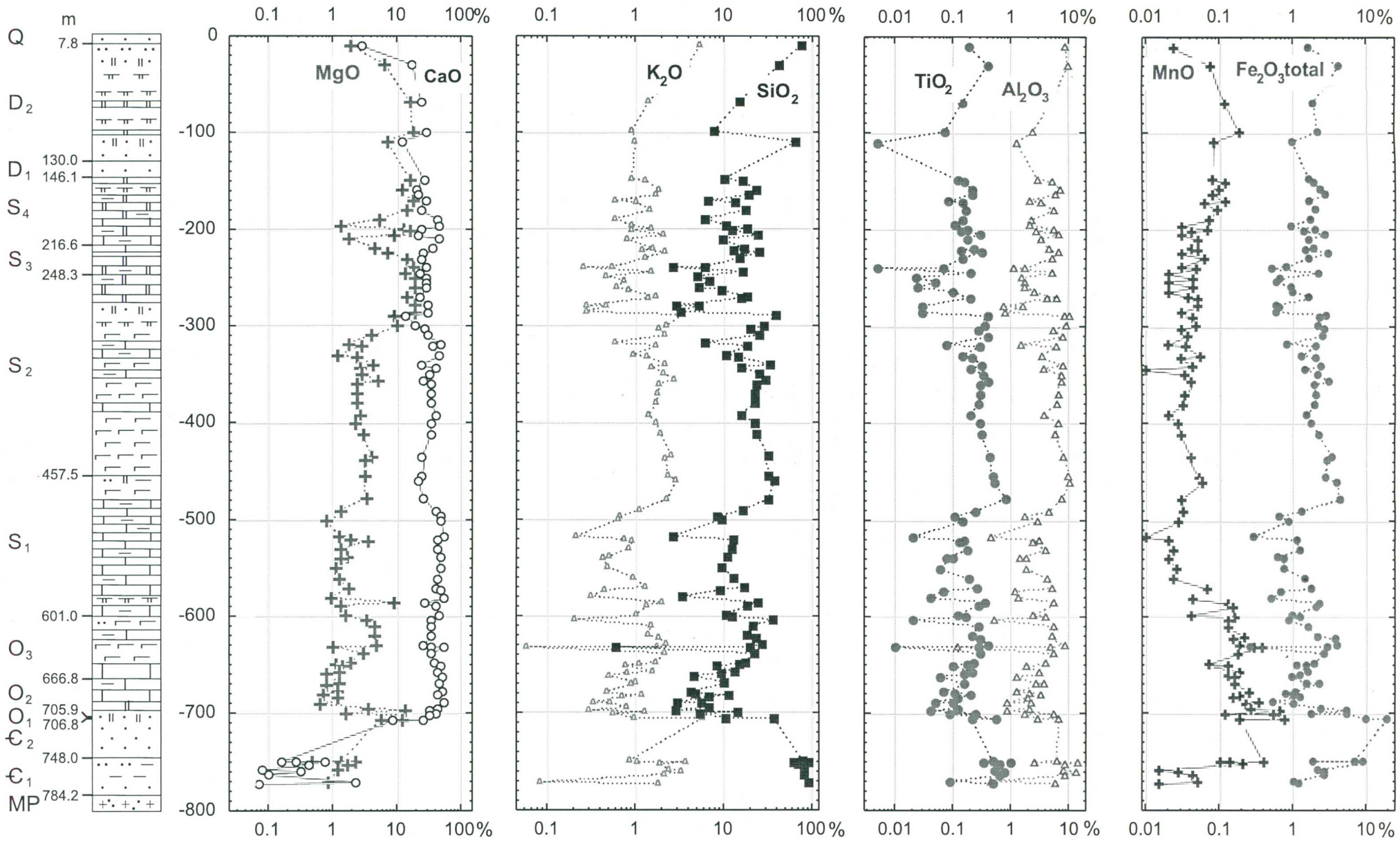


Fig. 8. Chemical composition of the Ruhnu (500) core. MP – Mesoproterozoic; $Є_1$ – Lower Cambrian; $Є_2$ – Middle Cambrian; O_1 – Lower Ordovician; O_2 – Middle Ordovician; O_3 – Upper Ordovician; S_1 – Llandovery; S_2 – Wenlock; S_3 – Ludlow; S_4 – Přídoli; D_1 – Lower Devonian; D_2 – Middle Devonian. Refer to Appendix 1 for lithology.

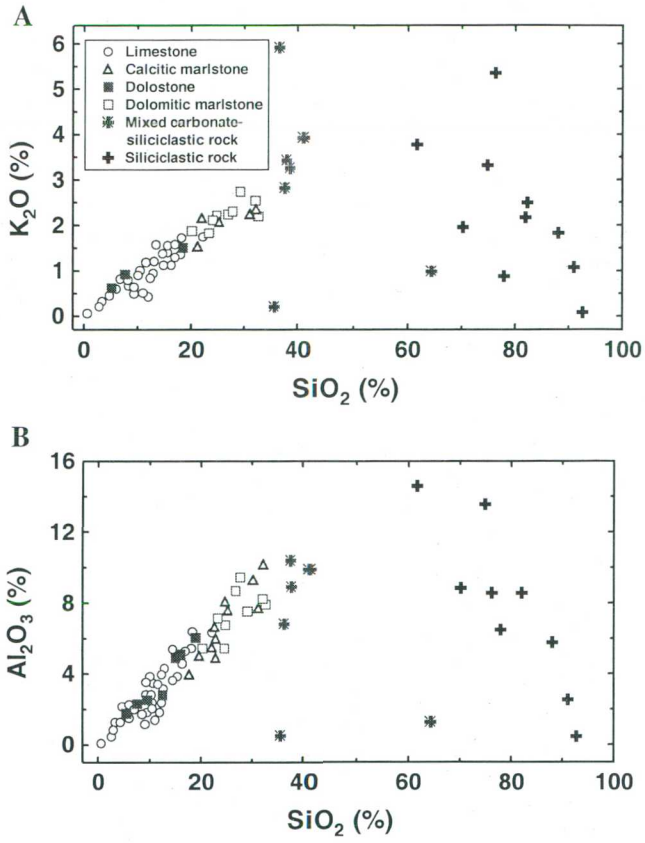


Fig. 9. (A) K_2O content versus SiO_2 content. $R = 0.96$ for carbonate rocks. (B) Al_2O_3 content versus SiO_2 content. $R = 0.96$ for carbonate rocks.

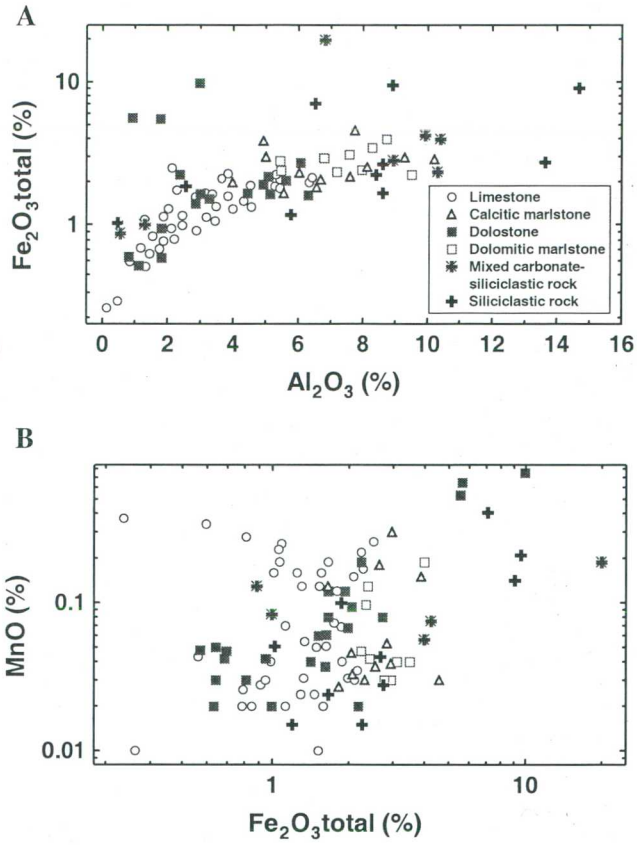


Fig. 10. (A) Total iron content versus Al_2O_3 content as the index of clay content. $R = 0.78$ for limestones and calcitic marlstones. (B) MnO content versus total iron content. $R = 0.90$ for dolomites and dolomitic marlstones.

was negative in most of the studied rocks (Fig. 16). Dolostones, dolomite-cemented mixed carbonate-siliciclastic rocks with the total iron content less than 1% and siliciclastic rocks (sandstones with a high quartz content) had the highest thermal conductivity among the studied lithological groups.

Magnetic susceptibility

The total iron content of the studied rocks changed from 0.26% in the pure limestone of the Silurian Saarde Formation (Fig. 8, see also Appendix 1, sheets 18–21) to 19.9% in Lower Ordovician glauconite-bearing carbonate-cemented sandstone (705.9 – 706.8 m). The correlation coefficient (R) between the total iron content and the IR content was 0.8 in limestones and calcitic marlstones. Low-field magnetic susceptibility in the studied rock sequence has a strong correlation with the total iron content (Fig. 17) and increases from diamagnetic to paramagnetic or even ferromagnetic minerals. Pure limestones with the total iron content less than 1% had the lowest magnetic susceptibility (below 1 x 10^{-5} SI) in the studied rock sequence. Dolostones from different stratigraphic levels had different total iron content (Fig. 8) and magnetic susceptibility (Fig. 11). Pure Silurian dolostones had the total iron content less than 1% (Fig. 8) and magnetic susceptibility less than 2.5 x 10^{-5} SI (Fig. 11). The total iron content of Devonian and Silurian argillaceous dolostones was in the range 1.6–3.0%, being the highest (up to 9.9% and 45 x 10^{-5} SI) in the Ordovician dolomites which include iron minerals. Magnetic susceptibility varied largely in the mixed carbonate-siliciclastic rocks (from 3 x 10^{-5} to 84.6 x 10^{-5} SI) and in the siliciclastic rocks (from 3 x 10^{-5} to 105.6 x 10^{-5} SI).

Conclusions

Distinct correlation lines and different correlation coefficients of porosity-dependent parameters (density, P-wave velocity, electric resistivity and thermal conductivity) were found for primary sedimentary rocks (limestones, calcitic marlstones) and for dolomitized rocks (dolostones, dolomitic marlstones). Primary porosity depends on the IR content ($R = 0.9$ for primary and $R = 0.61$ for dolomitized rocks) determined by cyclicity of sedimentation. Secondary porosity depends on diagenetic processes. The correlation coefficients between porosity and other parameters for limestones together with calcitic marlstones were higher than for dolomites and dolomitic marlstones. Thermal conductivity depends on porosity and total iron content. These dependencies were different for the studied rock groups. The correlation of magnetic susceptibility with the total

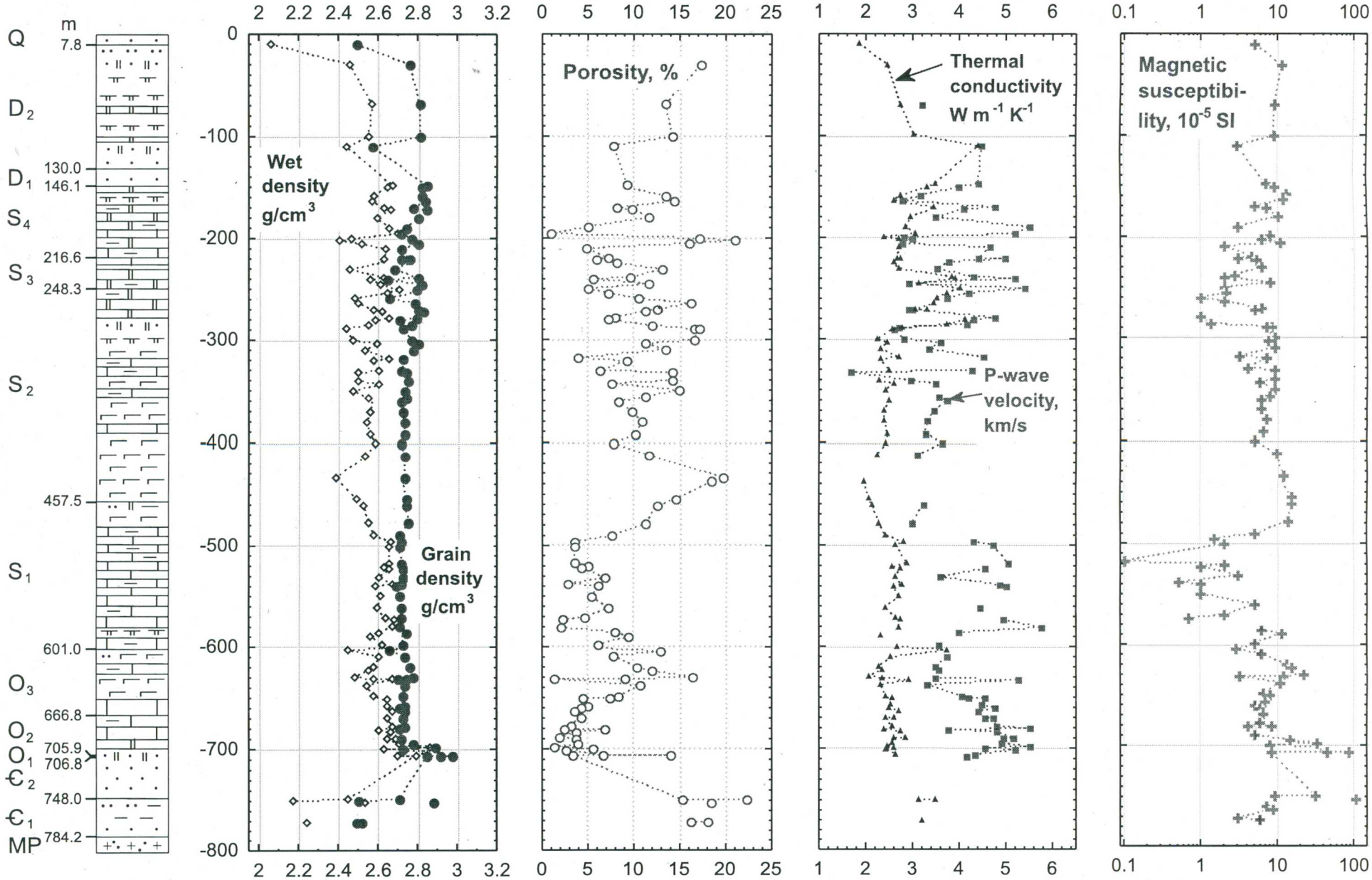


Fig. 11. Physical properties of the Ruhnu (500) core. Refer to Appendix 1 for lithology and Fig. 8 for abbrevations of stratigraphic units.

PLATES 1-3

Plate 1

Selected intervals of the Ruhnu (500) core

(depth increases from left to right)

Fig. 1. **Vadja to Leivu formations**; 92.5–94.1 m.

Fig. 2. **Ohesaare Formation**; 149.0–150.0 m.

Fig. 3. **Kaugatuma Formation (Lõo Beds)**; 178.8–179.8 m.

Fig. 4. **Kaugatuma Formation (Upper Äigu Beds)**; 191.9–193.0 m.

Fig. 5. **Kaugatuma Formation (Upper Äigu Beds)**; 197.0–198.0 m.

Fig. 6. **Kaugatuma Formation (Lower Äigu Beds)**; 206.1–207.1 m.

Fig. 7. **Rootsiküla Formation (Vesiku Beds)**; 259.4–260.3 m.

Fig. 8. **Sõrve Formation**; 277.8–279.3 m.

Fig. 9. **Sõrve Formation**; 316.2–317.2 m.

Selected intervals of the Ruhnu (500) core

(depth increases from left to right)

Fig. 10. **Jamaja Formation**; 386.6–387.6 m.

Fig. 11. **Jamaja Formation**; 406.9–407.9 m.

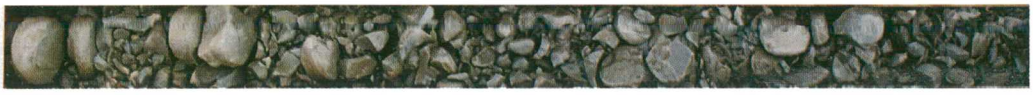


Fig. 12. **Jaani Formation (Paramaja Member)**; 427.2–428.6 m.

Fig. 13. **Saarde Formation (Ikla Member)**; 515.5–516.5 m.

Fig. 14. **Saarde Formation (Ikla Member)**; 540.1–541.1 m.

Fig. 15. **Saarde Formation (Slitere Member)**; 583.6–584.7 m.

Fig. 16. **Kuldiga Formation (Ēdole Member)**; 605.1–606.1 m.

Fig. 17. **Jonstorp Formation**; 624.4–625.4 m.

↑ 635.1 ↑ 635.3 ↑ 635.4

Fig. 18. **Mõntu Formation**; 635.1–636.0 m.

Plate 3

Selected intervals of the Ruhnu (500) core

(depth increases from left to right)

Fig. 19. **Adze Formation**; 648.6–649.6 m.

Fig. 20. **Adze Formation**; 654.9–655.9 m.

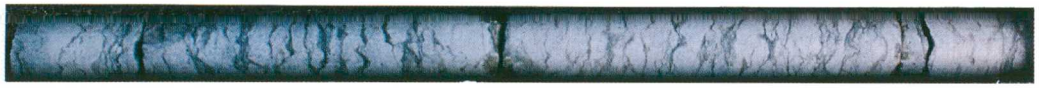
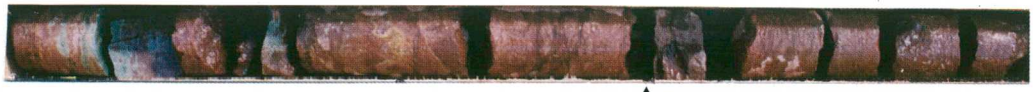


Fig. 21. **Dreimani Formation**; 662.9–663.9 m.

Fig. 22. **Taurupe Formation**; 674.7–675.7 m.

Fig. 23. **Segerstad Formation**; 682.6–683.6 m.

Fig. 24. **Baldone Formation**; 692.8–693.8 m.



↑ 700.6

Fig. 25. **Kriukai Formation**; 700.0–701.0 m.

↑ 786.9

Fig. 26. **Mesoproterozoic**; 786.0–787.4 m.

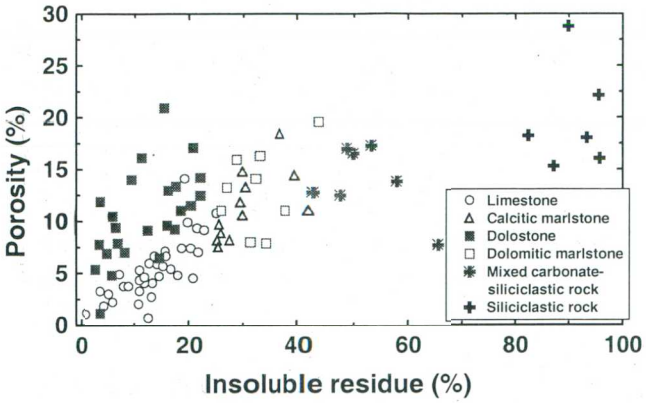


Fig. 12. Porosity versus insoluble residue (IR) content measured by wet chemical analysis. $R = 0.89$ for limestones and calcitic marlstones. $R = 0.56$ for dolostones and dolomitic marlstones.

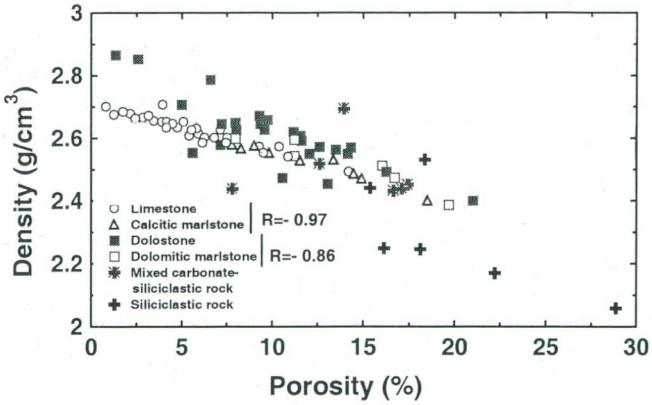


Fig. 13. Wet density versus porosity. $R = -0.97$ for limestones and calcitic marlstones. $R = -0.86$ for dolostones and dolomitic marlstones.

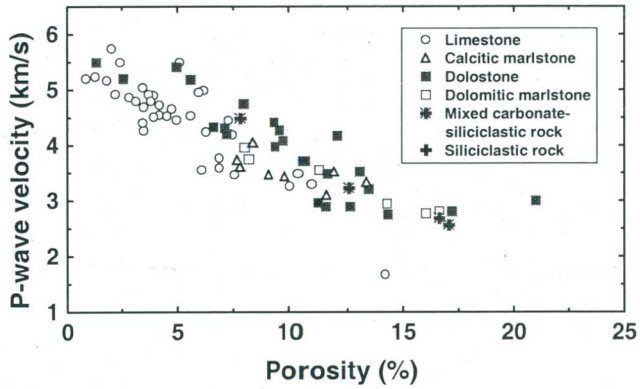


Fig. 14. P-wave velocity versus porosity. $R = -0.88$ for limestones and calcitic marlstones. $R = -0.86$ for dolostones and dolomitic marlstones.

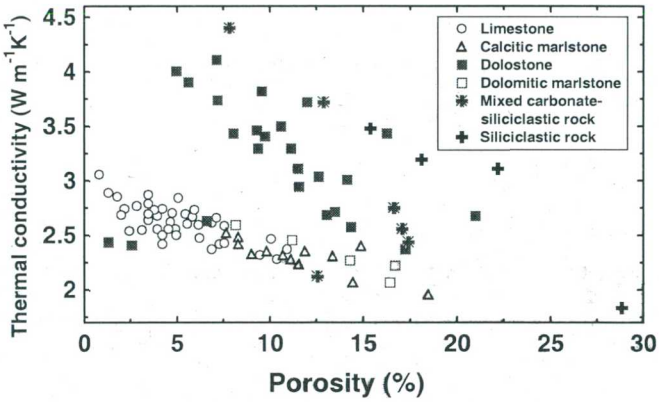


Fig. 15. Thermal conductivity versus porosity. $R = -0.85$ for limestones and calcitic marlstones.

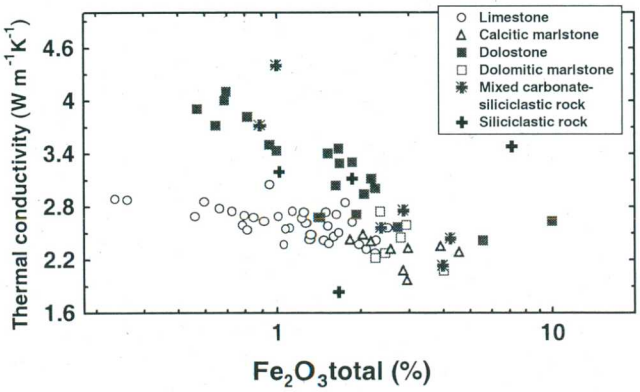


Fig. 16. Thermal conductivity versus total iron content. $R = -0.73$ for limestones and calcitic marlstones. $R = -0.59$ for dolostones and dolomitic marlstones.

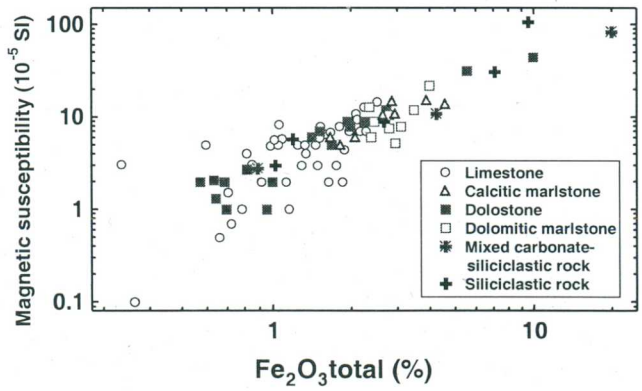


Fig. 17. Magnetic susceptibility versus total iron content. $R = 0.83$ for limestones and calcitic marlstones. $R = 0.97$ for dolostones and dolomitic marlstones.

iron content was high in the studied sedimentary rocks, but the correlation coefficient was the highest (0.97) for the dolostones and dolomitic marlstones.

The porosity and iron content were lowest in pure limestones. Primary porosity and iron content had a high positive correlation with the IR content of the studied rocks. Secondary porosity was determined in dolomitized carbonate rocks. The highest porosity and the lowest density were measured in siliciclastic rocks represented by sandstones and siltstones. Porosity, density, P-wave velocity, electric resistivity, thermal conductivity and magnetic susceptibility of dolostones were higher than those of limestones. The obtained results may serve as a basis for interpretation of geophysical, petrophysical and geological data in Estonia and for correlation of sedimentary layers in the other parts of the Baltic sedimentary basin.

REFERENCES

Ainsaar, L. 2001. *The middle Caradoc facies and faunal turnover in the Late Ordovician Baltoscandian Palaeobasin: sedimentological and carbon isotope aspects*. Dissertationes Geologicae Universitatis Tartuensis, 12. Tartu, 108 pp.

Ainsaar, L. & Meidla, T. 2001. Facies and stratigraphy of the middle Caradoc mixed siliciclastic-carbonate sediments in eastern Baltoscandia. *Proceedings of the Estonian Academy of Sciences, Geology*, **50**, 5–23.

Ainsaar, L., Kirsimäe, K. & Meidla, T. 1996. Regression in Caradoc: evidences from southwestern Estonia (Ristiküla core). *Geological Survey of Denmark and Greenland Report*, **98**, 5–12.

Ainsaar, L., Meidla, T. & Martma, T. 1999. Evidence for a widespread carbon isotopic event associated with late Middle Ordovician sedimentological and faunal changes in Estonia. *Geological Magazine*, **139**, 49–62.

Aldridge, R. J., Jeppsson, L. & Dorning, K. J. 1993. Early Silurian oceanic episodes and events. *Journal of the Geological Society, London*, **150**, 501–513.

Barker, F. 1979. Trondhjemite: definition, environment and hypotheses of origin. In: *Trondhjemites, dacites and related rocks* (Barker, F., ed.). Elsevier, Amsterdam, 1–12.

Bauert, G. & Bauert, H. 1998. Distribution of chitinozoans in the Tartu (453) core. Appendix 14. In: *Tartu (453) drill core* (Männik, P., ed.), *Estonian Geological Sections*, **1**.

Bergström, S. M. 1971. Conodont biostratigraphy of the Middle and Upper Ordovician in Europe and eastern North America. *Geological Society of America Memoir*, **127**, 83–157.

Bergström, S. M., Huff, W. D. & Kolata, D. R. 1998. The Lower Silurian Osmundsberg K-bentonite. Part I: stratigraphic position, distribution and paleogeographic significance. *Geological Magazine*, **135**, 1–13.

Bergström, S., Finney, S. C., Chen, Xu, Pålsson, C., Wang, Zhi-hao & Grahn, Y. 2000. A proposed global boundary stratotype for the base of the Upper Ordovician Series of the Ordovician System: The Fågelsång section, Scania, southern Sweden. *Episodes*, **23**, 102–109.

Blom, H., Märss, T. & Miller, G. C. 2002. Silurian and earliest Devonian Birkeniid anaspids from the Northern Hemisphere. *Transactions of the Royal Society of Edinburgh: Earth Science*, **92**, 263–323.

Brenchley, P. J., Marshall, J. D., Carden, G. A. F., Robertson, D. B. R., Long, D. F. G., Meidla, T., Hints, L. & Anderson, T. F. 1994. Bathymetric and isotopic evidence for a short-lived Late Ordovician glaciation in a greenhouse period. *Geology*, **22**, 295–298.

Brenchley, P. J., Marshall, J. D., Hints, L. & Nõlvak, J. 1997. New isotopic data solving an old biostratigraphic problem: the age of the upper Ordovician brachiopod *Holorhynchus giganteous*. *Journal of the Geological Society, London*, **154**, 335–342.

Brenchley, P. J., Carden, G. A., Hints, L., Kaljo, D., Marshall, J. D., Martma, T., Meidla, T. & Nõlvak, J. 2003. High-resolution stable isotope stratigraphy of Upper Ordovician sequences: constraints on the timing of bioevents and environmental changes associated with mass extinction and glaciation. *Geological Society of America Bulletin*, **115**, 89–104.

Calner, M. & Jeppsson, L. 2003. Carbonate platform evolution and conodont stratigraphy during the middle Silurian Mulde Event, Gotland, Sweden. *Geological Magazine*, **140**, 173–203.

Dulski, P. 2001. Reference materials for geochemical studies: new analytical data by ICP-MS and critical discussion of reference values. *Geostandards Newsletter: The Journal of Geostandards and Geoanalyses*, **25**, 87–125.

Dulski, P. & Longerich, H. P. 2002. Positive bias in yttrium concentrations in geological reference materials. *The Geoanalyst*, **5**, 5–8.

Dunham, R. J. 1962. Classification of carbonate rocks according to depositional texture. In: *Classification of carbonate rocks* (Ham, W. E., ed.), *AAPG Memoirs*, **1**, 108–121.

Dzik, J. 1978. Conodont biostratigraphy and paleographical relations of the Ordovician Mójcza Limestone (Holy Cross Mts, Poland). *Acta Palaeontologica Polonica*, **23**, 51–72.

Epstein, A. G., Epstein, J. B. & Harris, L. D. 1977. Conodont color alteration – an index to organic metamorfism. *United States Geological Survey Professional Paper*, **995**, 1–27.

Ewart, A. 1979. A review of the mineralogy and chemistry of Tertiary–Recent dacitic, rhyolitic and related salic volcanic rocks. In: *Trondhjemites, dacites and related rocks* (Barker, F., ed.). Elsevier, Amsterdam, 13–121.

Ewart, A. 1982. The mineralogy and petrology of Tertiary–Recent orogenic volcanic rocks: with special reference to the andesitic–basaltic compositional range. In: *Andesites* (Thorpe, R. S., ed.). Wiley, Chichester, 25–94.

Folk, R. L., 1980, *Petrology of sedimentary rocks*. 2nd ed., Austin, TX, Hemphill Publishing Co, 182 pp.

Gailite, L. K., Ulst, R. Z. & Yakovleva, V. I. 1987. *Stratotipičeskie i tipovye razrezy silura Latvii* [Stratotype and type sections of the Silurian of Latvia]. Zinatne, Riga, 184 pp. [In Russian].

Harris, M., Sheehan, P., Ainsaar, L., Hints, L., Männik, P., Nõlvak, J. & Rubel, M. Late Ordovician sequences of Baltica (Estonia). *Palaeogeography, Palaeoclimatology, Palaeoecology* (in press).

Heath, R. J., Brenchley, P. J. & Marshall, J. D. 1998. Early Silurian carbon and oxygen stable-isotope stratigraphy of Estonia: implications for climate change. In: *Silurian cycles. Linkages of dynamic stratigraphy with atmospheric, oceanic, and tectonic changes* (Landing, E. & Johnson, M. E., eds), *New York State Museum Bulletin*, **491**, 313–327.

Hints, L & Meidla, T. 1997a. Porkuni Stage. In: *Geology and mineral resources of Estonia* (Raukas, A. & Teedumäe, A., eds). Estonian Academy Publishers, Tallinn, p. 89.

Hints, L. & Meidla, T. 1997b. Vormsi Stage. In: *Geology and mineral resources of Estonia* (Raukas, A. & Teedumäe, A., eds). Estonian Academy Publishers, Tallinn, 81–82.

Hints, O. & Nõlvak, J. 1999. Proposal for the lower boundary-stratotype of the Keila Regional Stage (Upper Ordovician). *Proceedings of the Estonian Academy of Sciences, Geology*, **48**, 158–165.

Hints, L., Meidla, T., Nõlvak, J. & Sarv, L. 1989. Some specific features of the Late Ordovician evolution in the Baltic Basin. *Proceedings of the Estonian Academy of Sciences, Geology*, **38**, 83–87.

Hints, L., Meidla, T. & Nõlvak, J. 1995. Ordovician sequences of the East European Platform. *Geologija*, **17**, 58–63.

Hints, L., Oraspõld, A. & Kaljo, D. 2000. Stratotype of the Porkuni Stage with comments on the Röa Member (uppermost Ordovician, Estonia). *Proceedings of the Estonian Academy of Sciences, Geology*, **49**, 177–199.

Hutt, J. E. 1975. The Llandovery graptolites of the English Lake District. Part 2. *Palaeontographical Society Monograph*, **129**, 57–137.

Jaanusson, V. 1995. Confacies differentiation and upper Middle Ordovician correlation in Baltoscandian basin. *Proceedings of the Estonian Academy of Sciences, Geology*, **44**, 73–86.

Jeppsson, L. 1997. A new latest Telychian, Sheinwoodian and Early Homerian (Early Silurian) standard conodont zonation. *Transactions of the Royal Society of Edinburgh: Earth Sciences*, **88**, 91–114.

Jeppsson, L. & Calner, M. 2003. The Silurian Mulde Event and a scenario for secundo-secundo events. *Transactions of the Royal Society of Edinburgh: Earth Sciences*, **93**, 135–154.

Jeppsson, L. & Männik, P. 1993. High-resolution correlations between Gotland and Estonia near the base of the Wenlock. *Terra Nova*, **5**, 348–358.

Jeppsson, L., Viira, V. & Männik, P. 1994. Conodont-based correlations between Estonia and Gotland. *Geological Magazine*, **131**, 201–218.

Jürgenson, E. 1976. Über Untersuchungen des unlöshlichen Rückstandes der Karbonatgesteine. In: *Methodik und Interpretation der Ergebnisse mineralogischer und geochemischer Untersuchungen* (Narbutas, V., ed.). Mokslas, Vilnius, 31–36. [In Russian with German summary].

Jürgenson, E. 1982. Distribution and mineralogy of silt-sized terrigenous material in the North Baltic Upper Silurian deposits. In: *Ecostratigraphy of the East Baltic Silurian* (Kaljo, D. & Klaamann, E., eds). Valgus, Tallinn, 25–33.

Jürgenson, E. & Kleesment, A. 1992. A comparison of two mineralogical methods applied to the determination of the terrigenous component. *Proceedings of the Estonian Academy of Sciences, Geology*, **41**, 108–114.

Kala, E., Kajak, H., Remmel, S., Saadre, T., Kajak, K., Puura, V., Perens, R. & Gromov, O. 1973. Otčet o kompleksnoj geologo-gidrogeologičeskoj s'emke masštaba 1: 200 000 o. Saaremaa (list O-34-XVI, XVII) [Report on complex geological mapping on Saaremaa Island at a scale of 1:200 000]. Unpublished report of the Geological Survey of Estonia, Keila, 275 pp. [In Russian].

Kala, E., Mens, K. & Pirrus, E. 1984. On the stratigraphy of the Cambrian in West Estonia. In: *Stratigrafija drevnepaleozojskih otloženij Pribaltiki* [Stratigraphy of the Early Palaeozoic deposits of the East Baltic] (Männil, R. & Mens, K., eds). Tallinn, 18–37. [In Russian with English summary].

Kaljo, D. 1990. The Silurian of Estonia. In: *Field Meeting, Estonia. An excursion guidebook* (Kaljo, D. & Nestor, H., eds). Institute of Geology, Estonian Academy of Sciences, Tallinn, 21–26.

Kaljo, D. 1997. Graptolites. In: *Geology and mineral resources of Estonia* (Raukas, A. & Teedumäe, A., eds). Estonian Academy Publishers, Tallinn, p. 241.

Kaljo, D. & Martma, T. 2000. Carbon isotopic composition of Llandovery rocks (East Baltic Silurian) with environmental interpretation. *Pro-*

ceedings of the Estonian Academy of Sciences, Geology, **49**, 267–283.

Kaljo, D. & Vingisaar, P. 1969. On the sequence of the Raikküla Stage in southernmost Estonia. *Eesti NSV Teaduste Akadeemia Toimetised, Keemia, Geoloogia*, **18**, 270–277. [In Russian with English summary].

Kaljo, D., Paškevičius, J. & Ulst, R. 1984. Graptolite zones of the East Baltic Silurian. In: *Stratigrafija drevnepaleozojskih otloženij Pribaltiki* [Stratigraphy of the Early Palaeozoic deposits of the East Baltic] (Männil, R. & Mens, K., eds). Tallinn, 94–118. [In Russian with English summary].

Kaljo, D., Boucot, A. J., Corfield, R. M., Le Herisse, A., Koren, T. N., Kriz, J., Männik, P., Märss, T., Nestor, V., Shaver, R. H., Siveter, D. J. & Viira, V. 1995. Silurian bio-events. In: *Global events and event stratigraphy in the Phanerozoic* (Walliser, O. H:, ed.). Springer, Verlag, Berlin, 173–224.

Kaljo, D., Nõlvak, J. & Uutela, A. 1996. More about Ordovician microfossil diversity patterns in the Rapla section, Northern Estonia. *Proceedings of the Estonian Academy of Sciences, Geology*, **45**, 131–148.

Kaljo, D., Kiipli, T. & Martma, T. 1997. Carbon isotope event markers through the Wenlock–Pridoli sequence at Ohesaare (Estonia) and Priekule (Latvia). *Palaeogeography, Palaeoclimatology, Palaeoecology*, **132**, 211–223.

Kaljo, D., Kiipli, T. & Martma, T. 1998. Correlation of carbon isotope events and environmental cyclicity in the East Baltic Silurian. *Silurian cycles. Linkages of dynamic stratigraphy with atmospheric, oceanic, and tectonic changes* (Landing, E. & Johnson, M. E., eds). *New York State Museum Bulletin*, **491**, 297–312.

Kaljo, D., Hints, L., Martma, T. & Nõlvak, J. 2001. Carbon isotope stratigraphy in the latest Ordovician of Estonia. *Chemical Geology*, **175**, 49–59.

Kaljo, D., Martma, T., Männik, P. & Viira, V. 2003. Implications of Gondwana glaciations in the Baltic late Ordovician and Silurian and a carbon isotopic test of environmental cyclicity. *Bulletin de la Societe Geologique de France*, **174**, 59–66.

Kaljo, D., Hints, L., Martma, T., Nõlvak, J. & Oraspõld, A. Late Ordovician carbon isotope trend in Estonia, its significance in stratigraphy and environmental analysis. *Palaeogeography, Palaeoclimatology, Palaeoecology* (in press).

Kiipli, E., Kiipli, T. & Kallaste, T. 2002. Correlation between deep and shallow shelf on the basis of O-bentonite, East Baltic. In: *The Fifth Baltic Stratigraphical Conference, Basin Stratigraphy–Modern Methods and Problems: Extended abstracts* (Satkūnas, J. & Lazauskienė, J., eds). Vilnius, Lithuania, 77–80.

Kiipli, T & Kallaste, T. 2002. Correlation of Telychian sections from shallow to deep sea facies in Estonia and Latvia based on the sanidine composition of bentonites. *Proceedings of the Estonian Academy of Sciences, Geology*, **51**, 143–156.

Kiipli, T., Kiipli, E. & Kallaste, T. 1997. Metabentonite composition related to sedimentary facies in the Lower Silurian of Estonia. *Proceedings of the Estonian Academy of Sciences, Geology*, **46**, 93–104.

Kiipli, T., Männik, P., Batchelor, R. A., Kiipli, E., Kallaste, T. & Perens, H. 2001. Correlation of Telychian (Silurian) altered volcanic ash beds in Estonia, Sweden and Norway. *Norwegian Journal of Geology (Norsk Geologisk Tidskrift)*, **81**, 179–193.

Kleesment, A. 1981. Lemsi svita [Lemsi Formation]. In: *Devon i karbon Pribaltiki* [Devonian and Carboniferous of the East Baltic] (Sorokin, V. S., ed.). Zinatne, Riga, 80–82. [In Russian].

Kleesment, A. 1997. Devonian sedimentation basin. In: *Geology and mineral resources of Estonia* (Raukas, A. & Teedumäe, A., eds). Estonian Academy Publishers, Tallinn, 205–208.

Kleesment, A. 1988. Authigenic overgrowths of detrital feldspar grains in the Devonian sequence of the East Baltic. *Proceedings of the Estonian Academy of Sciences, Geology*, **44**, 229–241.

Kleesment, A. & Mark-Kurik, E. 1997. Devonian. Lower Devonian. Middle Devonian. In: *Geology and mineral resources of Estonia* (Raukas, A. & Teedumäe, A., eds). Estonian Academy Publishers, Tallinn, 107–121.

Koistinen, T., Laitakari, I., Virransalo, P., Korsman, K., Puura, V., Vaher, R., Klein, V., Niin, M., Koppelmaa, H., Tihhomirov, S., Amantov, A., Savitski, A., Saltykova, T. & Janovski, A. 1994. Precambrian basement of the Gulf of Finland and surrounding area, 1:1 000 000. In: *Explanation to the map of Precambrian basement of the Gulf of Finland and surrounding area 1 : 1 mill.* (Koistinen, T., ed. 1996), *Geological Survey of Finland Special Paper,* **21**, 141 pp.

Loog, A. & Oraspõld, A. 1982. *Settekivimite ja setete (setendite) uurimismeetodid* [Methods of the study of sediments and sedimentary rocks]. TRÜ geoloogia kateeder, Tartu, 83 pp. [In Estonian].

Loydell, D. K., Kaljo, D. & Männik, P. 1998. Integrated biostratigraphy of the lower Silurian of the Ohesaare core, Saaremaa, Estonia. *Geological Magazine*, **135**, 769–783.

Loydell, D. K., Männik, P. & Nestor, V. 2003. Integrated biostratigraphy of the lower Silurian of the Aizpute-41 core, Latvia. *Geological Magazine*, **140**, 205–229.

Mägi, S., Viira, V. & Aru, H. 1989. On the correlation of the Tremadocian and Arenigian boundary beds in the East Baltic. *Proceedings of the Estonian Academy of Sciences, Geology*, **38**, 63–67.

Männik, P. 1992. *Upper Ordovician and Lower Silurian conodonts in Estonia. Abstract.* Doctoral thesis at the University of Tartu. 50 pp.

Männik, P. 2001a. Distribution of conodonts. In: *Valga (10) drill core* (Põldvere, A., ed.), *Estonian Geological Sections*, **3**, 10–12.

Männik, P. 2001b. Evolution of early Silurian conodont faunas, and high-resolution stratigraphy. In: *Evolution of Life on the Earth. Proceedings of the II International Symposium "Evolution of life on the Earth", November 12–15, Tomsk* (Podobina, V. M., ed.). NTL Press, 202–205.

Männik, P., Kallaste, T. & Martma T. 2002. Dating of the Ireviken Event and the problem of the Llandovery–Wenlock boundary, some possible developments. In: *The Fifth Baltic Stratigraphical Conference Basin Stratigraphy–Modern Methods and Problems: extended abstracts* (Satkūnas, J. & Lazauskienė, J., eds). Vilnius, Lithuania, 114–116.

Männil, R. 1966. *Evolution of the Baltic basin during the Ordovician.* Valgus, Tallinn, 200 pp. [In Russian with English summary].

Männil, R. 1986. Stratigraphy of kukersite-bearing deposits C_1b-C_{III}. In: *Geology of the kukersite-bearing beds of the Baltic oil shale basin* (Puura, V., ed.). Valgus, Tallinn, 12–24. [In Russian with English summary].

Männil, R. & Meidla, T. 1994. The Ordovician System of the East European Platform (Estonia, Latvia, Lithuania, Byelorussia, parts of Russia, the Ukraine and Moldova). In: *The Ordovician System of the East European Platform and Tuva (Southeastern Russia). Correlation charts and explanatory notes* (Webby, B. D., Ross, R. J. & Zhen, Y. Y., eds). *IUGS Publ.*, **28**, 52 pp.

Männil, R., Põlma, L. & Hints, L. 1968. Stratigraphy of the Viru and Harju Series (Ordovician) of the Central East Baltic Area. *Stratigraphy of the Baltic Lower Paleozoic and its correlation with other areas.* Mintis, Vilnius, 81–110. [In Russian with English summary].

Marshall, J. D. 1992. Climatic and oceanographic isotopic signals from the carbonate rock record and their preservation. *Geological Magazine*, **129**, 143–160.

Marshall, J. D., Brenchley, P. J., Mason, P., Wolff, G. A., Astin, R. A., Hints, L. & Meidla, T. 1997. Global carbon isotopic events associated with mass extinction and glaciation in the Late Ordovician. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **132**, 195–210.

Märss, T. 1986. Silurian vertebrates of Estonia and West Latvia. *Fossilia Baltica*, Vol 1, Valgus, Tallinn, 104 pp. [In Russian with English summary].

Märss, T. 1990. Vertebrates. In: *Field Meeting, Estonia. An excursion guidebook* (Kaljo, D. & Nestor, H., eds). Institute of Geology, Estonian Academy of Sciences, Tallinn, 93–96.

Märss, T. 1996. *Loganellia* (Thelodonti, Agnatha) from the Jaagarahu Stage, Wenlock, Estonia. *Proceedings of the Estonian Academy of Sciences, Geology*, **45**, 189–202.

Märss, T. & Miller, C. G. 2003. Thelodonts and distribution of associated conodonts from the Llandovery–lowermost Lochkovian of the Welsh borderland. *Palaeontology* (in press).

Meidla, T. 1996a. *Late Ordovician ostracodes of Estonia.* Fossilia Baltica, 2, Tallinn, 222 pp.

Meidla, T. 1996b. Latest Ordovician ostracodes of Baltoscandia. In: *WOGOGOB–94 Symposium. Working Group of Ordovician Geology of Baltoscandia, Bornholm–94* (Stouge, S., ed.). Geological Survey of Denmark and Greenland Report 1996/98, 65–71.

Meidla, T. 1997. Hunneberg Stage. Billingen Stage. In: *Geology and mineral resources of Estonia* (Raukas, A. & Teedumäe, A., eds). Estonian Academy Publishers, Tallinn, 58–61.

Meidla, T. 2001. Distribution of ostracodes. In: *Valga (10) drill core* (Põldvere, A., ed.), *Estonian Geological Sections*, **3**, 14–16.

Meidla, T., Ainsaar, L. & Tinn, O. 1998. Volkhov Stage in North Estonia and sea level changes. *Proceedings of the Estonian Academy of Sciences, Geology*, **47**, 141–157.

Mens, K. & Pirrus, E. 1997a. Cambrian. In: *Geology and mineral resources of Estonia* (Raukas, A. & Teedumäe, A., eds). Estonian Academy Publishers, Tallinn, 39–49.

Mens, K. & Pirrus, E. 1997b. Vendian–Tremadoc clastogenic sedimentation basins. In: *Geology and mineral resources of Estonia* (Raukas, A. & Teedumäe, A., eds). Estonian Academy Publishers, Tallinn, 184–191.

Miller, G. & Märss, T. 1999. A conodont, thelodont

and acanthodian fauna from the lower Přidoli (Silurian) of the Much Wenlock area, Shropshire. *Palaeontology*, **42**, 691–714.

Mullins, G. L. 2000. A chitinozoan morphological linage and its importance in Lower Silurian stratigraphy. *Palaeontology*, **43**, 359–373.

Mullins, G. L. & Loydell, D. K. 2001. Integrated Silurian chitinozoans and graptolite biostratigraphy of the Banwy River section, Wales. *Palaeontology*, **44**, 731–781.

Nestor, H. 1997. Silurian. In: *Geology and mineral resources of Estonia* (Raukas, A. & Teedumäe, A., eds). Estonian Academy Publishers, Tallinn, 89–106.

Nestor, H. & Einasto, R. 1997. Ordovician and Silurian carbonate sedimentation basin. In: *Geology and mineral resources of Estonia* (Raukas, A. & Teedumäe, A., eds). Estonian Academy Publishers, Tallinn, 192–204.

Nestor, H. & Nestor, V. 2002. Upper Llandovery to middle Wenlock (Silurian) lithostratigraphy and chitinozoan biostratigraphy in southwestern Estonia and northernmost Latvia. *Proceedings of the Estonian Academy of Sciences, Geology*, **51**, 67–87.

Nestor, H., Einasto, R., Männik, P. & Nestor, V. 2003. Correlation of lower–middle Llandovery sections in central and southern Estonia and sedimentation cycles of lime muds. *Proceedings of the Estonian Academy of Sciences, Geology*, **52**, 3–27.

Nestor, V. 1982. Chitinozoan zonal assemblages (Wenlock, Estonia). In: *Communities and biozones in the Baltic Silurian* (Kaljo, D. & Klaamann, E., eds). Valgus, Tallinn, 84–96. [In Russian with English summary].

Nestor, V. 1990. Silurian chitinozoans. In: *Field Meeting, Estonia. An excursion guidebook* (Kaljo, D. & Nestor, H., eds). Institute of Geology, Estonian Academy of Sciences, Tallinn, 80–83.

Nestor, V. 1994. Early Silurian chitinozoans of Estonia and North Latvia. *Academia,* Vol. 4, Estonian Academy Publishers, Tallinn, 163 pp.

Nestor, V., Einasto, R. & Loydell, D. K. 2002. Chitinozoan biostratigraphy and lithological characteristics of the Lower and Upper Visby boundary beds in the Ireviken 3 section, Northwest Gotland. *Proceedings of the Estonian Academy of Sciences, Geology*, **51**, 215–226.

Nõlvak, J. 1980. Chitinozoans in biostratigraphy of the northern East Baltic Ashgillian. A preliminary report. *Acta Palaeontologica Polonica*, **25**, 253–260.

Nõlvak, J. 1997. Ordovician. Introduction. In: *Geology and mineral resources of Estonia* (Raukas, A. & Teedumäe, A., eds). Estonian Academy Publishers, Tallinn, 52–55.

Nõlvak, J. 1999a. Ordovician chitinozoan biozonation of Baltoscandia. *Acta Universitatis Carolinae. Geologica*, **43**, 287–290.

Nõlvak, J. 1999b. Distribution of chitinozoans. In: *Taga-Roostoja (25A) drill core* (Põldvere, A., ed.), *Estonian Geological Sections*, **2**, 10–12.

Nõlvak, J. 2001. Distribution of chitinozoans. In: *Valga (10) drill core* (Põldvere, A., ed.), *Estonian Geological Sections*, **3**, 8–10.

Nõlvak, J. 2002. *Chitinozoan biostratigraphy in the Ordovician of Baltoscandia*. Ph.D. thesis, Institute of Geology at Tallinn Technical University, 200 pp.

Nõlvak, J. & Grahn, Y. 1993. Ordovician chitinozoan zones from Baltoscandia. *Review of Palaeobotany and Palynology*, **79**, 245–269.

Nõlvak, J., Grahn, Y. & Sturkell, E. F. F. 1999. Chitinozoan biostratigraphy of the Middle Ordovician Dalby Limestone in the Fjäcka section, Siljan District, Sweden. *Proceedings of the Estonian Academy of Sciences, Geology*, **48**, 75–85.

Obut, A. M. & Rytzk, G. V. 1958. Ordovician and Silurian dendroidea of Estonia. *Trudy Instituta Geologii AN ÈSSR*, 5, 143–158. [In Russian with English summary].

Oraspõld, A. 1975. Lithology of the Pirgu Stage in South Estonia. *Acta et Commentationes Universitatis Tartuensis*, 359, 14–32. [In Russian with English summary].

Paris, F., Verniers, J., Achab, A., Albani, R., Ancilleta, A., Asselin, E., Brocke, R., Chen, X., Fatka, O., Grahn, Y., Molyneux, S., Nolvak, J., Samuelsson, J., Sennikov, N. V., Soufiane, A., Wang, X. & Wincester-Seeto, T. 1999. Correlation of Ordovician regional chitinozoan biozonations. *Acta Universitatis Carolinae. Geologica*, **43**, 291–294.

Paškevičius, J. 1979. *Biostratigraphy and graptolites of the Lithuanian Silurian.* Mokslas, Vilnius, 268 pp. [In Russian with English summary].

Pettijohn, F. J., Potter, P. E. & Siever, R. 1987. *Sand and sandstone.* Springer–Verlag, New York, 553 pp.

Puura, V. & Flodén, T. 1996. Subjotnian igneous structures in the Svekofennian Domain of the Baltic region. *Geologiska Föreningen i Stockholm Förhandlinger (GFF)*. **188**, Jubilee Issue, A22–A23.

Puura, V. & Flodén, T. 2000. Rapakivi-related basement structures in the Baltic Sea area: a regional approach. *Geologiska Föreningen i Stockholm*

Förhandlinger (GFF), **122**, 257–272.

Puura, V., Klein, V., Koppelmaa, H & Niin, M. 1997. Precambrian basement. In: *Geology and mineral resources of Estonia* (Raukas, A. & Teedumäe, A., eds). Estonian Academy Publishers, Tallinn, 27–34.

Põldvere, A. 1999. Core description and terminology. In: *Taga-Roostoja (25A) drill core* (Põldvere, A., ed.), *Estonian Geological Sections*, **2**, 4–5.

Põldvere, A. 2001. Core description and terminology. In: *Valga (10) drill core* (Põldvere, A., ed.), *Estonian Geological Sections*, **3**, 4–5.

Põldvere, A. & Kleesment, A. 1998. Basic concepts and methodology. Description and terminology. In: *Tartu (453) drillcore* (Männik, P., ed.), *Estonian Geological Sections*, **1**, 7–10.

Põldvere, A., Meidla, T., Bauert, G., Bauert, H. & Stouge, S. 1998. Ordovician. In: *Tartu (453) drill core* (Männik, P., ed.), *Estonian Geological Sections*, **1**, 11–17.

Põldvere, A., Kleesment, A., Mens, K. & Niin, M. 2001. Tugiläbilõigete täienduurimine. IV etapp [Complementary study of type sections, stage IV]. Unpublished report of the Geological Survey of Estonia, Tartu, 89 pp. [In Estonian].

Põlma, L. 1982. *Comparative lithology of the Ordovician carbonate rocks in the Northern and Middle East Baltic*. Valgus, Tallinn, 164 pp. [In Russian with English summary].

Saltzman, M. R. 2002. Carbon and oxygen isotope stratigraphy of the Lower Mississippian (Kinderhookian–lower Osagean), western United States: Implications for seawater chemistry and glaciation. *Geological Society of America Bulletin*, **114**, 96–108.

Samtleben, C., Munnecke, A., Bickert, T. & Pätzold, J. 1996. The Silurian of Gotland (Sweden): facies interpretation based on stable isotopes in brachiopod shells. *Geologische Rundschau*, **85**, 278–292.

Sarv, L. 1959. Ordovician ostracods in the Estonian S.S.R. *ENSV TA Geoloogia Instituudi Uurimused*, 4, 1–207. [In Russian with English summary].

Scholle, P. A. 1978. *A color illustrated guide to carbonate rock constituents, textures, cements, and porosities*. American Association of Petroleum Geologists, Tulsa, Oklahoma, U.S.A., 241 pp.

Schultze, H.-P. & Märss, T. 2003. Revisiting *Lophosteus* Pander 1856, a primitive osteichthyan. In: *The Gross Symposium 2. Advances in Palaeoichthyology, Riga, Latvia, September 8–14* (Schultze, H.-P., Lukševičs, E. & Unwin, D., eds), *Ichthyolith Issues Special Publication*, **7**, 45 pp.

Shogenova, A., Fabricius, I. L., Korsbech, U., Rasteniene, V. & Šliaupa, S. 2003. Glauconitic rocks in the Baltic area: estimation of specific surface. *Proceedings of the Estonian Academy of Sciences, Geology*, **52**, 69–86.

Štorch, P. 1988. Earliest Monograptidae (Graptolithina) in the lower Llandovery sequence of the Prague Basin (Bohemia). *Sbornik geologickych vēd, Paleontologie*, **29**, 9–48.

Tinn, O. & Meidla, T. 2001. Middle Ordovician ostracods from the Lanna and Holen Limestones, south-central Sweden. *Geologiska Föreningen i Stockholm Förhandlinger (GFF)*, **123**, 129–136.

Ulst, R. Ž. 1973. Llandoverian deposits of Northern Latvia and their correlation. In: *Problemy regional'noi geologii Pribaltiki i Belorussii* [Problems of regional geology of the East Baltic and Belarus] (Kuršs, V. M., ed.). Zinatne, Riga, 71–85. [In Russian with English summary].

Ulst, R. Ž., Gailite, L. K. & Jakovleva, V. I. 1982. *Ordovik Latvii* [Ordovician of Latvia]. Zinatne, Riga, 294 pp. [In Russian].

Valiukevičius, J. 1998. Acanthodians and zonal stratigraphy of Lower and Middle Devonian in East Baltic and Byelorussia. In: *Sonder-Abdruck aus Palaeontographica*. Abt. A, Bd. 248, Stuttgart, 1–53.

Valiukevičius, J. J., Kleesment, A. E., Kurik, E. J. & Vaitekunene, G. K. 1986. Correlation and organic remains in the deposits of the Narva Regional Stage. In: *Biofacies and fauna of the Silurian and Devonian basins of the East Baltic* (Brangulis, A. P., ed.). Zinatne, Riga, 73–86. [In Russian].

Verniers, J. 1999. Calibration of chitinozoa versus graptolite biozonation in the Wenlock of Builth Wells district (Wales, U. K.), compared with other areas in Avalonia and Baltica. *Bolletino della Società Paleontologica Italiana*, **38**, 359–380.

Verniers, J., Nestor, V., Paris, F., Dufka, P., Sutherland, S. & Van Grootel, G. 1995. A global Chitinozoa biozonation for the Silurian. *Geological Magazine*, **132**, 651–666.

Vidal, G. & Moczydłowska, M. 1996. Lower Cambrian acritarch biostratigraphy of the central Caledonia fold belt in Scandinavia and the palaeogeography of the Iapetus–Tornquist seaway. *Norvegian Journal of Geology (Norsk Geologisk Tidsskrift)*, **96**, 147–168.

Viira, V. 1974. *Ordovician conodonts of the East Baltic*. Valgus, Tallinn, 142 pp.

Viira, V. & Männik, P. 1999. Distribution of conodonts. In: *Taga-Roostoja (25A) drill core* (Põld-

vere, A., ed.), *Estonian Geological Sections*, **2**, 9–10.

Vingisaar, P., Oraspõld, A., Einasto, R. & Jürgenson, E. 1965. *Karbonaatkivimite ühtne klassifikatsioon ja legend* [Unified classification of carbonate rocks and legend]. Tallinn, 49 pp. [In Estonian and in Russian].

Winchester, J. A. & Floyd, P. A. 1977. Geochemical discrimination of different magma series and their differentiation products using immobile elements. *Chemical Geology*, **20**, 325–343.

APPENDIX 1

DESCRIPTION OF THE RUHNU (500) CORE

The description is given in a standardized form. The tables are divided into vertical columns based on the type of information. The values occurring rarely are given in parentheses.

STANDARD UNITS — Chronostratigraphic and geological time units.

LOCAL STRATIGRAPHIC UNITS — Stages, substages, formations, members, beds and batholith.

CORE BOX NO./FIGURES — Numbers of boxes, location of the intervals of core illustrated in Plates 1–3 and on compact disc in the read-only memory (details marked as D-1...25, thin sections as T-1...54).

DEPTH/SAMPLES — Depth of the boundaries and sample levels: Ac, acanthodians; B, brachiopods; C, conodonts; Ch, chitinozoans; F, X-ray fluorescence samples; G, granulometric samples; Gr, graptolites; Is, stable isotope analyses ($\delta^{18}O$ and/or $\delta^{13}C$); K, chemical samples; M, mineralogical samples; O, ostracods; Ph, physical properties; T, thin sections; V, vertebrates (agnathans and fishes); X, X-ray diffractometry.

LITHOLOGY — For legend see the next page. The core section is given at a scale of 1:200.

SEDIMENTARY STRUCTURES — According to thickness of beds: micro- (< 0.2 cm), thin- (0.2–2.0 cm), medium- (2–10 cm) and thick-bedded (10–50 cm); massive – visible bedding is missing. According to size of nodules: thin-nodular (vertical diameter of nodules < 0.2 cm), medium-nodular (2–5 cm) and thick-nodular (> 5 cm).

MARLSTONE BEDS — The most frequent thicknesses of the marlstone beds; in parentheses – infrequent thicknesses. Contacts between marlstone and other types of rock may be distinct (D) or indistinct (IND). Colours were identified on damp core.

MARLSTONE PERCENTAGE — The content of marlstone beds in the described interval was estimated visually.

SHORT DESCRIPTION — Main types of rocks are in bold. The colour of rocks was identified on damp core; the dominant size of limestone crystals (in italics) was estimated visually: cryptocrystalline < 0.005 mm; microcrystalline 0.005–0.01 mm; very finely crystalline 0.01–0.05 mm; finely crystalline 0.05–0.1 mm; medium-crystalline 0.1–1.0 mm and coarsely crystalline (> 1.0 mm). The percentage of allochems, e.g. bioclasts and clastic material, is also indicated. In descriptions the rock types according to Dunham (1962) are given, if possible, in parentheses. Clastic fractions (size of particles; in italics) are described as follows: clay < 0.005 mm; fine silt 0.005–0.01 mm; coarse silt 0.01–0.05 mm; very fine sand 0.05–0.1 mm; fine sand 0.1–0.25 mm; medium sand 0.25–0.5 mm, coarse sand 0.5–1.0 mm, very coarse sand > 1 mm and gravel 2–10 mm.

Appendix 1 continued

LEGEND

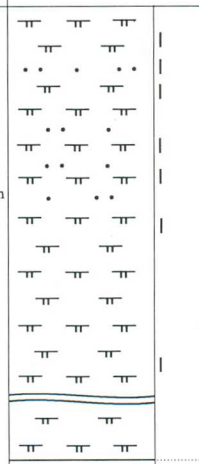
- limestone (in general)
- argillaceous limestone
- a dolomitized (a) and b dolomitic (b) limestone
- a sandy (a) and b silty (b) limestone
- dolostone
- argillaceous dolostone
- a calcitic (a) and b sandy (b) dolostone
- eurypterid-dolostone
- biohermal dolostone
- marlstone (in general)
- calcitic marlstone
- dolomitic marlstone (in general)
- claystone (dolomitic claystone)
- silty claystone
- a siltstone (a) and b cemented siltstone (b)
- argillaceous siltstone
- a sandstone (a) and b cemented sandstone (b)
- weathered granite
- a K-bentonite bed, on (a) or b under (b) the boundary
- a skeletal limestones: grains 10–25% (a) and b grains 25–50% (b)
- a crypto- and microcrystalline limestone (a) b and dolostone (b)
- fine bioclasts, pyritized (0.05–1.0 mm)
- coarse bioclasts, pyritized (> 1 mm)
- a horizontal bedding; b thin- (a), medium- (b) and c thick-bedded (c)
- wavy bedding
- nodular
- thin intercalation
- cross-bedding
- a nodules with distinct (a) b or indistinct (b) contacts
- discontinuity surface
- 4 number of discontinuity surfaces between the upper and the lower surface
- slickenside
- veins
- stylolites
- caverns (vugs)
- porous
- burrows, pyritized
- pyritic mottles
- ooliths
- clastic material
- silicification
- glauconite grains
- Q quartz grains
- F feldspar grains
- kerogen
- pyrite
- calcite
- dolomite
- micas (in general)
- bitumen
- mottled, red-coloured and yellow streaks
- tabulate corals
- stromatoporoids
- stromatolites
- brachiopods
- trilobites
- ostracodes
- echinoderms (crinoids)
- oncolites
- graptolites
- bryozoans
- calcareous algae
- pelecypods
- gastropods
- cephalopods
- lingulates
- 8 arenaceous foraminifers
- fishes

DESCRIPTION OF THE RUHNU (500) CORE

APPENDIX 1, SHEET 1

Location: 57° 48.200' N, 23° 14.609' E. Length of the core 787.4 m. Elevation of the top above sea level 6.0 m.

STANDARD UNITS	LOCAL STRATIGRAPHIC UNITS	CORE BOX NO.	FIGURES	DEPTH (m)	SAMPLES	LITHOLOGY	SEDIMENTARY STRUCTURES	MARLSTONE BEDS	MARLSTONE PERCENTAGE	SHORT DESCRIPTION
Holocene, Quaternary		1		0.0			! (Core is missing)			Beigish-grey, *fine-grained* **sand** with few siltstone pebbles (diameter 2-3 cm). Rusty spots and little humus occur at 3.0 m
				4.6						Grey **sandy loam** with few pebbles and little gravel (quartz clasts 0.1-2 cm and amphibolite up to 10 cm in diameter). In places Devonian sand and siltstone clasts are present
Middle Devonian Eifelian	Narva Stage Kernave Substage Gorodenka Formation			7.8			Inclined, indistinctly thin-bedded (core yield 50%)			Yellowish-brown, upper 0.2 m light grey, *very fine-grained*, medium-cemented **sandstone**. Bedding surfaces are covered with mica flakes
				8.8	XMG Ac		Indistinctly bedded			Brown, argillaceous, medium-cemented **siltstone**
			T-1	9.3	TFPh XMG	Q F	Horizontal thin-bedded			Intercalation of light grey and reddish-brown silty, variously argillaceous medium-cemented *very fine-grained* **sandstone**, in the lower part strongly cemented (by dolomite)
		2		11.2			Indistinctly bedded (massive)	3-30 cm IND reddish-brown	< 95	Reddish-brown and greenish-grey mottled, argillaceous **dolomitic marlstone**. The clay content changes vertically
				15.5	MG		Horizontal thin-bedded			Intercalation of grey and reddish-brown (mainly in the lower part), medium-cemented **siltstone**. The clay content increases downwards; a 0.2 m thick reddish-brown silty **claystone** bed lies on the lower boundary
		3		18.0	XMG		Indistinctly thin-bedded (core yield 45%)	2-5 cm D and IND violet-grey	< 2	Brown and brownish-grey, rarely violet, medium-cemented, in the upper part argillaceous **siltstone**. At 19.0-20.0 m occur thin **dolomitic marlstone** beds. The sand content increases downwards; the lowermost 0.8 m is silty **sandstone**
				25.0	MG					

STANDARD UNITS	LOCAL STRATIGRAPHIC UNITS	CORE BOX NO. / FIGURES	DEPTH (m)	SAMPLES	LITHOLOGY	SEDIMENTARY STRUCTURES	MARLSTONE BEDS	MARLSTONE PERCENTAGE	SHORT DESCRIPTION
Middle Devonian Eifelian	Narva Stage, Kernave Substage, Gorodenka Formation	3, 4	25.0 – 37.0	MGFPh		Massive, in places medium-bedded	10-30, >50 cm IND reddish-brown, in places greenish-grey	85	Reddish-brown with greenish-grey spots, in places greenish-grey, brownish- or violetish-grey mottled **dolomitic marlstone**. The clay content of beds changes vertically. Grey, in places brownish-grey **siltstone** (cemented by dolomite) and **sandstone** interbeds are medium-cemented. The interval 35.3-35.4 m is a grey *microcrystalline* **dolostone** interbed (in the lower part argillaceous)
			37.0 – 38.6	XMG		Indistinctly thin-bedded			Grey, silty, medium-cemented, *very fine-grained* **sandstone**. The clay and silt content increases downwards. Bedding surfaces are covered with mica flakes
	Narva Stage, Leivu Substage, Leivu Formation	5, 6	38.6 – 49.6	XMG, AcXMG		Massive or indistinctly bedded, at 40.0-41.0 and 49.0-49.6 m rubbly	5-20, >50 cm, IND reddish-brown, greenish-grey mottled	95	Reddish-brown and greenish-grey mottled, argillaceous **dolomitic marlstone**. The lower part includes thin **siltstone** and **claystone** interbeds
			49.6 –		core is missing	Indistinctly bedded, rubbly (core yield 10%)		< 85	Reddish-brown with greenish spots, argillaceous **dolomitic marlstone** with dolomitic **claystone** and thin **siltstone** interbeds

STANDARD UNITS	LOCAL STRATIGRAPHIC UNITS	CORE BOX NO.	FIGURES	DEPTH (m)	SAMPLES	LITHOLOGY	SEDIMENTARY STRUCTURES	MARLSTONE BEDS	MARLSTONE PERCENTAGE	SHORT DESCRIPTION
Middle Devonian Eifelian	Narva Stage Leivu Substage Leivu Formation	6 7 8 9 10	T-2	62.4 66.6	XMG XMG TFPh AcG MG		! (Core yield 10%)			☞ follow up
							Medium- to thick-bedded, with rubbly interbeds	10-20 cm, IND reddish-brown	100	Mottled **dolomitic marlstone**, in the upper part reddish-brown with grey spots, in the lower part reddish-brown and grey
							Wavy and horizontal, indistinctly thick- to thin-bedded, in places rubbly	5-20 cm, IND grey, reddish-brown	90	Grey, argillaceous, medium-cemented **dolomitic marlstone**, in the middle part reddish-brown and grey mottled. Varicoloured and grey **dolomitic claystone** interbeds (5%) are 5-15 cm and grey, argillaceous, *crypto-* and *microcrystalline* **dolostone** interbeds (< 7%) 2-10 cm thick

STANDARD UNITS	LOCAL STRATIGRAPHIC UNITS	CORE BOX NO.	FIGURES	DEPTH (m)	SAMPLES	LITHOLOGY	SEDIMENTARY STRUCTURES	MARLSTONE BEDS	MARLSTONE PERCENTAGE	SHORT DESCRIPTION
Middle Devonian Eifelian	Narva Stage Leivu Substage Leivu Formation	10		86.8						☞ follow up
		11		91.6	XMG		Wavy and inclined, thick- to medium-bedded, massive, in the lower part thin-bedded	20-50 cm, IND grey	85	Grey with rare brown spots, **dolomitic marlstone**, in the lower part highly argillaceous. The interval 89.8-90.5 m is dark grey **dolomitic claystone** with thin **dolostone** interbeds
			1	93.0			Thick- to thin-bedded	< 20 cm, D grey	70	Intercalation of grey **dolomitic marlstone** and light or yellowish-grey **dolostone**. In the lower part the dolomitic marlstone is silty
	Vadja Substage Vadja Formation	12		95.8	XMG FPh		Wavy and planar, thin-bedded; claystone microbedded Wavy, indistinctly medium- to thin-bedded; in the lower part dolostone is rubbly	2-10 cm, IND grey	10-15	Intercalation of light yellowish-grey *micro- and cryptocrystalline* **dolostone**, grey argillaceous *very finely crystalline* **dolostone** and dark grey to brownish-grey **dolomitic claystone** Light grey and yellowish-white, in places with violetish-red spots, *very finely crystalline* **dolostone** with grey **dolomitic marlstone** interbeds. On bedding planes occur films of dark grey and brownish-grey **dolomitic claystone**. In the lower part dolostone is cracked and chemically weathered
		13		100.5	MG		Wavy, indistinctly thin-bedded, rubbly	< 2 cm, IND dark grey	40	Intercalation of yellowish-grey and grey with rusty-brown spots *very finely crystalline* **dolostone** and dark grey with violet spots **dolomitic marlstone**
				102.2	XMG		Breccia-like, rubbly	< 2 cm, IND	80	Greenish-grey **dolomitic marlstone** with light grey **dolostone** pebbles, thinly interbedded with yellowish-grey **dolostone** and dark grey **claystone**
				103.1	XMG		Indistinctly medium-bedded, rubbly	< 10 cm, IND grey	< 95	Grey **dolomitic marlstone** and **claystone**, with rare violet spots. The lower part includes whitish-grey **dolostone** interbeds
	Pärnu Stage Pärnu Formation Tamme Member			104.8 105.5	XMG XMG		Horizontal or inclined, thin-bedded			Greyish-yellow, with rare pinkish-grey or violet spots, *cryptocrystalline* **dolostone**, in places argillaceous. Bedding surfaces are covered with dark greyish-brown **claystone** films
		14	T-3	111.0	XMG TFPh		Indistinctly bedded, in places patchy (core yield 25%)			Light grey, in the lower part violetish-grey, *fine-grained*, medium- and strongly cemented (by dolomite) **sandstone**

STANDARD UNITS	LOCAL STRATIGRAPHIC UNITS	CORE BOX NO. FIGURES	DEPTH (m)	SAMPLES	LITHOLOGY	SEDIMENTARY STRUCTURES	MARLSTONE BEDS	MARLSTONE PERCENTAGE	SHORT DESCRIPTION
Middle Devonian Eifelian	Pärnu Stage Pärnu Formation Tori Member	14, 15	111.0	XMG, XMG, XMG		! (Core yield 40%)			Brownish-grey, weakly cemented *fine to medium-grained* **sandstone** with dark violetish-grey **siltstone** interbeds at 111.0-112.0 m and violetish-grey **claystone** interbeds at 120.0-121.0 and 124.0-124.5 m
		15	130.0 130.6	XMG		Indistinctly bedded, rubbly			Violetish- and greenish-grey, argillaceous, slightly dolomitic medium-cemented **siltstone**
Lower Devonian Emsian	Rēzekne Stage Lemsi Formation	16		XMG, XMG		! (Core yield 25%)			Brownish-grey, weakly cemented, *fine- to medium-grained* **sandstone**. Gamma logging revealed argillaceous and silty interbeds in the lower part

STANDARD UNITS	LOCAL STRATIGRAPHIC UNITS	CORE BOX NO.	FIGURES	DEPTH (m)	SAMPLES	LITHOLOGY	SEDIMENTARY STRUCTURES	MARLSTONE BEDS	MARLSTONE PERCENTAGE	SHORT DESCRIPTION
Lower Devonian Emsian	Rēzekne Stage Lemsi Formation	16			XMG		! (Core yield 25%)			☞ follow up
										Intercalation of greenish-grey, argillaceous, weakly cemented **siltstone** rich in muscovite-flakes and violetish-grey, dolomitic, silty **claystone**
Přidoli	Kaavi Beds		T-4	146.1 147.3 148.0	Ch K TFPh V V MG V K		! (Core yield 40%) Massive			Light grey, slightly argillaceous, *crypto-* to *microcrystalline* **dolostone** (grains 10-25%; wackestone) with light green glauconite grains and brownish-black bioclasts. The **dolostone** bed (thickness 2 cm) on the lower boundary contains quartz, glauconite and dusky *fine* sand grains
	Ohesaare Stage Ohesaare Formation		2		Ch V V					Greyish-green with violet and brown spots, argillaceous, *very finely crystalline* **dolostone** (grains 10-25%; wackestone). Light grey glauconite grains and brownish-black fine bioclasts are present. In the light green to violet mottled intervals (148.4-148.7 and 151.7-152.0 m; grains 25-50%) the clay content is lower and upper contacts of intervals are distinct
		17			K V V V V V FPh K KM V V K		Horizontal microbedded; at 148.4-148.7 and 151.7-152.0 m thick-bedded			
				152.9 153.8	V Ch V KM V K		Massive			Light greenish-grey with violet spots, slightly argillaceous, *very finely crystalline* **dolostone** (grains mainly in the upper and lower parts < 20%)
			D-1	156.6	V Ch C V K Ch C V V		Horizontal, indistinctly bedded, in places thin-nodular Horizontal and wavy, indistinctly micro- to thick-bedded	2-20 cm, IND greyish-green 0.2-2 cm, D green	< 95 < 10	Greyish-green with indistinct violetish-brown beds, argillaceous, **dolomitic marlstone**. The clay content changes vertically. Fine bioclasts are dark Pinkish-white *very finely crystalline* **dolostone** (grains < 10%, partly eroded; mudstone). The upper part includes green **dolomitic marlstone** interbeds, lenses and pebbles
		18			K					
				158.5	Ch V FPh					
		19			Ch K Ch C V V V V FPh KM Ch C V V V K V K		Horizontal, indistinctly (micro-), thin- to thick-bedded	0.2-20 cm, D and IND greyish-green	80-95	Greyish-green, argillaceous **dolomitic marlstone**. The clay content changes vertically. The lower part includes violetish-brown or pinkish-white, argillaceous *very finely crystalline* **dolostone** interbeds
				165.0						
		20			V Ch K V K		Horizontal, indistinctly (micro-), thin- to thick-bedded	< 0.2, 0.3-1 cm, D and IND dark grey		Greyish-white *microcrystalline* and *very finely crystalline* **dolostone**. The interval 165.7-167.0 m is dark grey, argillaceous, **sandy dolostone** containing dark grey **dolomitic marlstone** interbeds

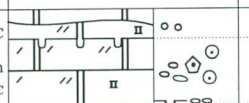
STANDARD UNITS	LOCAL STRATIGRAPHIC UNITS	CORE BOX NO.	FIGURES	DEPTH (m)	SAMPLES	LITHOLOGY	SEDIMENTARY STRUCTURES	MARLSTONE BEDS	MARLSTONE PERCENTAGE	SHORT DESCRIPTION
Přidoli	Ohesaare Stage, Ohesaare Formation	20	T-5	170.3	ChV, VTFPh					☞ follow up
		20, 21	T-6		K, KMTFPh, ChC, VV, V, VCh, V, V, VV, ChC, V		Horizontal, wavy or inclined, medium- to thin-bedded or nodular; dolomitic marlstone microbedded	< 0.2, 0.2-1 (5) cm IND greyish-green	< 5; 50-90	Intercalation of greyish-white *very finely crystalline* to *finely crystalline* **dolostone** and greyish-green **dolomitic marlstone** with silt, sand and bioclasts containing interbeds. The clay content increases downwards
	Kaugatuma Stage, Kaugatuma Formation, Lõo Beds	21	D-2	175.0	VV, Ch, V, K		Horizontal, indistinctly wavy, thin- to microbedded	< 0.2, 0.2-0.5 (10) cm IND greyish-green	< 20	Intercalation of light grey *very finely crystalline* **dolostone** and greyish-green **dolomitic marlstone** with interbeds containing silt, sand and bioclasts. The clay content changes vertically. Light grey **dolostone** microbeds occur at 175.0-175.7 m and brownish-grey, bituminous? **dolomitic marlstone** interbeds in the lower part
		21, 22	3	177.0	ChV, VCh, KMChV, FPh, Ch, K		Indistinctly bedded or thin-nodular	<0.2, 1-10 cm; D or IND greenish-grey	20-60	
		22, 23			ChV, VCh, KMChV, ChV				80-90; 90-95	Greenish-grey **dolomitic marlstone** (at 180.7-187.0 m argillaceous) with lenses and interbeds of light grey to grey *very finely crystalline* **dolostone**. Excavated discontinuity surfaces and horizontal burrows are pyritized. The clay content of dolostone changes vertically
		23, 24	T-7	187.0	ChV, Ch, ChVK, ChV, ChV, ChKTFPh, ChV, KM, K		Irregularly thin-nodular, in the lower part thin- to medium-bedded	<0.2, 1-2 (4) cm; D or IND greenish-grey	10-30	Light greenish-grey, dolomitized, *very finely crystalline* **limestone** (grains 10-25%, in basal 50 cm 25-50%) with **marlstone** interbeds (thickness decreases downwards). Pyritized limestone pebbles (diameter up to 1 cm) occur on the lower boundary. Bioclasts are impregnated dark grey. The pyritized discontinuity surface on the lower boundary is wavy and with 2 cm deep excavations
	Upper Äigu Beds	24, 25	D-3, 4	191.8	Ch, V, V, KM, Ch, ChC, FPh, VCh		Indistinctly nodular, wavy thin- to medium-bedded	<0.2, 1-2 (3-6) cm; D greenish-grey	5-10	Light grey, dolomitized, *very finely* to *finely crystalline* **limestone** (grains 10-25%, in some 2-10 cm thick interbeds 25-50%). Bioclasts are rounded, limestone pebbles 1 cm in diameter. Discontinuity surfaces are pyritized
		26	5	196.9	K		Horizontal or wavy, micro- to medium-bedded	<0.2, 1-2 cm; D greyish-brown	<5	Brownish-grey, calcitic, *micro-* to *finely crystalline* **dolostone** with **dolomitic marlstone** interbeds, containing greyish-brown, bituminous?, black bioclasts (in the lower part) and *microcrystalline* **limestone** interbeds (in the upper part; thickness 1-2 cm). The clay content changes vertically. At 197.1-197.4 m limestone clasts (diameter 0.2-20 mm) are present

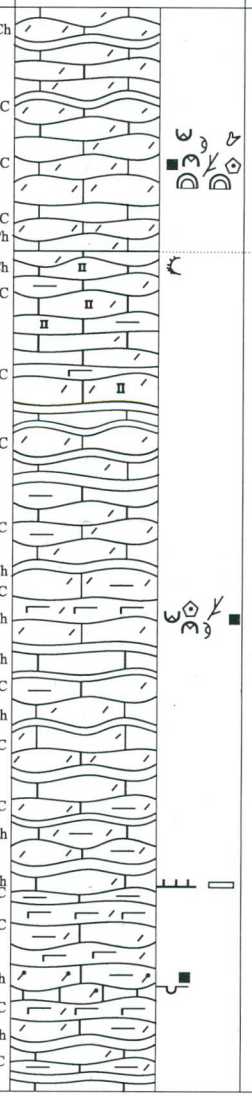
STANDARD UNITS	LOCAL STRATIGRAPHIC UNITS	CORE BOX NO.	FIGURES	DEPTH (m)	SAMPLES	LITHOLOGY	SEDIMENTARY STRUCTURES	MARLSTONE BEDS	MARLSTONE PERCENTAGE	SHORT DESCRIPTION
Přidoli	Kaugatuma Stage, Kaugatuma Formation, Upper Äigu Beds	26	T-8	200.0	Ch, V, ChTFPh, K, K					☞ follow up
							Horizontal, indistinctly bedded	<0.2, 0.5-1, 5 cm; D and IND greenish-grey	< 5 40-60 1-2	Whitish-green, argillaceous, *finely crystalline* **dolostone** (lower 1.2 m calcareous) with greenish-grey argillaceous **dolomitic marlstone** interbeds
										Greenish-grey argillaceous **calcitic dolostone** with thin interbeds and lenses (thickness 1-2 cm) of *very finely crystalline* **limestone** (grains 25-50 or >50%)
				202.7	VCh, FPh, K, ChK		Indistinctly wavy bedded			
	Kaugatuma Formation, Lower Äigu Beds	27		204.1	V, ChFPhK		Massive	Up to 70 cm; D and IND dark grey	95	Dark grey, calcareous, bituminous **dolomitic marlstone**. The carbonate content increases downwards
				205.9						
		28	6		Ch, VK, Ch, FPh, VCh		Indistinctly bedded or medium- to thin-nodular	<0.5, 1-5 cm; D greenish-grey	70	Greenish-grey, dolomitized, calcareous **marlstone** (grains 10-25%) with nodules and interbeds of dolomitized, argillaceous, *very finely crystalline* **limestone** (grains 25-50%). At 208.4-212.3 m occur crinoidal **limestone** (grains 25-50 or >50%) interbeds
				212.3	K, Ch, V, Ch		Irregularly thin- to medium-nodular, indistinctly bedded	<0.2, 1-2 (3) cm; D greenish-grey	<5	Light grey, *very finely crystalline* **limestone** (bioclasts >50%) with **marlstone** interbeds. The marl content decreases downwards. The intervals 212.4-212.5, 213.6-213.7 and 214.8-215.0 m are coarse bioclasts of crinoidal limestone. Discontinuity surfaces are pyritized
		29			K, Ch, KM					
				216.6	Ch V					
Ludlow	Kuressaare Stage, Kuressaare Formation, Tahula Beds	30	T-9		KM, ChK, K, TFPh, Ch, V		Indistinctly medium- to thin-nodular, irregularly bedded	< 1, 1-2 (4) cm; D or IND greenish-grey	10-30	Light, greenish-grey, argillaceous, dolomitized, *microcrystalline* to *very finely crystalline* **limestone** (grains 10-50%, poorly sorted) with **calcitic marlstone** interbeds. The clay and calcitic marl content increases in the lower part. Excavated discontinuity surfaces are pyritized
			T-10		TFPh, ChVK, V					Bluish-grey, K-bentonite **claystone**, lower part is argillaceous, upper part calcareous. Sand and black grains? occur on the lower boundary
				221.8 222.0	XF		Horizontal-bedded			
		31	T-11		VK, ChTFPh, V, Ch, K, V, Ch		Medium- to thin-nodular, in places irregularly bedded; on the lower boundary inclined bedding	<0.2, 0.2-5 cm; D grey	20-40	Light-grey, argillaceous, *very finely crystalline* **dolomitic limestone** (grains 10-25%) with **calcitic marlstone** interbeds. At 223.2 and 227.8 m the interbeds are poorly sorted, rich in brachiopod fragments. Discontinuity surfaces are pyritized, wavy and excavated

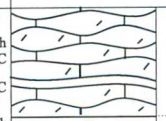
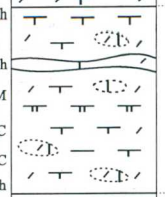
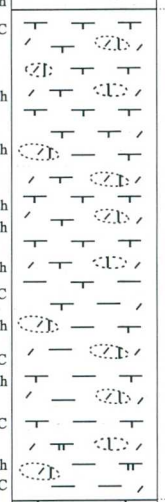
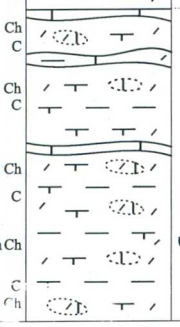
STANDARD UNITS	LOCAL STRATIGRAPHIC UNITS	CORE BOX NO.	FIGURES	DEPTH (m)	SAMPLES	LITHOLOGY	SEDIMENTARY STRUCTURES	MARLSTONE BEDS	MARLSTONE PERCENTAGE	SHORT DESCRIPTION
Ludlow	Kure* Kure* Tahu*			228.6	Ch K					follow up
	Paadla Stage Torgu Formation	32	T-12		Ch K TFPh V K Ch KM V		Horizontal, indistinctly thin- to medium-bedded or nodular, in the upper part homogenous	<0.2, 1-2 (3) cm; IND dark grey and greenish-grey	< 5	Grey, argillaceous, *microcrystalline* to *very finely crystalline* **dolostone** (grains 10-50%). Poorly sorted bioclasts and carbonate grains are 1-2 mm in diameter. The lower part comprises **dolomitic marlstone** with brown plant? remnants. Discontinuity surfaces are pyritized
		33		234.1	Ch K				10-30	
					V Ch V V K KM C Ch V		Irregularly wavy, bedded or nodular	<0.2, 1-2 cm; IND dark grey and greenish-grey	< 10	Greenish-grey, argillaceous, *very finely crystalline* **dolostone** with **dolomitic marlstone** interbeds. The clay content changes vertically. Fine skeletal particles are black and brown, often rounded and pyritized. Discontinuity surfaces are pyritized
		34	T-13 T-14	238.0	TFPh Ch TFPh K KM		Massive			White, *micro-* and *finely crystalline* to *very finely crystalline* **dolostone** (grains 10-50%, poorly sorted). The clay content changes vertically. The upper part contains **claystone** pebbles (diameter 0.5-2.0 cm). Caverns (vugs) 0.5-2.0 cm in diameter
		35		242.2	Ch C K V F Ph Ch K V		Wavy, indistinctly bedded	<0.2 (1-2) cm; IND dark grey	< 5	Bluish-grey, *very finely crystalline* **dolostone**. The clay content increases downwards. At 243.2-246.4 m occur **dolomitic marlstone** interbeds and lenses. Pyritized bioclasts (algae?) are often numerous in argillaceous interbeds
				246.4	V Ch K		Indistinctly bedded, in places microbedded	<0.2, 1 cm; IND grey	< 5	Greenish-grey *very finely crystalline* **dolostone**. The clay content increases upwards. The upper part includes thin **dolomitic marlstone** interbeds
Wenlock	Rootsikülä Stage Rootsikülä Formation Soeginina Beds	36	T-15	248.3	K M V TFPh K		Horizontal, thick-bedded, in places thin-bedded	<0.2, 1-3 cm; D bluish- and brownish-grey	1-2	Yellowish-white, *finely crystalline* to *microcrystalline* **dolostone** (grains 10-25 and >50%; boundstone interbeds). At 250.4-252.9 m bluish-white **dolostone** is *very finely crystalline* or *microcrystalline*. Rare **dolomitic marlstone** interbeds (thickness 1-3 cm) are present. Frequency of caverns (vugs) changes vertically
				252.9	K Ch		Thick-bedded			Yellowish-grey, *finely crystalline* **dolostone** (boundstone)
		37		253.6	V K F Ph		Horizontal thick-bedded	<0.2, 1 cm; IND and D brownish-grey	1-2	Yellowish-white, calcareous, *very finely crystalline* **dolostone** (grains 10-25, rarely 25-50%) with rare **marlstone** interbeds
				256.1	K					

Tahu*– Tahula Beds; Kure*– Kuressaare Stage and Formation

STANDARD UNITS	LOCAL STRATIGRAPHIC UNITS	CORE BOX NO.	FIGURES	DEPTH (m)	SAMPLES	LITHOLOGY	SEDIMENTARY STRUCTURES	MARLSTONE BEDS	MARLSTONE PERCENTAGE	SHORT DESCRIPTION
Wenlock	Rootsiküla Stage, Rootsiküla Formation, Vesiku Beds	37		256.1	V, K M		Wavy, irregularly thick-bedded, in places microbedded			Dark brownish-grey mottled, slightly argillaceous, *very finely crystalline* **dolostone**. At 256.3 m occur blackish-grey **dolostone** pebbles and at 256.1-256.8 m white **dolostone** microbeds. Discontinuity surfaces are pyritized on the lower boundary
		38	7	259.3	F Ph, V, K M		Wavy irregularly thin- to thick-bedded	<0.2, 1 cm; D and IND brownish-grey	2-3	Yellowish- to bluish-grey, in places brownish-grey, calcareous *very finely crystalline* **dolostone** (grains 10-25%) with **dolomitic marlstone** interbeds. Rare carbonaceous clasts (diameter 1-5 mm) occur below 259.3 m. Discontinuity surfaces are pyritized
	Kuusnõmme Beds			261.5	V		Wavy, massive, in places microbedded	<0.5 cm; IND dark grey	1-2	Bluish-grey mottled, *finely crystalline* to *microcrystalline* **dolostone** with interbeds and lenses of **argillaceous dolostone** and **dolomitic marlstone**. Some lenses are pale green (microconcretional glauconite?). A dark grey **claystone** interbed lies at 265.4-265.5 m
		39	T-16	265.7	T F Ph, K M		Massive			Grey, argillaceous, *very finely crystalline* **dolostone** (grains 10-25%)
				267.0	V, K M		Massive	<0.4 cm; IND dark grey	1-2	Grey, argillaceous, *very finely crystalline* **dolostone** (grains 25-50%). Two pyritized discontinuity surfaces occur on the lower boundary
	Viita Beds			267.4	Ch, V		Wavy, indistinctly thick- to medium-bedded, in places microbedded	<0.2 (1-2) cm; D or IND dark grey	1-2	Light grey to grey, argillaceous, calcareous *microcrystalline* to *very finely crystalline* **dolostone** and **eurypterid-dolostone** with rare **dolomitic marlstone** interbeds. Numerous rhythmic units are present, with the light grey lower part and upward increasing clay and clast content
		40	T-17		Ch, F Ph, Ch V, T F Ph					
			D-4	273.9	K M, V, Ch V		Horizontal, medium-bedded	<0.2, 1 cm; IND dark grey	1-2	Greenish- and brownish-grey, argillaceous, *finely crystalline* and *very finely crystalline* **dolostone** (grains 10-25%). The rock is cavernous and calcareous on the lower boundary
				275.1	V, K M		Massive		100	Greenish-grey, in places brownish-grey, argillaceous **dolomitic marlstone**
	Jaagarahu-Rootsiküla stages, Sõrve Formation			275.5			Wavy, medium-bedded		1-2	Light grey, *very finely crystalline* **dolostone** (grains 25-50%). The clay content decreases, bioclast and cavern content increases downwards
		41		276.1	Ch		Massive			Light grey and dark bluish-grey (pyritic) mottled, calcareous **biohermal dolostone** (grains > 50%; boundstone) with trace fossils
			8		F Ph					
			T-18	279.8	T F Ph		Thick-bedded			Light grey, calcareous, *very finely crystalline* **dolostone** (grains 25-50%)
		42		280.4	K M, V, C, Ch		Massive, (thick-bedded, nodular)			Brownish-grey, argillaceous, *very finely crystalline* **dolostone** (grains 25-50%). The clay content changes vertically
				282.9						Similar to the complex at 276.1-279.8 m
				283.2	C		Thick-bedded		1-2	Same as complex at 280.4-282.9 m. K-bentonite bed is white to light grey
				284.5	X Ch F, C, Ch		Med.- to thick-nodular	1-3 cm; brownish-grey	1-2	Light grey, calcareous, *very finely crystalline* **dolostone** (grains 25-50%)
		43								

STANDARD UNITS	LOCAL STRATIGRAPHIC UNITS	CORE BOX NO. / FIGURES	DEPTH (m) / SAMPLES	LITHOLOGY	SEDIMENTARY STRUCTURES	MARLSTONE BEDS	MARLSTONE PERCENTAGE	SHORT DESCRIPTION
								☞ follow up
Wenlock	Jaagarahu-Rootsiküla stages	43	285.8 FPhC; Ch; C; 287.6		Wavy, irregularly thick-bedded, in places microbedded			Grey **dolostone** (grains >50%; rudstone) containing fine, well-rounded carbonaceous clasts (diameter 1-3 mm) with pyritized surface, crusts with ooliths and rare bioclasts of crinoids. On the rugged lower boundary lies a conglomerate bed (thickness 4 cm) with pyritized pebbles (diameter up to 3 cm)
		D-5; T-19; 44	C; KM Ch C; C; TFPh; FPhCh C; C; KM Ch C; C; C; Ch; 293.9		Wavy and horizontal, irregularly medium- to thin-bedded, in places microbedded	Up to 5 cm; IND greenish-grey	> 90	Greenish-grey, in places argillaceous **dolomitic marlstone** with argillaceous **dolostone** interbeds and lenses. The marlstone contains silt and sand grains
	? Sõrve Formation	45; T-20	C; Ch; C; Ch; C; Ch; C; KM TFPhC; C Ch		Indistinctly nodular, marlstone microlaminated and bioturbated		5-15	Greenish-grey, dirty, *very finely crystalline* **dolostone** (grains 10-25%) with **calcitic** and **dolomitic marlstone** interbeds. The clay, silt and sand content changes vertically. Indistinct pyritized burrows are present. The basal 1 m contains fine bioclasts
		46; T-21	301.9; Ch; Ch C Ch TFPh; C; Ch; C; 305.7		Indistinctly nodular	Up to 4 cm; IND greenish-grey	< 20	Light greenish-grey, slightly argillaceous, dolomitized, *microcrystalline* and *very finely crystalline* **limestone** (grains 25-50%; unsorted) with dolomitized, **calcitic** and **dolomitic marlstone** interbeds containing bioclasts. The clay content increases downwards
	Jaagarahu Stage	47	KM Ch C; Ch; 308.1		Indistinctly nodular or bedded	Up to 15 cm; IND greyish-green	90	Greyish-green, dolomitized **calcitic marlstone** (fine bioclasts 10-25%) with argillaceous **limestone** (grains 10-25%) nodules. The clay content increases and bioclast content decreases in the middle part
			Ch C; FPh; Ch C; 311.0 Ch		Indistinctly nodular or bedded	Up to 5 (10) cm; IND greyish-green	40-70	Light grey, argillaceous, *very finely crystalline* **limestone** (grains 25-50%) with **calcitic marlstone** interbeds (fine bioclasts 10-25%)
		48	C; Ch; 314.3 C		Indistinctly nodular or bedded	0.2-5 cm; IND and D greyish-green	40-60	Greyish-green **calcitic marlstone** (bioclasts <10%) with argillaceous **limestone** (grains 10-25%) nodules. Nodules are more numerous in the basal part

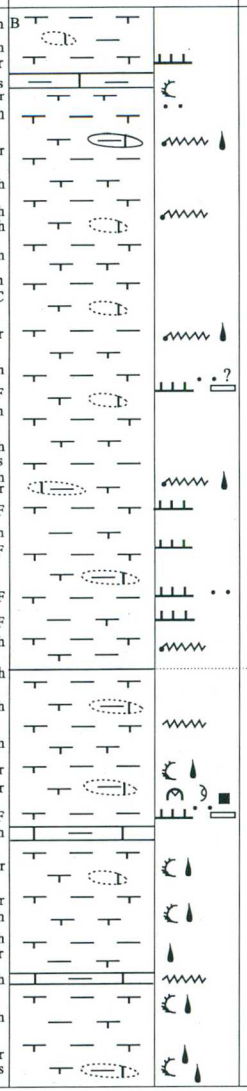
STANDARD UNITS	LOCAL STRATIGRAPHIC UNITS	CORE BOX NO. / FIGURES	DEPTH (m) / SAMPLES	LITHOLOGY	SEDIMENTARY STRUCTURES	MARLSTONE BEDS	MARLSTONE PERCENTAGE	SHORT DESCRIPTION
Wenlock	Jaagarahu Stage Sõrve Formation	48 9 49 T-22	314.3 Ch C Ch ChC TFPhChC ChC FPh 320.7		Wavy, irregularly thin- to thick-nodular or indistinctly bedded	0.2-7 (10) cm; D greyish-green	20-40	Light grey, slightly argillaceous, dolomitized, *microcrystalline* and *very finely crystalline* **limestone** (unsorted grains 25-50%; packstone) with **calcitic marlstone** (bioclasts 10-25%) interbeds
			Gr Ch C					
		50	Ch C ChC		Wavy, irregularly thin- to thick-nodular or indistinctly bedded	0.2-4, 10-15 cm; IND and D greyish-green	30-50	Light grey to greenish-grey, slightly argillaceous, *microcrystalline* and *very finely crystalline* **limestone** (grains 10-25 and 25-50%) with **calcitic marlstone** (fine bioclasts <25%) interbeds. The clay content changes vertically
		51 T-23	ChC Ch C TFPh				30 60-70	
		52	Ch FPhC Ch ChC ChC Ch				10 40-50	
		53	X Ch C Ch C Ph ChC Ch				60-70 25	
		54	C				50-60	

STANDARD UNITS	LOCAL STRATIGRAPHIC UNITS	CORE BOX NO.	FIGURES	DEPTH (m)	SAMPLES	LITHOLOGY	SEDIMENTARY STRUCTURES	MARLSTONE BEDS	MARLSTONE PERCENTAGE	SHORT DESCRIPTION
Wenlock	Sõrve Fm.	54		345.9	F Ph, Ch C, C, Ch					☞ follow up
Wenlock	Jaagarahu Stage, Jamaja Formation	54, 55		345.9–350.8	Ch, Ch, KM, Ch C, F Ph C, Ch		Wavy, irregularly nodular or indistinctly bedded	0.2-10 (20) cm; IND greyish-green	60, 20, 20-40	Greyish-green, **dolomitic marlstone** and calcareous **marlstone** (fine bioclasts 10-25%; unsorted) with light grey **limestone** (grains 10-25%) nodules
Wenlock	Jaagarahu Stage, Jamaja Formation	55, 56, 57		350.8–363.8	C, C Ch, C Ch, C Ch F Ph, Ch, C, Ch, C, F Ph Ch, Ch C, F KM Ch, C		Wavy, irregularly nodular or indistinctly bedded	0.2-10 (30) cm; IND and D greyish-green	25-40, 50, 70-80	Greyish-green **marlstone** (in places calcareous or **dolomitic marlstone**), with light grey *very finely crystalline* **limestone** (grains 10-25%) nodules. The bioclast content in marlstone changes vertically (in the upper part 10-25% and in the lower part <10%)
Wenlock	Jaagarahu Stage, Jamaja Formation	58, 59	T-24	363.8	Ch C, Ch C, Ch C, T F Ph Ch, C, Ch		Wavy, in the lower part horizontal, irregularly medium- to thick-nodular, lens-shaped or indistinctly medium- to thick-bedded, in places bioturbated	0.2-20 cm; in the lower part 20-40 cm IND and D greyish-green	50-60	Greyish-green, calcareous **marlstone** (bioclasts < 25%) with greenish-grey, in places dolomitized, argillaceous *microcrystalline* and *very finely crystalline* **limestone** (grains 10-25%) nodules, lenses and interbeds. In places **dolostone** interbeds occur. The bioclast, clay and carbonate content in marlstone changes vertically

STANDARD UNITS	LOCAL STRATIGRAPHIC UNITS	CORE BOX NO.	FIGURES	DEPTH (m)	SAMPLES	LITHOLOGY	SEDIMENTARY STRUCTURES	MARLSTONE BEDS	MARLSTONE PERCENTAGE	SHORT DESCRIPTION
Wenlock	Jaagarahu Stage Jamaja Formation	59 60 61 62 63 64	10 T-25	400.8	C Ch XF Ch Ch C Ch Is Ch FPh ChC ChC Ch C Ch Ch C Ch Is XF C Ch C Ch C Ch Is T FPh C Ch Ch C C Ch Ch KM Is Ch C Ch F Ph C Ch Gr				☞ follow up

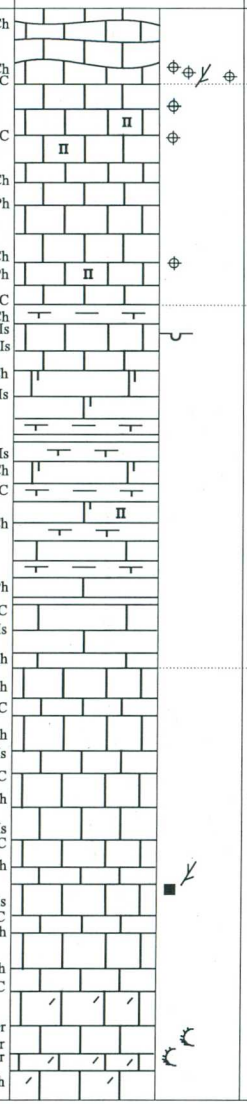
STANDARD UNITS	LOCAL STRATIGRAPHIC UNITS	CORE BOX NO.	FIGURES	DEPTH (m)	SAMPLES	LITHOLOGY	SEDIMENTARY STRUCTURES	MARLSTONE BEDS	MARLSTONE PERCENTAGE	SHORT DESCRIPTION
Wenlock	Jaagarahu Stage Jamaja Formation	64		400.8	KM Is BIs Ch; BIs Ch C; Is Ch; C		Horizontal, indistinctly thick- to thin-bedded, in places nodular	4-10, 20 cm; IND greenish-grey, with brown shade	60-90	Greenish-grey with brown shade, argillaceous **dolomitic marlstone** (bioclasts 10-25%). Skeletal fragments are unsorted, in places brachiopods and trilobites are accumulated. The lower part includes rare interbeds and nodules of light grey *very finely crystalline* **limestone** (grains 10-25%)
		65	11	405.6	Is BIs Ch C; BIs BIs Ch C; BIs Is Ch C; Gr Ch C		Horizontal, thin- to microbedded (homogenous)	0.2-2 cm; IND and D greenish-grey, with brown shade	90-95	Greenish-grey with brown shade, argillaceous **dolomitic marlstone** (in places **calcitic marlstone**) with rare **limestone** nodules and clasts. The interval 411.4-411.45 m is light grey to white, microbedded K-bentonite **claystone**
		66	T-26	411.45	KM XF TF Ph Ch C; Ch C Is		Wavy, in places nodular or indistinctly bedded (homogenous)	Up to 40 cm; IND grey with brown shade	90-95	Grey with brown shade, argillaceous **marlstone** (bioclasts 10-25%), with calcareous **marlstone** (bioclasts < 10%) and rare argillaceous *microcrystalline* **limestone** nodules and interbeds. Skeletal fragments are unsorted
	Jaani Stage Jaani Formation Paramaja Member	67		414.0	BIs; BIs Is Ch C; C BIs; Is Ch C; KM Ch C; Ch Is		Horizontal or slightly wavy, thin- to thick-bedded in places homogenous (core yield 75%)	0.2-20 cm; IND and D grey with brown shade	50-90	Grey with brown shade, argillaceous **marlstone** (bioclasts 10-25%), with calcareous **marlstone**, **dolomitic marlstone** and rare argillaceous **limestone** nodules and interbeds. Skeletal fragments are unsorted. At 423.5, 430.5, 435.8 and 437.4 m lie dark bluish-grey, crusty (oxidized zones of iron?) **K-bentonite claystone** interbeds (thickness 1-10 mm). The clay content increases and the bioclast content decreases downwards
		68			C Ch; C; X C Ch Is KM; BIs; Ch C; BIs Is					
		69	12		BIs C; Ch Is C; KM BIs Is C Ch					

STANDARD UNITS	LOCAL STRATIGRAPHIC UNITS	CORE BOX NO. FIGURES	DEPTH (m) SAMPLES	LITHOLOGY	SEDIMENTARY STRUCTURES	MARLSTONE BEDS	MARLSTONE PERCENTAGE	SHORT DESCRIPTION
Wenlock	Jaani Formation Paramaja Member	69					60-90	☞ follow up
		70	440.0					
	Jaani Stage				Horizontal, homogenous, indistinctly bedded, with rare nodules (core yield 40 %)	Up to 40 cm; IND dark brownish-grey	90-100	Dark brownish-grey, argillaceous and calcareous, in places shale-like **marlstone** containing graptoloid stipes. The upper part includes rare argillaceous **limestone** nodules and interbeds
	Riga Formation Tõlla Member	71						
		72	457.5					

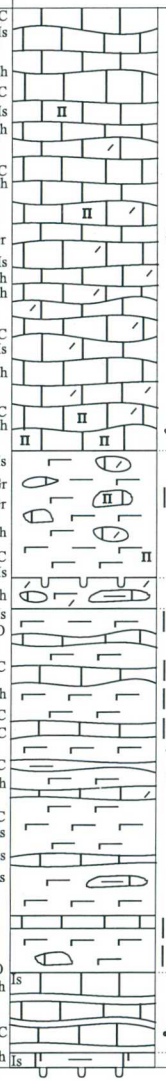
STANDARD UNITS	LOCAL STRATIGRAPHIC UNITS	CORE BOX NO. / FIGURES	DEPTH (m) / SAMPLES	LITHOLOGY	SEDIMENTARY STRUCTURES	MARLSTONE BEDS	MARLSTONE PERCENTAGE	SHORT DESCRIPTION
Llandovery	Adavere Stage Velise Formation	72 73 74 75	457.5 IsCCh B CCh XF BIs Ch CCh Gr CCh XF Is BIs C Ch F Ph Ch C Ch Is C Gr C Ch C Ch Ch C Ch BIs Is C Ch C Ch Is Ch C C Ch C Ch Gr C Ch BIs Is Ch C Ch F C Ch Ch C Ch Is C Ch Gr BIs C Ch XF BIs Ch Is C Ch C Ch XF Ch C Ch F Is C Ch XF C Ch		Horizontal, indistinctly bedded, homogenous; limestone thin- to medium-bedded	Up to 40 cm; IND greenish-grey	90-100	Greenish-grey, argillaceous and calcareous **marlstone** with rare argillaceous *very finely crystalline* and *microcrystalline* **limestone** interbeds. Skeletal remnants are not found. Pyritized burrows are present. The lower part includes brownish-grey, bituminous shale-like argillaceous **marlstone** beds. **K-bentonite claystone** interbeds (thickness 0.3-5 cm) are yellowish- or greyish-white to white, in places with kaolinite? and silt
		75 76 77	475.0 C Ch Is Ch C Ch C Ch Is Gr T-27 TF Ph C Ch Gr BIs C Ch F Is Ch C Ch Gr C Ch Ch C Ch Gr Is Ch C Ch Gr C Ch BIs Is Ch C Ch Ph Ch C Ch Gr C Ch Gr Gr Is		Horizontal, indistinctly bedded, homogenous; limestone thin- to medium-bedded	0.1-100 cm; IND greenish-grey and brownish-grey	90-100	Intercalation of greenish-grey, argillaceous and calcareous **marlstone** (bioclasts <10%; dominating in the upper part) and brownish-grey bituminous argillaceous graptolite-bearing **marlstone**, with numerous burrows and rare light greenish-grey, argillaceous *very finely crystalline* **limestone** (grains < 10%) nodules. **K-bentonite claystone** interbeds (thickness 0.2-6 cm) are yellowish- or greenish-white to dark grey, in places consisting of two parts (at 488.24 m)

STANDARD UNITS	LOCAL STRATIGRAPHIC UNITS	CORE BOX NO.	FIGURES	DEPTH (m)	SAMPLES	LITHOLOGY	SEDIMENTARY STRUCTURES	MARLSTONE BEDS	MARLSTONE PERCENTAGE	SHORT DESCRIPTION
Llandovery	Adavere Stage, Velise Fm. Ru*	77								☞ follow up
		78		489.2, 490.3			Wavy, medium- to thin-bedded and medium-nodular	2-3 cm; D greyish-green	30	Greenish-grey, argillaceous *very finely crystalline* **limestone** (grains 10-25%) with **calcitic marlstone** (bioclasts 25-50%) interbeds. The 1-5 cm thick limestone (bioclasts >50%; well sorted) interbeds at 489.7, 489.9 and 490.1 m contain marl-filled burrows and diagenetic calcite cement in their upper parts. Shells of *Pentamerida* are present
	Raikküla Stage, Staicele Member	79					Wavy, medium- to thin-bedded	< 2 cm; IND and D greenish-grey	25-30	Light grey, argillaceous *very finely crystalline* **limestone** (grains < 10%) with **calcitic marlstone** interbeds. The marl content increases downwards. *Very finely crystalline* limestone interbeds (thickness 0.2-3.0 cm), cemented by diagenetic calcite, occur at 490.5, 491.4, 494.4, 494.6, 494.8, 495.1, 495.8, 496.0, 497.1, 497.2, 497.3, 497.8 and 498.1 m
	Raikküla Stage, Saarde Formation	80		500.9						
	Raikküla Stage, Lemme Member	81					Wavy, medium- to thin-bedded	< 2, 1-2, (10-15) cm; IND and D greenish-grey	20, 60	Light grey, argillaceous *very finely crystalline* **limestone** (grains < 10%; in places up to 50%) with **calcitic marlstone** interbeds. The clay content changes vertically
		82		509.4			Wavy, microbedded	< 0.2 cm; IND and D greenish-grey	20-60	Greenish-grey, argillaceous **calcitic marlstone** (thickness of intervals 10-30 cm) with *very finely crystalline* **limestone** (grains < 10%) interbeds (thickness 1-5 cm)
	Ikla*	83		513.2			Wavy, medium-bedded, lens-shaped to nodular	< 2 cm; D greenish-grey	< 10	Yellowish-grey *finely crystalline* (upper 1.6 m) and *microcrystalline* **limestone** (grains < 10%) with **calcitic marlstone** interbeds

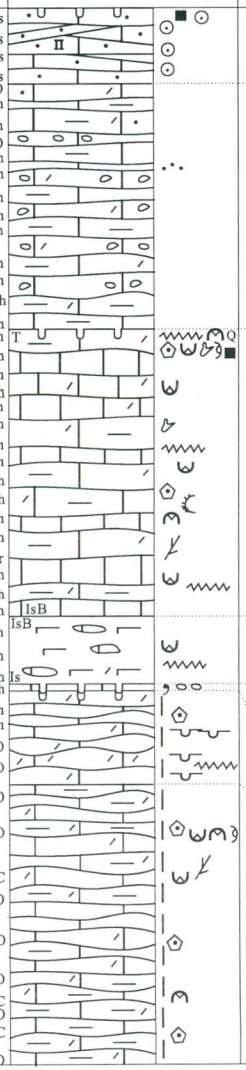
Ikla*– Ikla Member; Ru*– Rumba Formation

STANDARD UNITS	LOCAL STRATIGRAPHIC UNITS	CORE BOX NO.	FIGURES	DEPTH (m)	SAMPLES	LITHOLOGY	SEDIMENTARY STRUCTURES	MARLSTONE BEDS	MARLSTONE PERCENTAGE	SHORT DESCRIPTION
Llandovery	Raikkila Stage Saarde Formation Ikla Member	83	13	517.0	Ch Is Ch T F Ph C T-28					☞ follow up
		84			Is Ch C Ch C Is F Ph Is Ch F Ph		Horizontal, laminated, medium-bedded, in places thin- or thick-bedded	0.5-3 cm; D dark yellowish-grey	5-10	Yellowish-grey, slightly argillaceous *microcrystalline* **limestone** (grains <10%) with **calcitic marlstone** interbeds
		85		522.8	Is C Ch B Is B Is O Is C Ch B Is B Is Is B Is Ch Ch B Is C B Is Is C Ch		Horizontal, thin- to thick-bedded, in places rare nodules; marlstone microbedded	< 0.2 cm; IND and D greenish-grey	60-80	Intercalation of greenish-grey, argillaceous **marlstone** (thickness of intervals 10-40 cm) and slightly to medium argillaceous, in places dolomitized *very finely crystalline* and *microcrystalline* **limestone** (grains < 10%)
		86		532.5	F Ph Ch Is C O B Is B Is Ch Is Ch C				30-40	
		87	T-29		Ch Is B Is C Ch Is C T F Ph Ch Is C Ch F Ph Is B Is B Is Ch Is C		Horizontal, in the lower part wavy, thin- to thick-bedded, at 546.2 m micro-cross-bedded	< 0.2, 0.2-1 (2) cm; D grey, in the lower part dark grey	< 5	Yellowish-grey to light grey, in places slightly argillaceous *micro-* to *very finely crystalline* and *cryptocrystalline* **limestone** (grains < 10%, in 0.5-5.0 cm thick interbeds at 541.35, 541.5, 542.9, 543.5, 543.7 and 543.9 m 10-25%) with **calcitic marlstone** and **marlstone** interbeds. The clay content in marlstone beds increases in the lower part
		88	14		Ch Gr Gr C Gr Ch					

STANDARD UNITS	LOCAL STRATIGRAPHIC UNITS	CORE BOX NO.	FIGURES	DEPTH (m)	SAMPLES	LITHOLOGY	SEDIMENTARY STRUCTURES	MARLSTONE BEDS	MARLSTONE PERCENTAGE	SHORT DESCRIPTION
Llandovery	Raikküla Stage, Saarde Formation, Ikla Member	89, 90, 91	D-6		Is Gr, C Gr, Ch, Is, Ch C, B Is, Is, Ch, C B Is, Gr, Ch Gr, C F Ph, Ch Gr Is, C Gr, Ch, Is Gr, Ch C, Is Ch Gr, Ch C Gr Gr, Ch Is, Gr Gr, 558.5 O B Is					☞ follow up
									< 5	
									10	
									5	
	Kolka Member	91, 92		558.5 – 561.9	B Is Gr, Ch, Is C, Gr, F Ph, Is Gr, Is		Horizontal, thin- to medium-bedded; marlstone microbedded	< 0.2 cm; IND and D grey, bluish-grey and dark grey	20-30, 40	Intercalation of grey, compact, argillaceous **marlstone**, dark grey to bluish-grey, bituminous graptolite-bearing **marlstone** and light grey, in places argillaceous *very finely crystalline* and *microcrystalline* **limestone**. The upper part includes pelletal **limestone** (grains > 25%) interbeds (thickness 1-3 mm)
		92		561.9 – 563.5	Is Ch, Gr Is, B Is C, Is, Is		Horizontal, thin- to medium-bedded	< 0.2, 2-10 cm; IND greenish-grey and grey	10-20, 80	Light grey *microcrystalline* (upper 0.3 m *cryptocrystalline)* **limestone** (grains < 10%) and **marlstone** (thickness of intervals up to 20 cm)
		92		563.5 – 568.0	Is, O B Is C Ch, Is, B Is Ch, B Is, C, Is Ch		Horizontal, thin-bedded, irregularly nodular	1-10 cm; IND and D greenish-grey	50-80	Greenish-grey, argillaceous **marlstone** with interbeds and nodules of *micro-* and *very finely crystalline*, variably argillaceous **limestone**
	Slitere Member	93, 94		568.0 –	B Is Ch C Gr, Is, F Ph, Ch Gr, C, Is, Ch, B Is F Ph		Wavy, medium-bedded, in the lower part irregularly nodular (conglomeratic?)	0.2, 0.2-1, 2-4 cm; D greenish-grey	10-20, 5	Light grey, in places slightly to medium argillaceous *cryptocrystalline*, in places *microcrystalline* **limestone** (grains < 10%; in the lower part 10-25%) with argillaceous **marlstone** interbeds. The upper part includes pelletal **limestone** (grains >25%) interbeds

STANDARD UNITS	LOCAL STRATIGRAPHIC UNITS	CORE BOX NO.	FIGURES	DEPTH (m)	SAMPLES	LITHOLOGY	SEDIMENTARY STRUCTURES	MARLSTONE BEDS	MARLSTONE PERCENTAGE	SHORT DESCRIPTION
Llandovery	Raikküla Stage, Saarde Formation, Slitere Member	94, 95, 96	15	584.7	Ch C, Bl Is Is, Ch, C, Is, Ch, C, Is Ch, Ch Gr, C, Is, F Ph, Ch, Is Ch C, Is, Ch, Is C, Ch, O Is				< 5 10	☞ follow up
	Heinaste Mb.	97		588.1	Is F Ph Ch Gr, C Gr, Is, Is Ch, Is Ch C, Is		Wavy, thin- to medium-nodular, irregularly bedded	0.2-7 (10) cm; D (IND) greenish-grey	30 50-80	Greenish-grey, dolomitized compact **calcitic marlstone** with light grey, slightly argillaceous *very finely crystalline* and *microcrystalline* **limestone** (grains <10%) nodules. At 585.9 m occurs a violetish-brown limestone interbed (thickness 1 cm). The wavy discontinuity surface is pyritized
	Juuru Stage, Õhne Formation, Rozeni Member			588.9	Is Ch, C, Ch F Ph Is, O		Wavy, medium- to thin-nodular	0.2-10 cm; D and IND greyish-green	60-80	Intercalation of greenish-grey, slightly argillaceous *very finely crystalline* **limestone** (grains < 10%) and **calcitic marlstone** (in places argillaceous)
		98			Bl Is Bl Is Bl Is C, Bl Is Is Ch, C, Is C, C, Is Ch, O C, Is, Bl Is, Is		Wavy, irregularly medium- to thin-bedded, irregularly medium- to thin-nodular (core yield 55%)	0.2-3, 4-10 cm; IND and D greyish-green and violetish-brown	70 70-80	Greyish-green and violetish-brown, in places argillaceous **calcitic marlstone** with interbeds and nodules of slightly argillaceous, *very finely crystalline* and *microcrystalline* **limestone** (grains <10%)
	Puikule Mb. Ruja Mb.			598.5	O F Ph Ch Is		Wavy, irregularly nodular (core yield 50%)	< 0.2, 0.2-10 cm; D (IND) greyish-green	20-40	Light grey, slightly argillaceous *cryptocrystalline* **limestone** (grains <10%) with **calcitic marlstone** interbeds
			D-7	600.6 601.0	Is Bl Is Ch C, Ch F Ph Is		Horizontal, massive, (fluidized microbedding)			Greyish-green, slightly to highly argillaceous, dolomitized *very finely crystalline* **limestone**. The wavy discontinuity surface is pyritized

APPENDIX 1, SHEET 22

STANDARD UNITS	LOCAL STRATIGRAPHIC UNITS	CORE BOX NO.	FIGURES	DEPTH (m)	SAMPLES	LITHOLOGY	SEDIMENTARY STRUCTURES	MARLSTONE BEDS	MARLSTONE PERCENTAGE	SHORT DESCRIPTION
Upper Ordovician (Ashgill)	Saldus Fm.		D-7, D-8	601.0	Is		Horizontal, cross-bedded, micro- to thin-bedded			Light grey, sandy, ooliths containing **limestone** (grains 10-50 %, in some layers >50%). Content and diameter (mostly up to 1 mm) of carbonate ooliths increase upwards. Well-rounded carbonate? and quartz sand (diameter up to 0.5 mm) interbeds (thickness 0.5-2.0 cm) are present
	Porkuni Stage, Kuldiga Formation, Edole Member	99	16	603.0	Is O Is F Ph C Ch O Is CO Is Ch B Is Is C Ch Is C Ch Is O Ch Is C Ch Is O Ch Is C O Ch O C Is Ch Is Ch B Is O Ch		Wavy, medium- to thin-bedded and thick- to thin-nodular or lens-shaped			Dark greenish-grey *very finely crystalline* **limestone** (grains 10-25%) with **calcitic marlstone** interbeds. The clay content changes vertically. Irregular, up to 5 cm thick, bluish-grey limestone interbeds (more numerous in the upper part) contain carbonate clasts or pellets (diameter < 1.0 mm; 25-50 and >50%) and quartz sand. The discontinuity surface on the lower boundary is pyritized
		100	T-30	609.5	Is C Ch F Ph Is B Is Is B Is O Ch O Is C Ch B Is Is C O Ch Ch B Is Is Is C Ch Is C O Ch		Wavy, irregularly thin- to thick-bedded	0.2-2 (7) cm; D (IND) dark grey	< 5	Greenish-grey, slightly argillaceous *very finely crystalline* to *micro-crystalline* **limestone** (grains 10-25%; in the upper part well rounded) interbedded with **calcitic marlstone** (bioclasts < 10%) containing skeletal fragments. The clay content increases upwards
		101		617.1	Is O Ch Is Is C Ch Is Ch Is O C Ch Is O Ch		Massive, in places nodular	Up to 10 cm; IND light greenish-grey	95	Light greenish-grey **calcitic marlstone** with nodules and clasts of highly argillaceous *very finely crystalline* and *microcrystalline* **limestone** (grains 10-25%, in places 25-50%). In the lower part skeletal fragments concentrate in layers. Burrows are filled with brown marlstone and rust-coloured iron compound. The discontinuity surface is pyritized
	? Bernati*			618.9	Is O Ch Ch					
	Pirgu Stage, Jonstorp Formation		D-9	619.1	Is C O Ch Is O Ch B Is Is C O F Ph		Wavy, irregularly bedded	< 0.2, 0.2-1 cm; IND green	10-20	Light greenish-grey, slightly argillaceous *very finely crystalline* **limestone** (grains 10-25%) with **calcitic marlstone** interbeds. Bedding surfaces have thin black coatings
		102		621.6	B Is O Is C O C Is O		Wavy, medium- to thin-nodular	< 0.2, 0.2-2 cm; IND dark brown	10-20	Brownish-red, at some levels dark yellow (at 619.4-619.6 m light green) *very finely crystalline* **limestone** (grains 10-25%) with **calcitic marlstone** interbeds. The marl content changes vertically. Crinoids are dominating. Discontinuity surfaces are goethitized or not impregnated
			T-31		Is T F Ph C O				20	
		103	17		C Is C O C O C O C O X C O		Wavy, thin-nodular, lower 0.6 m medium-bedded or medium-nodular	< 0.2, up to 0.5 (1) cm; D dark brown	40 40-50	Brownish-red (basal 0.1 m greenish-grey), argillaceous *very finely crystalline* **limestone** (grains 10-25%; unsorted) with **calcitic marlstone** (bioclasts 10-25%) interbeds. The clay content decreases upwards. Flat iron ooliths occur on the lower boundary

Bernati*– Bernati Member

STANDARD UNITS	LOCAL STRATIGRAPHIC UNITS	CORE BOX NO.	FIGURES	DEPTH (m)	SAMPLES	LITHOLOGY	SEDIMENTARY STRUCTURES	MARLSTONE BEDS	MARLSTONE PERCENTAGE	SHORT DESCRIPTION
										☞ follow up
Upper Ordovician (Caradoc) (Ashgill)	Pirgu St. Jonstorp Fm. V* F*	103	T-32 D-10	631.1 631.8			Wavy, nodular or bedded	Up to 20 cm; D dark grey and greenish-grey	35	Greenish-grey and light grey with limonitized spots, argillaceous *very finely crystalline* **limestone** (grains <10%; unsorted) and argillaceous, in places shale-like **marlstone**. Discontinuity surface is bumpy
	Nabala Stage S* Mõntu Formation	104	T-33 D-11	632.7			Wavy, irregularly medium-bedded	< 0.2, up to 0.5 cm; D light brownish-grey	< 5	Yellowish-grey, *very finely crystalline* to *cryptocrystalline* **limestone** (grains 10-25 and 25-50%). The discontinuity surface is pyritized
			18	636.0			Wavy, irregularly thin- to medium-bedded, in places thick-bedded	< 0.2, up to 1 (2) cm; D greyish-green, in the basal part dark greenish-grey	5-7	Light greenish-grey (upper 0.5 m with violet spots, at 636.0-636.8 m light grey) *very finely* to *finely crystalline* **limestone** (grains 10-25%, in the lower part 25-50%) with **calcitic marlstone** interbeds. Discontinuity surfaces are rust-coloured (limonitized?)
	Rakvere? Pr*	105	T-34	638.0 638.6 638.8			Wavy, irregularly nodular	Up to 7 cm; IND dark grey	40	Light grey to greenish-grey, in places slightly argillaceous *very finely crystalline* **limestone** (grains <10 and 10-25%) with **calcitic marlstone** (bioclasts 10-25%) interbeds. Discontinuity surfaces are pyritized
	Oandu* Mossen Formation			639.4 640.5			Visually massive, in places nodular	0.2-7 cm; IND greenish-grey	70-80	Greenish-grey **calcitic marlstone** (bioclasts 10-25%) with rare nodules of argillaceous *very finely crystalline* **limestone** (grains <10%)
		106		642.0			Wavy, indistinctly bedded, in places thin-nodular	0.2-10? cm; IND dark greenish-grey	90-100	Dark greenish-grey, in the lower part argillaceous, dolomitized **calcitic** (**dolomitic**?) **marlstone** with bioclasts (10-25%) and angular fine quartz grains
	Bli*			644.8 645.7 647.1			Wavy, indistinctly bedded or nodular	1-10 cm; IND dark greenish-grey	60	Dark greenish-grey, dolomitized **calcitic** (**dolomitic**?) **marlstone** (bioclasts 10-25%; in places angular fine quartz grains) with rare **limestone** nodules. Basal 0.5 m is greenish-grey, highly argillaceous *very finely crystalline* **limestone** (in places grains 10-25%) with **calcitic marlstone** interbeds
	Keila Stage	107	T-35 19				Wavy, thin- to medium-bedded, irregularly nodular	< 0.2, 1-3 (5) cm; D dark grey	30	Light grey and greenish-grey, argillaceous *microcrystalline* to *finely crystalline* **limestone** (unsorted grains 10-25, in some layers >50%) with **calcitic marlstone** interbeds and greenish-yellow to light grey micro-bedded **K-bentonite claystone** (thickness 0.2 m) on the lower boundary
	Haljala Stage Jõhvi Subst. Adze Formation		T-36	650.1 652.4			Wavy, thin- to medium-bedded, irregularly nodular	0.1-2 cm; D (IND) dark grey	30-40	Light greenish-grey, argillaceous *microcrystalline* and *very finely crystalline* **limestone** (grains 10-25%) with interbeds of **calcitic marlstone**. Iron ooliths are found
	Idavere Substage	108		653.5			Wavy, irregularly bedded or nodular	0.3-1 cm; IND dark greenish-grey	20-30	Light greenish-grey, slightly argillaceous *very finely crystalline* **limestone** (in some layers grains 25-50%) with **marlstone** interbeds
		109	D-12 20				Wavy, irregularly thin- to medium-bedded	< 0.2, 0.2-0.3 cm; D dark grey	< 5	Light grey, slightly to medium argillaceous *very finely crystalline*, in places *microcrystalline* **limestone** (grains 25-50%). Interbeds containing iron ooliths (diameter 0.5 mm) are yellow and violet

Bli*– Blidene Formation; Oandu*– Oandu Stage; Pr*– Priekule Member; Rakvere? – Rakvere? Stage; S*– Saunja Formation; F*– Fjäcka Formation; V*– Vormsi Stage

STANDARD UNITS	LOCAL STRATIGRAPHIC UNITS	CORE BOX NO. / FIGURES	DEPTH (m) / SAMPLES	LITHOLOGY	SEDIMENTARY STRUCTURES	MARLSTONE BEDS	MARLSTONE PERCENTAGE	SHORT DESCRIPTION
Upper Ordovician (Caradoc)	H* Ida* Fm.	T-37	658.2					follow up
	Adze Fm.	109	659.7					
	Kukruse Stage, Dreimani Formation	T-38, T-39, 21, 110			Wavy, irregularly nodular and medium-bedded	< 0.2, 0.1-0.7 (1) cm; D dark grey	< 5	Light brownish- or yellowish-grey, in places slightly argillaceous *microcrystalline* and *very finely crystalline*, in places *coarsely* to *medium-crystalline* **limestone** (grains 10-25 and 25-50%) with **calcitic marlstone** interbeds
Middle Ordovician (Llanvirn)	Uhaku Stage, Taurupe Formation	666.8, 111, T-40, D-13, 112, D-14, 22			Wavy, indistinctly thin- to medium-bedded	< 0.2, 0.2-1 cm; D dark grey	< 5	Light greenish-grey, in places slightly argillaceous *cryptocrystalline* (thickness of intervals 2-8 cm) and *microcrystalline* to *very finely crystalline* **limestone** (grains 10-50 and >50%) with **calcitic marlstone** interbeds. In places yellow and brown spots surround iron ooliths
	Lasnamägi Stage, Stirnas Fm.	T-41, 677.2, 113, 678.1, D-15			Wavy, medium-bedded	< 0.2, 0.2-1 cm; D grey	1-2	Light grey, *crypto-* and *microcrystalline* **limestone** (grains 25-50%; goethitized and rounded) with **marlstone** interbeds. Some layers contain iron ooliths
					Wavy, thin- to medium-bedded	< 0.2, 0.2-6 cm; D grey	1-2	Light grey, *crypto-* and *microcrystalline* **limestone** (grains >50%) with rare **marlstone** interbeds. Some layers contain iron ooliths. Discontinuity surfaces are wavy, phosphatized (at 679.55 m) and limonitized
	Lasnamägi Stage, Segerstad Fm.	680.5, T-42, 682.5, 114, 23, T-43			Wavy, medium- to thin-nodular, in places indistinctly bedded	< 0.2, 0.3-1 cm; IND dark brown	10-20	Light brown to brownish-red, with rare grey spots (particularly 682.5-684.0 and 687.0-687.9 m), in places argillaceous (particularly 684.0-687.0 m) *microcrystalline* (in the upper part) and *very finely crystalline* **limestone** (grains 25-50 and >50%; unsorted) with **marlstone** interbeds. Carbonate clasts (diameter up to 0.5 cm) are found

H* – Haljala Stage; Ida*– Idavere Substage

STANDARD UNITS	LOCAL STRATIGRAPHIC UNITS	CORE BOX NO. / FIGURES	DEPTH (m) / SAMPLES	LITHOLOGY	SEDIMENTARY STRUCTURES	MARLSTONE BEDS	MARLSTONE PERCENTAGE	SHORT DESCRIPTION
Middle Ordovician (Llanvirn)	Aseri Stage, Segerstad Formation	115						☞ follow up
			687.9; T-44; T-45; 690.0		Wavy, irregularly thin- to medium-bedded	< 0.2, 0.3-0.5 cm; D dark grey	< 5	Greyish-red, with brownish-grey and grey interlayers (thickness 5-20 cm), dolomitized *microcrystalline* and *very finely crystalline* **limestone** (grains 10-50%; unsorted) with **marlstone** interbeds
	Kunda Stage, Baldone Formation	116; 24			Wavy, irregularly thin- to medium-bedded or thin-nodular	< 0.2, 0.2-0.5 (1) cm; D grey	< 5	Greyish-red, with brownish-grey and grey interlayers (thickness 5-20 cm), dolomitized *microcrystalline* and *very finely crystalline* **limestone** (grains 10-50%; unsorted) with **marlstone** interbeds
		T-46; D-16; 117; 697.5; T-47						Yellowish-grey with green shade, calcareous *medium-crystalline* **dolostone** (grains >50%) with **dolomitic marlstone** interbeds. Caverns (vugs) up to 2 cm in diameter. In the lower part greenish-grey, in places dolomitized *microcrystalline* and *very finely crystalline* **limestone** (grains >50%) with **marlstone** interbeds. Wavy discontinuity surfaces are limonitized and phosphatized
	Sa*		698.5; 698.8		Wavy, medium-bedded	< 0.3 cm; D dark grey	1-2	
	(Arenig) Volkhov Stage, Kriukai Formation	T-48; 25; 118; T-49	700.6		Wavy, irregularly thin- to medium-bedded	< 0.5; D dark brown	1-2	Brown, grey or yellow mottled and violetish-red (lower 1 m), in places argillaceous *micro-* to *very finely crystalline* **limestone** (grains < 25, >50%) with rare **marlstone** interbeds. In the middle violet-brown calcareous *medium-crystalline* **dolostone**. Wavy discontinuity surfaces are limonitized
		T-50; D-17			Wavy, thin- to medium-bedded, irregularly thin-nodular	< 0.2, 0.2-2 cm; D (IND) dark brown	5-10	Violetish-brown (at 703.7, 704.5 and 704.75 m grey), calcareous, slightly argillaceous *coarsely* to *very finely crystalline* **dolostone** (grains 25-50 and >50%; well rounded) with **dolomitic marlstone** interbeds. Wavy or flat discontinuity surfaces are limonitized and haematized
L. O*	H*	T-51; D-18; D-19; 705.9; 706.65; 706.8			Wavy, medium-bedded	< 0.2 cm; IND dark brown	1-2	Violetish-brown mottled, pinkish-white (706.1-706.14 m) and greenish-grey (706.6-706.65 m), in places weathered, argillaceous, sandy *finely* to *coarsely crystalline* **dolostone** and **marlstone**. Well-rounded glauconite grains (10-30%, in the lower part rare) 0.5-2 mm in diameter. Wavy discontinuity surfaces are limonitized
	L*Z*				Not visible, lower 10 cm conglomerate-like			
Middle Cambrian	Deimena Stage, Ruhnu Formation	119; 120						Greenish-grey, medium-cemented (by dolomite), *fine- to coarse-grained* **glauconitic quartz sandstone**. The lower strongly cemented (by dolomite) 10 cm contains inarticulate brachiopods, glauconite and well-rounded quartz grains
								☞ follow down

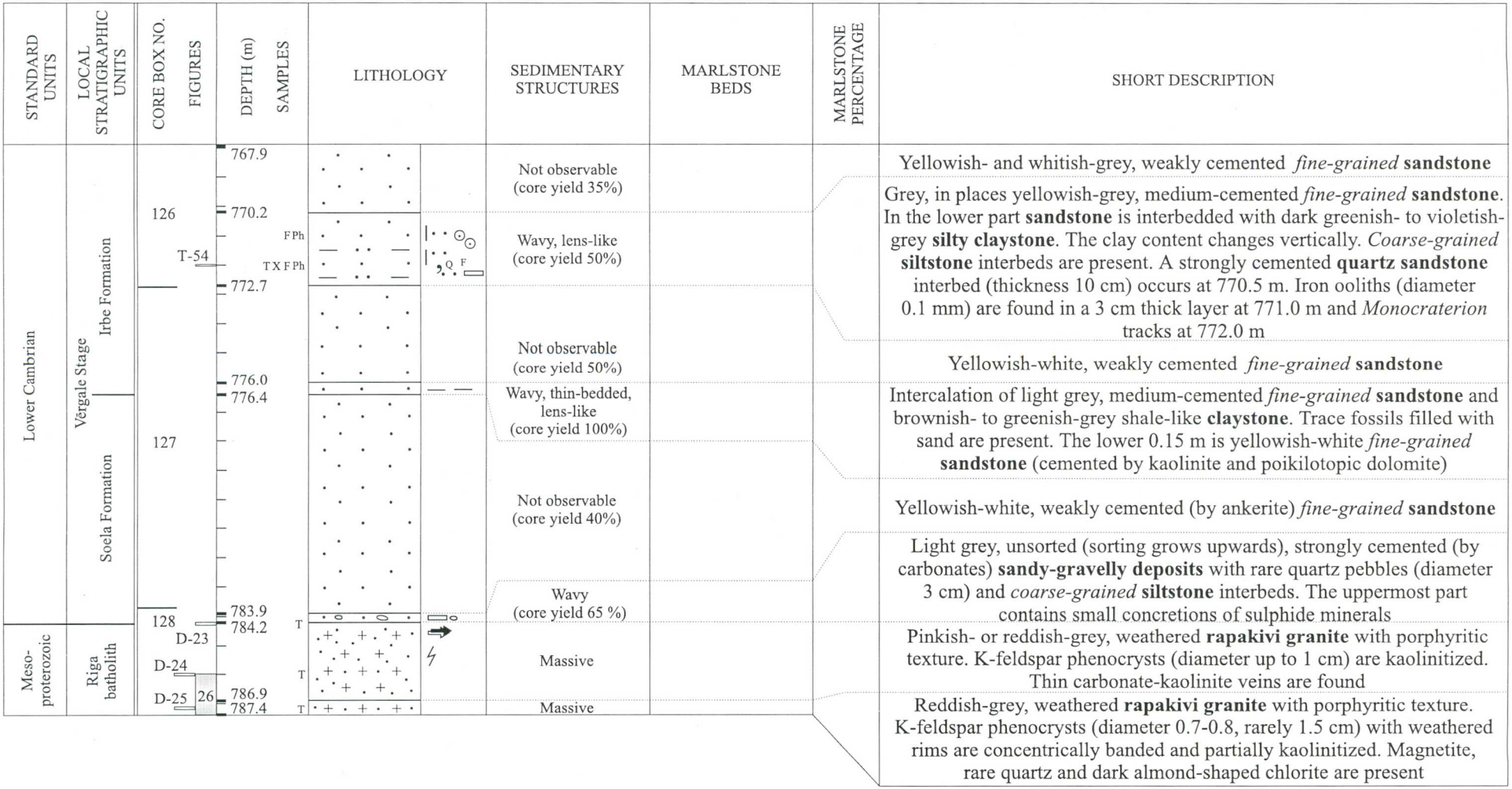
L. O* – Lower Ordovician; H*– Hunneberg-Billingen stages; L*– Leetse Formation; Z*– Zebre Formation; Sa*– Sakyna Formation

APPENDIX 1, SHEET 26

STANDARD UNITS	LOCAL STRATIGRAPHIC UNITS	CORE BOX NO.	FIGURES	DEPTH (m)	SAMPLES	LITHOLOGY	SEDIMENTARY STRUCTURES	MARLSTONE BEDS	MARLSTONE PERCENTAGE	SHORT DESCRIPTION
Middle Cambrian	Deimena Stage Ruhnu Formation	120					Not observable (separate fragments; core yield 70%)			Yellowish-grey and pinkish-white, weakly cemented *very fine-grained* to *fine-grained* **quartz sandstone**. Grains are well rounded
		121	D-20	724.2			Massive, homogenous (core yield 55%)			Light whitish-grey with violet and grey spots, argillaceous (kaolinite-containing), medium-cemented **siltstone** (or *very fine-grained* **quartz sandstone**). Muscovite flakes are present
				725.0			Not observable (separate fragments; core yield 75%)			Pinkish-white, weakly cemented *very fine-grained* to *fine-grained* **quartz sandstone**. In the lower part rock is well sorted. At 746.6-746.8 m occur fragments of argillaceous, kaolinite-containing **siltstone** (or *very fine-grained* **sandstone**; similar to interval 724.2-725.0 m)
		122								
		123								

STANDARD UNITS	LOCAL STRATIGRAPHIC UNITS	CORE BOX NO. / FIGURES	DEPTH (m) / SAMPLES	LITHOLOGY	SEDIMENTARY STRUCTURES	MARLSTONE BEDS	MARLSTONE PERCENTAGE	SHORT DESCRIPTION
Middle Cambrian	Deimena Stage Ruhnu Formation	123						☞ follow up
		124	748.0					Pinkish-, brownish- and greenish-grey *fine-grained* to *very fine-grained* **quartz sandstone** with films and interbeds of grey and violet **silty claystone**. The chamosite cement content in rock decreases upwards. Brownish-grey, wavy and horizontal burrows are pyritized. In the upper part the claystone contains quartz grains and sandstone intervals are thicker. The upper 1 m includes goethitized layers. At 751.5-751.7 m occur strongly cemented (by dolomite) microbedded burrowed **sandstone** interbeds (thickness 3-5 cm). Poorly preserved arenacous foraminifers are present
Lower Cambrian	Vergale Stage Irbe Formation	T-52	T Ph X F Ph X F F Ph		Horizontal, in the lower part wavy; claystone microbedded, in the lower part thin-bedded (core yield 85%)			
		T-53	T X F Ph 752.5		Not observable (core yield 35%)			Yellowish- and whitish-grey, weakly cemented *fine-grained* to *very fine-grained* **sandstone**
		125	756.0					
		D-21	X F Ph F Ph		Wavy, bioturbated, in places soft sediment deformed (core yield 50%)			Medium-cemented *fine-grained* **sandstone** with interbeds, lenses and nodules of **silty claystone**. The clay content changes vertically. The complex is grey, in places brown, red and violet mottled. Burrows filled with sand penetrate the bedding. Trace fossils, at 760.0 m *Monocraterion*, are found
		D-22	763.1 X F Ph					Greyish-white, weakly cemented *fine-grained* **sandstone**
		126	765.4 T		Not observable (core yield 20%)			Medium-cemented *very fine-grained* **sandstone** with interbeds, lenses and nodules of **silty claystone**. The clay content changes vertically. The complex is greenish-, yellowish- to brownish-grey (goethitized). Burrows are filled with sand and bedding surfaces are uneven. The chamosite-cemented beds contain coarse quartz grains
			767.9		Wavy, bioturbated (core yield 60%)			

APPENDIX 1, SHEET 28



Other issues in the series

Estonian Geological Sections:

Tartu (453) drill core (Bulletin 1; 1998)
Taga-Roostoja (25A) drill core (Bulletin 2; 1999)
Valga (10) drill core (Bulletin 3; 2001)
Soovälja (K-1) drill core (Bulletin 4; 2002)

Forthcoming issue:

Mehikoorma (421) drill core