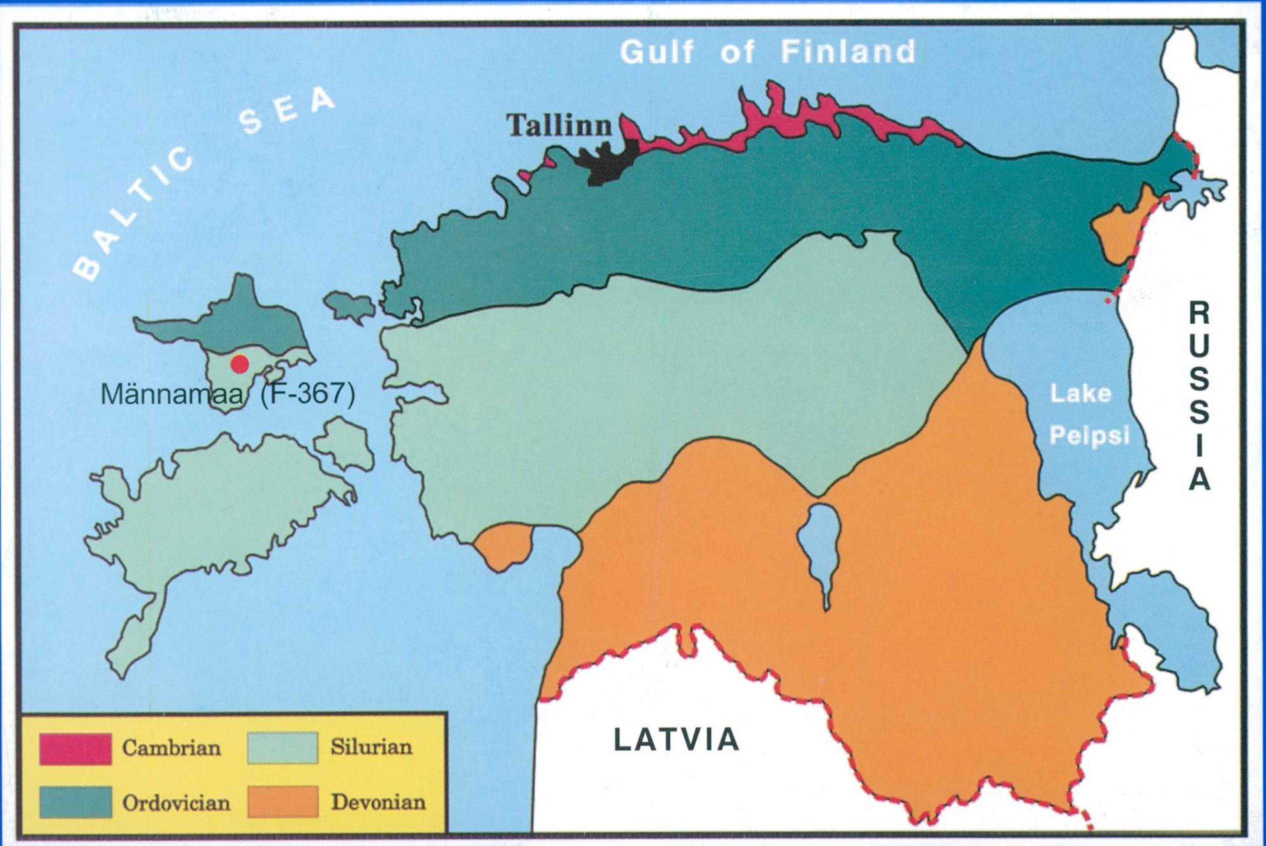
EESTI GEOLOOGIAKESKUS
GEOLOGICAL SURVEY OF ESTONIA

ESTONIAN GEOLOGICAL SECTIONS

BULLETIN 9

MÄNNAMAA (F-367) DRILL CORE



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CONTENTS

APPENDIXES ON CD-ROM

Appendix 2.	Photo-log of the Palaeoproterozoic, Cambrian, Ordovician and Silurian part of the Männamaa (F–367) core
Appendix 3.	Photos of selected intervals of the Männamaa (F–367) core
Appendix 4.	Geophysical logging of the Männamaa (F–367) borehole (Sheets 1, 2)
Appendix 5.	List of Ordovician and lowermost Silurian chitinozoan samples from the Männamaa (F–367) core
*Appendix 6.	Distribution of Ordovician and lowermost Silurian chitinozoans in the Männamaa (F–367) core (Sheets 1–3)
Appendix 7.	Distribution of Ordovician and lowermost Silurian acritarchs in the Männamaa (F–367) core (10 pages)
*Appendix 8.	Distribution of selected Ordovician and lowermost Silurian acritarchs in the Männamaa (F–367) core (Sheets 1–4)
Appendix 9.	List of Cambrian, Ordovician and lowermost Silurian acritarchs of the Männamaa (F–367) core
Appendix 10.	Whole-rock carbon ($\delta^{13}C$) and oxygen ($\delta^{18}O$) isotope composition of Ordovician and lowermost Silurian carbonates in the Männamaa (F–367) core
Appendix 11.	Chemical analyses data and physical properties of rocks from the Männamaa (F–367) core

*Also available as a foldout

INTRODUCTION

The Männamaa (F-367) borehole (58° 50′ 18″ N, 22° 37′ 42″ E) is located in the central part of Hiiumaa Island, northwestern Estonia (Fig. 1). It was drilled in the course of deep geological mapping (at a scale of 1:200 000) near Männamaa village in 1988 (Suuroja *et al.* 1991). The 358.3 m deep hole penetrates the Palaeoproterozoic (60.3 m), Cambrian (115.0 m), Ordovician (136.5 m) and Silurian (17.5 m) sedimentary rocks, and 29.0 m thick loose Quaternary deposits (Fig. 2).

The 4 km wide circular Kärdla meteorite crater, surrounded by an elliptical ring fault up to 15 km in diameter, lies about 10 km northeastward from the Männamaa (F-367) drill hole (Suuroja *et al.* 2002; Suuroja & Suuroja 2006). The Kärdla impact event, marked by well-preserved ejecta-influenced matter, is also reflected in the Männamaa core (Fig. 2). Generally, the investigated section contains sediments of the NW part of the East European Platform, which deposited in the marginal area of shallow sea, mainly in the conditions of the drift of the Baltica Palaeocontinent northwards towards the equator and interrupted sedimentation.

The core is housed at Arbavere field station of the Geological Survey of Estonia (GSE). The source material for the present study is available in unpublished reports (Suuroja *et al.* 1991, 1993) stored in the Depository of Manuscript Reports of the GSE, Kadaka tee 82, Tallinn. The results of earlier palaeontological (Grahn *et al.* 1996; Hints & Nõlvak 1999; Puura 1996) and stable isotope (Ainsaar *et al.* 2004) investigations are used in this work together with recently obtained data.

Mati Niin (GSE) contributed the macrolithological description of the Palaeoproterozoic crystalline basement. Kalle Suuroja (GSE) described the Cambrian, Ordovician, Silurian and Quaternary section (Suuroja *et al.* 1991) and re-examined it during complex geological mapping (at a scale of 1:50 000) of Hiiumaa Island (Suuroja *et al.* 1993). Kaisa Mens from the Institute of Geology at Tallinn University of Technology (IGTUT) provided the stratigraphy and development of Cambrian sediments. Aasa Aaloe's (IGTUT) field notes (interval 156.1–180.2 m) of 1991 and lithologi-

Fig. 1. Location of the Männamaa (F-367) drill hole.

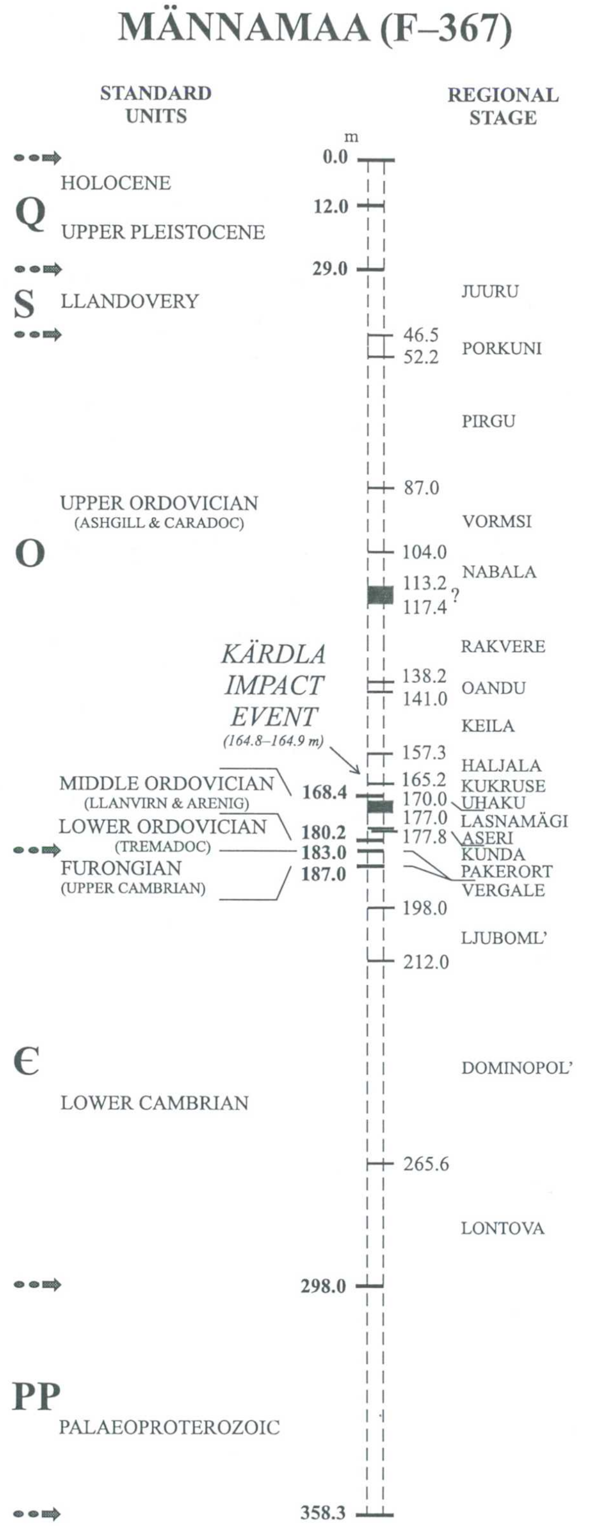


Fig. 2. Generalized stratigraphy of the Männamaa (F-367) core. Problematic boundaries of regional stages are shown with black intervals. PP – Palaeoproterozoic; Є – Cambrian; O – Ordovician; S – Silurian; Q – Quaternary.

cal samples collected together with Jaak Nõlvak (IGTUT) in the years 1991 and 1994 were used as supplementary material. A selection of split core specimens is stored at the IGTUT.

Anne Põldvere (GSE) investigated selected Cambrian, Ordovician and Silurian intervals (77 specimens) to specify the lithology of the rock. Additionally provisional data of 35 thin sections were used. The description of the core was improved using the results of laboratory studies.

The stratigraphic subdivision of the Ordovician section is based on the distribution of chitinozoans and acritarchs. Systematic long-term study of chitinozoans (Nõlvak 2002) enables the most precise stratification and regional and global correlation of Estonian sections. Jaak Nõlvak (IGTUT) examined Ordovician and Silurian chitinozoans in 196 samples, whereas 24 samples characterize the Kärdla impact event level and 21 samples the beds corresponding to the Kinnekulle K-bentonite.

Cambrian, Ordovician and Silurian acritarchs (131 samples) were identified by Anneli Uutela (University of Helsinki). The distribution of 276 species was compared with the earlier investigated Rapla core (Uutela & Tynni 1991) in northern Estonia to identify key assemblages for Estonian regional stages.

Tõnu Meidla and Oive Tinn (both from the Institute of Ecology and Earth Sciences at the University of Tartu, IEESUT) studied Upper Ordovician ostracods in 30 samples from Keila to Rakvere stages and the Ordovician–Silurian boundary beds.

Leho Ainsaar (IEESUT) and Tõnu Meidla contributed carbon ($\delta^{13}C$) and oxygen ($\delta^{13}C$) isotope data of the Ordovician and lowermost Silurian rocks, based on the analysis of 149 whole-rock samples.

The composition of twelve Upper Ordovician volcanic ash beds was investigated by Tarmo Kiipli, Toivo Kallaste (both from the IGTUT) and Kiira Orlova (GSE) on the basis of 15 X-ray fluorescence (XRF) analyses. Toivo Kallaste made also four X-ray diffractometry (XRD) analyses from selected samples.

Alla Shogenova and Kazbulat Shogenov (IGTUT) provided results of 70 chemical analyses and 54 measurements of physical properties from the Ordovician and Silurian sediments.

The description of Palaeoproterozoic rocks is based on 10 thin sections, 42 semiquantitative arc emission spectral analyses and one chemical analysis (Suuroja *et al.* 1991).

Photos of the core were taken by Heikki Bauert (GEOGuide Baltoscandia), Anne Põldvere and Tõnis Saadre (both from the GSE). Ranek Rohtla (GSE) and Elar Põldvere (IEESUT) provided various technical assistance.

Useful comments by Rein Einasto (University of Applied Sciences, Tallinn), Juho Kirs, Jüri Plado (both from the IEESUT), Jaak Nõlvak, Dimitri Kaljo (IGTUT), Ivo Paalits (Museum of Geology, University of Tartu) and Jaan Kivisilla (GSE) were of great help in finalizing the report.

CORE DESCRIPTION AND TERMINOLOGY

The description of the Männamaa (F-367) core is presented in the form of a table (Appendix 1) including the stratigraphical division, review of illustrations and sampling, and main lithological features of the rock. In places comments on core yield and supplementary data are added. The material provided is a summary of macrolithological characteristics and laboratory analyses described in the introduction to the bulletin. The depths and levels of all specimens are shown in the photo-log of the core (Appendix 2).

The global chronostratigraphic division is based on the International Stratigraphic Chart available on the website of the International Commission on Stratigraphy. For the regional chrono- and lithostratigraphy of the Männamaa (F-367) section, the Estonian charts were employed, referred to in Põldvere *et al.* in this volume. The Ordovician regional stages are tightly tied to Baltoscandian chronostratigraphy as well as to British Series (Grahn *et al.* 1996).

The descriptions of the textures of carbonate rocks are based on the traditional Estonian classification by Vingisaar *et al.* (1965), Loog & Oraspõld (1982) and Nestor (1990). The terms used for textures are explained in Appendix 1. The particles with the diameter > 0.05 mm are described as grains. The content of carbonate clasts (including bioclasts) is given in most cases in per cent. For the major part of the core, the amount of grains was determined with the magnifying glass on the slabbed surfaces of the core. Selected intervals were examined under the binocular microscope and thin section data were used. The micritic component consists of particles < 0.05 mm in diameter. 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.

Whereas the clay component forms the main part of insoluble residue, Estonian lime- and dolostones are additionally referred to as slightly argillaceous (insoluble residue 10–15%), medium argillaceous (15–20%) and highly argillaceous (20–25%) (Oraspõld 1975).

The sedimentary structures are presented in the style used in the previous eight issues of the bulletin. The classification of structures is given in Appendix 1 and their variation in the Männamaa (F–367) core is illustrated in Appendixes 2 and 3.

GENERAL GEOLOGICAL SETTING AND STRATIGRAPHY

The bedrock succession of the Männamaa (F–367) core includes the Palaeoproterozoic crystalline basement, Cambrian (Lower Cambrian and upper Furongian) terrigenous sediments, and Ordovician (Lower, Middle, Upper) and Silurian (Llandovery) carbonate strata (Fig. 2; Appendixes 1–4), overlain by the Quaternary cover. The stratigraphy of the section is based on the correlation charts for the Cambrian of Estonia by Mens & Pirrus (1997a, p. 39, table 6), for the Ordovician by Nõlvak (1997, p. 54, table 7) and for the Silurian by Nestor (1997, p. 90, table 8). Systematic data on Ordovician acritarchs and chitinozoans are used for the biostratigraphical subdivision of the section (see Uutela and Nõlvak in this volume).

The **Palaeoproterozoic crystalline basement** of Hiiumaa Island lies at a depth of –175 to –325 m and forms geologically and structurally an extension of the Svecofennian folded belt in Southern Finland (Koistinen *et al.* 1994). The Männamaa (F–367) drill hole penetrates the upper 60.3 m of the basement (interval 298.0–358.3 m; Appendix 1, sheet 11) consisting of migmatized biotite, sillimanite and cordierite gneisses together with migmatite granites. The rocks are cataclastic, rich in slickensides and veins of secondary minerals (carbonate, chlorite, epidote, etc.). Pinkish- and reddish-grey gneisses are mainly fine- to medium-grained, dipping at an angle of 20° to 40°. Migmatite granites, in colour similar to gneisses, are mainly medium-grained. The topmost 49.6 m of the basement has been subjected to pre-Ediacaran weathering.

The Ediacaran (Vendian) rocks are lacking in the Männamaa (F–367) core. The eroded and weathered surface of the Palaeoproterozoic crystalline basement in the southern part of Hiiumaa is overlain by Lower Cambrian rocks with a hiatus.

The **Lower Cambrian** in the Männamaa (F–367) section (interval 187.0–298.0 m; Appendix 1, sheets 8–10; core yield varying up to 50%) is represented by the Voosi (Lontova Stage), Sõru, Lükati (both Dominopol' Stage), Soela (Ljuboml' Stage) and Irbe (Vergale Stage) formations. This succession consists of clayey siltstone and quartz sandstone that occur on the islands of the West Estonian Archipelago and in the western part of mainland Estonia in different stratigraphical completeness, and are known only from core sections.

The lower boundary of the Cambrian is marked by a conglomerate bed. Quartz sands accumulated in Hiiumaa in the Lontova Age not far from the shoreline, pointing to a slow marine transgression and smooth topography. The transgression advanced from the east, where clayey sediments deposited on the East European Platform under quiet hydrodynamic conditions (Mens & Pirrus 1986, 1997b). At the end of the Lontova Age the sea regressed and extensive changes took place in the structure of the East European Platform.

The new transgression started in the Dominopol' Age in only the westernmost margin of the platform (Mens & Pirrus 1997b, p. 187, fig. 134c). The influx of clayey silts and clays was through gulf-like depressions. Frequent flooding and low stands of water are reflected in the composition of accumulated sediments. The Sõru and Lükati formations of the Dominopol' Stage are separated by a hiatus. The lower boundary of the Lükati Formation in Hiiumaa Island is marked by claystone and siltstone pebbles; the uppermost beds of the Dominopol' Stage show traces of weathering.

The sedimentation break and denudation were followed by new flooding in the Ljuboml' and Vergale ages (Mens & Pirrus 1997b, p. 189, fig. 135a). The basin widened from west to east. In the Ljuboml' Age quartz sand flats containing interbeds of coarser grains, pebbles and clayey silt were formed. In the Vergale Age slow marine transgression continued and the whole of the Baltic Basin was submerged (Vidal & Moczydłowska 1996). The influx of silt and clay material increased considerably. The lower boundary of the Vergale Stage (Irbe Formation) is marked by a violetish-grey clayey siltstone interbed; the upper boundary is erosional throughout the distribution area of the formation (Mens & Pirrus 1997a).

The late Cambrian Baltoscandian marine sedimentary basin was open to the west towards the Iapetus Ocean and extended to the Moscow Syneclise (Mens & Pirrus 1997b). Due to unstable hydrodynamic conditions and/or non-deposition periods during the Furongian (Upper Cambrian), and later post-Cambrian erosion of sediments, the Furongian section is incomplete in Estonia. The preserved deposits show also features of re-

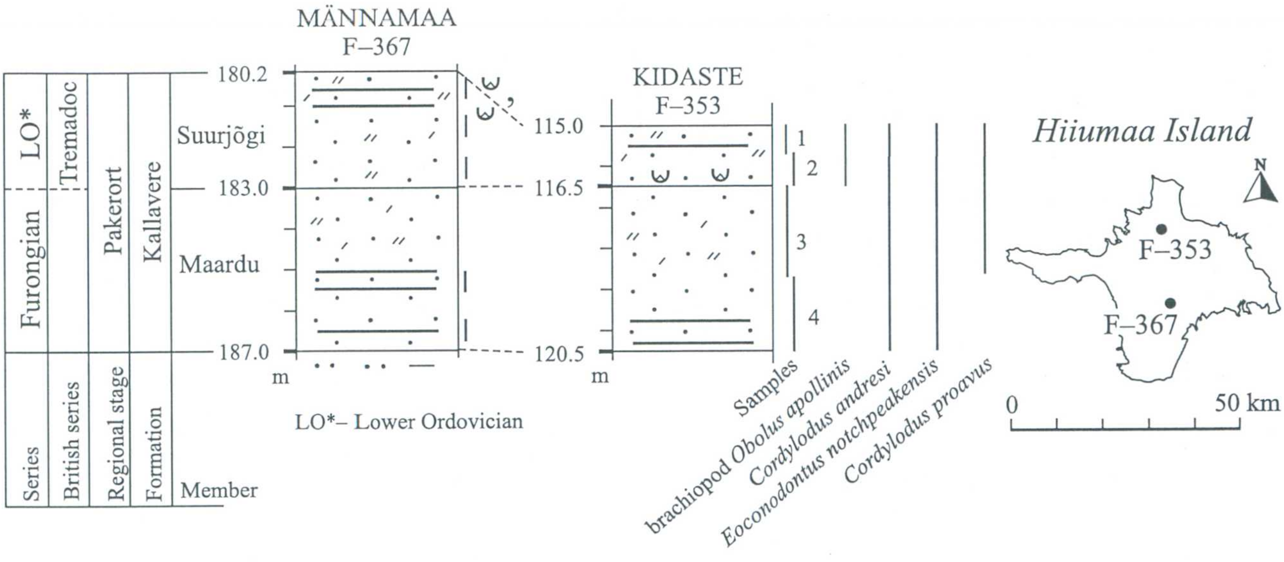


Fig. 3. Furongian (Upper Cambrian) and Lower Ordovician profile across the Männamaa (F–367) and Kidaste (F–353) core sections in Hiiumaa Island. Conodonts from the Kidaste section were found at 115.0–115.7 m (sample 1), 115.7–116.5 m (2), 116.5–118.7 m (3) and 118.7–120.5 m (4), the lingulate brachiopod was identified at 115.0–116.5 m. Refer to Appendix 1 for lithology.

deposition, which makes it difficult to define the palaeontological and lithological boundaries.

The **Furongian** is represented in the Männamaa (F–367) core by the Maardu Member of the Kallavere Formation of the Pakerort Stage (183.0–187.0 m; Appendix 1, sheet 8; core yield 40%). This unit consists of quartz sandstones with interlayers of kerogenous argillite (shale).

On the basis of the distribution of conodonts, lingulate brachiopods and acritarchs (Mens *et al.* 1993) in several key sections the Furongian of Estonia can be correlated with Swedish sections (Puura & Holmer 1993), but also basinwide Cambrian correlations are possible (Volkova 1990). The conodonts *Cordylodus andresi* Viira *et* Sergeeva, *C. proavus* (Miller) and *Eoconodontus notchpeakensis* (Miller), together with lingulate brachiopods *Obolus apollinis* (Eichwald), have been found at 115.0–120.5 m from the Kidaste (F–353) drill hole (Mens *et al.* 1993), located 17 km northwards from the Männamaa (F–367) section in Hiiumaa Island. A similar lithological interval occurs at 180.2–187.0 m in the Männamaa (F–367) core (Fig. 3). These conodonts have been identified in the Kallavere Formation (Mens *et al.* 1993; Heinsalu & Viira 1997) and point to sedimentation in the Furongian. The lower boundary of the *Obolus apollinis* brachiopod Zone falls within the *C. proavus* conodont Zone, and its upper boundary reaches the lowermost Ordovician in Estonian sections.

The upper boundary of the Furongian is problematic. Considering the lithological features and correlation data, we may suppose that the upper part of the Kallavere Formation (Pakerort Stage) is younger and was probably formed during the Lower Ordovician. According to recent studies (Heinsalu & Viira 1997), conodonts *Cordylodus intermedius* Furnish and *C. lindstromi* Druce *et* Jones, marking the lowermost Ordovician are not found in the Kidaste (F–353) section. In spite of the existing indirect data more detailed palaeontological investigations of the Männamaa (F–367) core section are needed to determine the Cambrian–Ordovician boundary, supposedly lying at a depth of 183.0 m (Fig. 3).

The presumable **Lower Ordovician** part of the Männamaa (F–367) section is represented by quartz sandstones, with bioclast-rich thin interbeds, and dark brown argillite (shale) in the upper part. These rocks correspond to the Suurjõgi Member of the Kallavere Formation (180.2–183.0 m; Appendix 1, sheet 8; core yield 55%), known only in a limited area in northwestern Estonia (thickness usually about 1 m, in places 5 m; Heinsalu & Viira 1997).

Sandstones of the Männamaa (F–367) section contain subangular to subrounded transparent quartz grains (less than 0.1 mm, in places up to 0.6 mm in diameter) with smooth surfaces. Grains of different size are mixed or sorted to inclined thin interbeds. In places quartz grains are yellow and coated with brittle black crusts of iron compounds and contain rare glauconite grains (up to 0.1 mm). Dark brown argillite layers comprise scattered pyrite aggregates, angular fragments of dolostone, and quartz grain (cemented by dolomite) interbeds containing shell fragments (see Appendix 3, D-77).

The lithology on the upper boundary of the terrigenous complex is very complicated in the Männamaa (F–367) section; generally sandstones are partly or entirely replaced by limestones (Appendix 1, sheets 7, 8). The boundary is marked by a 6 cm thick lens-shaped bed, where sub-angular dolostone clasts (80%; 3–5 mm across; contains calcite relicts) are cemented by argillite and dolomitic marlstone (Appendix 3, D-76). In places uniform clasts seem to form a rigid frame. Contact surfaces of dolostone and argillite (shale) are distinct. The lowermost 2 cm of the bed contain "ripped" dolostone fragments with visible horizontal bedding. This deformed layer is covered by a pyrite crust (thickness 3 mm) with cracks possibly filled with calc tufa. Pyrite aggregates (less than 3 mm across) are attached to argillite, and the pyrite (marcasite?) crust (thickness 3 mm) under the lens-shaped bed contains quartz grains (less than 0.2 mm across). The lens-shaped bed lies in sandy dolostone with well-sorted quartz sandstone patches, often without cement. Dolostone contains calcite relicts, subangular glauconite grains (up to 0.2 mm across; 1–2% of the rock), pyrite ooliths (less than 1 mm across; 1–2% of the rock; with rarely crushed, laminar ellipsoidal coatings) and aggregates, kerogen particles and rare skeletal fragments. Dolomite crystals are strongly zoned. Quartz grains (up to 0.3 mm across) are transparent, subrounded and grain surfaces are like polished.

The Lower Ordovician transition from terrigenous to carbonate sedimentation in the Männamaa (F–367) section is very condensed and interrupted by hiatuses. In the Suurjõgi Member mixed redeposited products of nearshore-marine and terrestrial environments are preserved. Quartz sandstone, argillite and carbonate have accumulated in separate parts, which developed through erosion on a loose sandy substrate during the regional transgressive-regressive events of shallow sea. The overlying sediments of Varangu, Hunneberg, Billingen (all Lower Ordovician) and Volkhov (Middle Ordovician) times (see Nõlvak 1997, p. 54, table 7) were removed during the period of regional denudation, which extended over the central and northern parts of Hiiumaa.

The **Middle Ordovician** (interval 168.4–180.2 m; Appendix 1, sheet 7; Appendix 3, D-69…75) is represented by dolostones and limestones of the Pakri, Loobu, Kandle, Väo and Kõrgekallas formations, corresponding to the Kunda, Aseri, Lasnamägi and Uhaku stages.

The Pakri Formation of the Kunda Stage is known only in northwestern Estonia. In the Männamaa (F–367) core (interval 179.2–180.2 m; Appendix 1, sheet 7) the lowermost part of the formation is represented by sandy, finely to medium-crystalline dolostone (Appendix 3, D-75) with calcite relicts, quartz sandstone (cemented by dolomite and calcite) patches, scattered kerogen particles and argillite pebbles. Rare disjointed argillaceous films are observed. Scattered skeletal fragments (1–2%) of shells and trilobites are in places limonitized. Pyrite (marcasite?) ooliths (less than 1 mm across; in the lower part up to 15% of the rock) are ellipsoidal and have laminar concentric coatings. Argillite pebbles (less than 3 cm across) are covered by pyrite crusts and contain pores, pyrite aggregates, glauconite and quartz grains. Some argillite fragments are angular. Transparent quartz grains (less than 0.3 mm across, rounded to subrounded) form in places more than 50% of the rock. Pyrite aggregates are scattered. Glauconite grains (less than 0.2 mm across; in places 10%) are subangular. The admixture of kerogen particles is usually attached to dolostone.

The middle and upper part of the Pakri Formation is represented by sandy finely crystalline and very finely crystalline limestone with frequent pyritized discontinuity surfaces (Appendix 3, D-74). Mainly coarse skeletal fragments (not oriented) of shells, trilobites, gastropods and crinoids are found; larger fragments are less rounded and crushed. Transparent rounded quartz grains (less than 0.5 mm across) form in places 30% of the rock. Pyrite aggregates (up to 5 mm across) are scattered and concentrated in surfaces. Rare glauconite grains (up to 0.1 mm across) and kerogenous patches are observed.

The limestones of the Pakri Formation are overlain by dolostones of the Loobu Formation in the Männamaa (F–367) core (interval 177.8–179.2 m; Appendix 1, sheet 7). The colour and primary texture of rocks changed during dolomitization. Dark brownish-grey dolostones contain phosphatized carbonate clasts, glauconite grains and about 10–30% skeletal fragments. The uppermost part of the Loobu Formation is represented by very finely crystalline limestone with skeletal fragments (about 25%, locally 40%; rounded, not oriented) of shells, trilobites, bryozoans and crinoids (Appendix 3, D-73). Subangular limestone clasts (up to 0.5 mm across) and phosphatized discontinuity surfaces are found. Glauconite grains (about 0.5 mm across) are concentrated in lenses and scattered. In places quartz grains (up to 0.5 mm across, mainly rounded) account for 20% of rock and rare sparry calcite patches occur. Vertical borings (depth up to 5 cm) at 178.0 m, proceeding from discontinuity surfaces, have pyritized edges and are filled with caliche? rich in grains: bioclasts and limestone clasts (up to 3 mm across).

The lower boundary of the Kandle Formation of the Aseri Stage (depth 177.8 m; Appendix 1, sheet 7) is marked by two rugged phosphatized discontinuity surfaces. The limestones of the formation are in places dolomitized (Appendix 3, D-72), slightly argillaceous and contain ellipsoidal iron ooliths with laminar concentric coatings. Iron ooliths (up to 1.0 mm across, locally about 30% of the rock) have often carbonate crusts on the outer surface. They are concentrated in patches and occur in different positions together with rare carbonate ooliths. Fine skeletal fragments (about 30%; rounded, crushed, not oriented) belong usually to crinoids, bryozoans, shells and cephalopods and are rarely recrystallized. Limonitized discontinuity surfaces are wavy and rugged.

The lowermost part of the Väo Formation (Appendix 1, sheet 7) contains rare calcareous ooliths. Grey to brownish-red mottled dolomitized limestones and dolostones in the lower part of the formation are overlain by light grey limestones. Rounded, crushed and not oriented skeletal fragments form mainly 10–25% of the rock and are often recrystallized, rarely pyritized and selectively silicified. More than 20 weak discontinuity surfaces are phosphatized, in the upper part often pyritized. A phosphatized and pyritized hardground complex, penetrated by vertical borings (depth 9 cm), occurs on the upper boundary of the formation, at 170.0 m. The borings have pyritized edges and sparry calcite crystals in the central part. Locally burrowed filling (seemingly composed of mud portions) contains subangular limestone clasts and less bioclasts than host rock (Appendix 3, D-71).

The hardground complex is overlain by medium- to thin-bedded, locally slightly argillaceous limestones of the Kõrgekallas Formation (interval 168.4–170.0 m; Appendix 1, sheet 7), intercalated by marlstone interbeds. The middle part of the formation is greenish-grey and indistinctly nodular. Rounded fine skeletal fragments (less than 25%) are often crushed, recrystallized, pyritized, not oriented. The discontinuity surfaces are pyritized and phosphatized. The thickness of the Kõrgekallas Formation decreases steadily from about 15 m in the eastern sections in North Estonia (Hints 1997; Põldvere 1999; Põldvere & Saadre 2006a) to 1.6 m in the Männamaa (F–367) section. The clay content of the rocks changes in a similar way: the content of marlstone beds (30–60% in eastern sections) decreases and medium- and highly argillaceous limestones disappear. The thin Kõrgekallas Formation in Hiiumaa Island (Suuroja *et al.* 1991, 1993) has specific lithological features and erosional lower and upper boundaries.

The long denudation period in Hiiumaa at the beginning of the Ordovician evidently ended with redeposition of older sediments in the Middle Ordovician. Hardground features, oolith accumulation, influx of quartz grains and roundness of carbonate particles show transition from high- to low-energy environments under inner to middle shelf conditions, with frequent fluctuation of sea level. The considerably thinned section of the Männamaa (F–367) core, cut by numerous erosional gaps, represents the northern marginal area of the North Estonian Confacies Belt (Fig. 4).

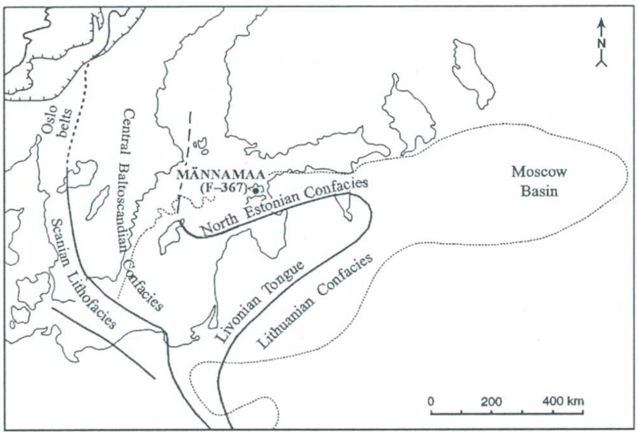


Fig. 4. Baltic Ordovician confacies belts (after Jaanusson 1995, modified from Nõlvak 1997).

The **Upper Ordovician** (interval 46.5–168.4 m; Appendix 1, sheets 2–7) limestone and rare marlstone complexes belong to the Pihla, Tatruse, Kahula, Hirmuse, Rägavere, Paekna, Saunja, Kõrgessaare, Moe, Adila and Ärina formations, corresponding to the Kukruse, Haljala, Keila, Oandu, Rakvere, Nabala, Vormsi, Pirgu and Porkuni stages.

The lower boundary of the Pihla Formation (interval 165.2–168.4 m; Appendix 1, sheet 7) is marked by a discontinuity surface, which is covered by a disjointed pyrite crust, cut by vertical U-shaped formations filled with argillaceous limestone and bioclasts. Scattered glauconite (or sulphide mottles?) occurs below and kukersite particles containing burrows are found above the discontinuity surface. The limestones of the formation are locally slightly kerogenous, often bioturbated, pyrite-mottled and contain mainly fine skeletal fragments forming on average 10–30% of the rock. Rounded, not oriented clasts of echinoderms, trilobites, brachiopods, ostracods, bryozoans, gastropods, etc. are often pyritized, recrystallized and selectively silicified (Appendix 3, D-66…69). Discontinuity surfaces on the upper boundary of the Pihla Formation (165.2 m) are covered by pyrite aggregates and excavated. The lower discontinuity surface at 165.25 m is strongly corroded and eroded by borings of organisms (visible depth up to 26 cm), which have pyritized edges often covered with pyrite crusts (Appendix 3, D-67). The inner part of borings has usually larger crystal size and contains kerogen particles. This surface is known as a marker of the upper boundary of oil shale bed III in northeastern sections of Estonia (Suuroja *et al.* 1991, 1993). Thus, the upper part of the Kukruse Stage, represented by an about 3.5 m thick limestone complex in the Kerguta (565) core (about 180 km eastwards; Põldvere & Saadre 2006a), is missing in the Männamaa (F-367) core (see also Nõlvak in this volume).

The discontinuity surfaces are directly overlain by slightly argillaceous limestones of the Tatruse Formation (interval 160.2–165.2 m; Appendix 1, sheet 6), containing quartz siltstone (cemented by carbonate) interbeds at 164.8–164.9 m (see Appendix 3, D-65). Microbedded siltstone is intercalated by carbonate and clay, and sparry calcite fractures with pyrite are observed. The siltstone beds are underlain by a 2 cm thick layer of bituminous limestone and overlain by bioturbated (60–70% of rock) limestone (thickness 5 cm). Burrows (up to 3 mm across) are horizontal, with limestone filling containing 1–2% bioclasts and little pyrite. Borings with geopetal fabric are also found. The burrowed layer is covered by an indistinct bedding plane overlain by a clay-poor layer. The described 10 cm thick interval is part of the ejecta-influenced matter that spread concentrically around the Kärdla crater in Hiiumaa Island (Suuroja *et al.* 2002; Suuroja & Suuroja 2006) and belongs to the Kärdla Formation in Estonian sections (Põldvere & Suuroja 2002). In detail it has been studied in the Soovälja (K-1) core, located inside the circular Kärdla impact structure (Põldvere & Suuroja 2002). The distance between the Männamaa (F-367) and Soovälja (K-1) drill holes is about 17 km.

The ejecta-influenced matter is covered by limestone of the Tatruse Formation, which is mainly slightly argillaceous and contains bioclasts (rounded, crushed, not oriented), locally up to 50%. Fine skeletal fragments of crinoids, trilobites, shells and bryozoans are often recrystallized, pyritized, selectively silicified and form in places cone-shaped patches (about 10 mm across). Burrows (about 3 mm across) are horizontal or sloping at an angle of up to 45°, with argillaceous filling (Appendix 3, D-64, D-65). One altered K-bentonite bed has been identified at 160.8 m (thickness 1 cm) in the Tatruse Formation of the Haljala Stage. Volcanic beds have formerly been determined on this level also in the Soovälja (K-1) core (Kiipli & Kallaste 2002).

The limestones of the lowermost part of the Kahula Formation (Appendix 1, sheet 6) intercalate with eleven mainly 1–13 cm thick K-bentonite beds (see Kiipli *et al.* in this volume and also Appendix 2). K-bentonite, which is widespread in Estonian sections at the lower boundary of the Keila Stage, lies at 156.9–157.3 m in the Männamaa (F-367) core. Vertical calcite veins rich in pyrite, penetrating the limestones of the Jõhvi Substage, occur between volcanic beds at 157.7–158.6 m. The veins are up to 3 cm thick and have clear contacts with limestone.

The main part of the Kahula Formation (interval 141.0–160.2 m; Appendix 1, sheet 6) is represented by intercalation of variously argillaceous limestones and calcitic marlstones. The marlstone interbeds of the Vasavere Member (interval 158.6–160.2 m; Appendix 1, sheet 6) contain spicules of the sponge *Pyritonema subulare*. In the middle and upper parts of the formation marlstone beds form up to 50% of the section. Burrows (about 1 mm across) are often horizontal in marlstone and at an angle of about 45° in limestone. Rounded bioclasts (10–60%; Appendix 3, D-53...63) are coarser and often oriented parallel to bedding in marlstone beds. Locally skeletal fragments in limestone layers are accumulated in cone-shaped formations. They have distinct edges and are up to 6 cm deep and up to 4 cm wide in the upper part. The filling contains skeletal fragments (about 70%, up to 2 mm across) and rare limestone clasts (up to 1 mm across), cemented in the upper part by sparry calcite and in the lower part by micrite containing silt-sized quartz. Some shells have geopetal filling. All grains are rounded, sorted, not oriented and rarely selectively silicified. Slickenside features and inclined beds of host rock are found on the outer border of a cone-shaped formation and pyrite aggregates near the base.

A specific surface, known over a wide area in northern Estonia, is observed on the lower boundary of the Hirmuse Formation in the Männamaa (F-367) core. An uneven pyritized discontinuity surface at 141.0 m (depth of impregnation 15 cm) is cut by erosional gullies (visible depth up to 5 cm), filled with impregnated limestone clasts (about 4 mm across) and bioturbated marlstone (Appendix 3, D-53). The overlying Hirmuse Formation is represented by microbedded calcitic marlstone with indistinct interlayers of variously argillaceous, dolomitized and bioturbated limestone comprising mainly fine skeletal fragments (locally up to 30%) of shells and crinoids. The fossil fragments are rounded, crushed, rarely oriented parallel to bedding. Burrows are mainly horizontal and only observed in limestone layers. Rare subangular, silt-sized quartz grains and pyrite aggregates (about 2 mm across) are concentrated in marlstone layers; scattered grains are found in limestone.

The discontinuity surface on the lower boundary of the Rägavere Formation (depth 138.8 m; Appendix 3, D-51) is covered by a pyrite crust (thickness about 1 mm), in places consisting of two laminae. Sparry calcite fractures extend through the impregnated part, and pyrite aggregates, burrows and eroded gullies (depth 7 cm) are common.

The limestones of the Rägavere Formation (interval 117.4–138.8 m; Appendix 1, sheet 5) have been divided (from below) into the Tõrremägi, Kiideva, Piilse and Tudu members. The lowermost Tõrremägi Member belongs to the Oandu Stage, and the Kiideva, Piilse and Tudu members form the Rakvere Stage. The boundary of these stages is marked by a wavy pyritized discontinuity surface.

In general, the Rägavere Formation is represented by very finely crystalline and crypto- to microcrystalline limestones (Appendix 3, D-45...51) with rare bioclasts (mainly up to 25%; often fragments of calcareous algae dominate), and sparry calcite fractures and patches. The rocks of the Tõrremägi Member are slightly argillaceous, often bioturbated and contain usually scattered pyrite grains and pyritized bioclasts. The limestones of the Kiideva Member contain weak indistinct pyrite mottles, contrary to the overlying rocks of the Piilse Member, which are characterized by small black pyrite mottles. The limestones of the Tudu Member are characterized by wavy and smooth pyritized discontinuity surfaces (Appendix 2) whose weak rock impregnation reaches 1–5 cm below the surfaces. Also thin kerogen-bearing lime- and marlstone interbeds are present. In the uppermost part, close to the lithostratigraphical boundary of the Rägavere and Paekna formations, a kukersite oil shale bed (thickness 5 cm) is found at 117.7 m. This bed is widespread in northeastern Estonia, where the argillaceous rocks of the Paekna Formation appear usually 0.1–0.7 m higher (Nõlvak 1987).

In the limestones of the Paekna Formation (interval 108.0–117.4 m; Appendix 1, sheets 4, 5) two complexes are distinguished. The lower complex (interval 113.2–117.4 m) is represented by unusually pure limestones with thin dark greenish-grey marlstone interbeds. Typical light beigish-grey very finely crystalline and microcrystalline interbeds with sharp borders, which intercalate with argillaceous limestone and are characteristic of the easternmost sections, are very hard to distinguish. The clay content of light grey host rock in the Männamaa (F-367) core is very low, only dark greenish-grey marlstone interbeds are more clayey than in the underlying Rägavere Formation. Peculiar burrowed kerogenous limestone interlayers (bioclasts oriented parallel to bedding) are found in the lower part of the complex and fine glauconite grains on the bedding planes in its uppermost part. Although lithology of the lower complex in the Männamaa (F-367) core and other Hiiumaa sections generally (Suuroja *et al.* 1991, 1993; Põldvere & Saadre 2006a) differs from that of the easternmost Estonian sections, it is believed to correlate with the lower part of the Paekna Formation, but further investigation is needed (see also Nõlvak in this volume). The upper boundary of the complex is marked by four uneven pyritized discontinuity surfaces.

The upper complex of the Paekna Formation (interval 108.0–113.2 m; Appendix 1, sheets 4, 5) is represented by variously argillaceous limestones containing 5–20% marlstone interbeds. In the upper part of the complex exceptional beigish-grey bioturbated micro- and cryptocrystalline limestone interbeds are found. The beds at 108.50–108.66 m contain borings (about 3 cm across) formed in rigid rock (Appendix 3, D-40). The repeatedly bioturbated filling includes pyrite crystals, and about 10% crushed skeletal and carbonate fragments. The limestone cover of the boring-rich interval is intercalated by marlstone films and contains rounded skeletal fragments (about 10%) oriented parallel to bedding.

The overlying micro- and cryptocrystalline limestones of the Saunja Formation (interval 104.0–113.2m; Appendix 1, sheet 4) contain stylolites, sparry calcite fractures and bioclasts (not oriented, crushed) less than 10% (Appendix 3, D-36...39). The colour, texture and composition of the rock change on the lower boundary of the formation. The upper boundary is marked by a hardground, which is phosphatized, eroded, bioturbated, rich in pyrite aggregates and covered by pyritized bioclasts and single subangular limestone fragments (< 10 mm across).

The bioturbated, variously argillaceous limestones of the Kõrgessaare Formation (interval 87.0–104.0 m; Appendix 1, sheet 4) contain marlstone interbeds forming 5–40% of the section. Contacts between marlstone and argillaceous limestone are usually indistinct. The bioclasts (mainly 10–25%) are rounded, crushed, not oriented, and in places deformed, pyritized and recrystallized (Appendix 3, D-32...36). The lower, less argillaceous part of the formation (interval 98.0–104.0 m) is cut by hardgrounds. The brownish tint of the lower hardground, denoting a zone of phosphatization and reworked subangular limestone fragments, indicates submarine lithification. Disturbed bedding and a vertical slickenside surface are found near the hardgrounds in argillaceous limestone. The overlying calcitic marlstones and bioturbated variously argillaceous limestones (interval 92.4–98.0 m; Appendix 1, sheet 4) form the most clay-rich transgressive part of the Kõrgessaare Formation. Higher, at 88.8–88.9 m are found rare bright green glauconite grains (about 0.5 mm across). In the same place there occurs an eroded gully (width 3.5 cm) filled with limestone, subrounded limestone clasts (about 2 mm across, derived from host rock) and skeletal fragments, which are outlined by glauconite grains (about 0.1 mm across). The occurrence of glauconite and high clay content are more characteristic of the Tudulinna Formation (Vormsi Stage), distinguished in central Estonia. Usually the features of the two formations are laterally interweaved in the southern area of the Kõrgessaare Formation over the Estonian territory (Hints & Meidla 1997).

Often bioturbated limestones of the Moe Formation (interval 68.2–87.0 m; Appendix 1, sheets 3, 4) are mainly finely crystalline and very finely crystalline in the Männamaa (F–367) core (Appendix 3, D-24…31). Marlstone films, interbeds (thickness 0.2–1 cm, rarely 2–5 cm) and nodules make up 5% of the section. Calcite-filled fractures, stylolites and rare pyritized discontinuity surfaces are found. Skeletal fragments (mainly 10–25%) are oriented parallel to bedding in marlstone layers and patches. In limestone they are rounded, not oriented and often selectively affected by silification near the hardgrounds at 79.4–79.6 m. Calcareous algae *Palaeoporella* are abundant, especially in the lower part of the formation. Bituminous patches and films occur close to bedding planes in the middle part of the Moe Formation.

In the overlying bioturbated micro- to very finely crystalline limestones of the Adila Formation (interval 52.2–68.2 m; Appendix 1, sheet 3) marlstone interbeds make up 5–20% of the section. Rounded skeletal fragments (mainly 10–25%) are often accumulated in patches and layers; larger fragments (0.5–3 mm across) are locally oriented and cemented by sparry calcite, and found mainly in the upper part of the formation (Appendix 3, D-14…23). Sometimes pyrite crystals are concentrated under smooth and uneven discontinuity surfaces without any changes in rock texture. The argillaceous limestones of the uppermost part (Kabala Member at 52.2–56.0 m; Appendix 1, sheet 3) comprise silt-sized quartz grains forming 1–10% of the rock.

The Upper Ordovician section ends with the Ärina Formation of the Porkuni Stage. The thickness and succession of different lithostratigraphic units of the Porkuni Stage are variable in Estonia (Hints & Meidla 1997; Hints *et al.* 2004). In the Männamaa (F–367) section (interval 46.5–52.2 m; Appendix 1, sheet 2) four members are distinguished in the Ärina Formation (from below): Röa (argillaceous dolomitized limestones and dolostones), Vohilaid (bioclast-rich dolomitized limestones), Siuge (bituminous, argillaceous limestones and calcitic marlstones) and Tõrevere (biohermal limestones). The limestones of the Ärina Formation comprise quartz grains that are concentrated in patches and layers. The content and size of quartz grains increase upwards: rounded and silt-sized grains are found in the lower part (about 10–20% of rock); in the upper part silt- and sand-sized grains make locally up to 50% of the layer and are in places subangular (Appendix 3, D-6…13). The size of bioclasts is various (0.5–50 mm across), but obviously increases upwards. Bioclasts are often cemented by sparry calcite. In the upper part of the Röa Member bioclasts are oriented parallel to bedding; in the Tõrevere Member they are locally silicified and occur together with carbonate clasts. The biohermal limestones of the Tõrevere Member (uppermost Ordovician) are overlain by micro- and very finely crystalline limestones of the Koigi Member (lowermost Silurian). The lithologically distinct upper boundary of the Ärina Formation (Ordovician) is marked by a wavy pyritized discontinuity surface in the Männamaa (F–367) core (Appendix 1, sheet 2).

In general the accumulation of Late Ordovician carbonate sediments on Estonian territory has been connected with drift of the Baltica Palaeocontinent northwards closer to the equator (Nestor & Einasto 1997) and sedimentation in middle and inner shelf conditions (Enos 1983; Wilson & Jordan 1983) was mainly related to eustatic sea level fluctuations and climate changes. Pure lime muds (see Rägavere and Saunja formations) were deposited in the conditions of epeiric seas without significant barriers. Fauna is sparse due to shoal water with large temperature fluctuations and poor circulation of water.

Periodic incursions of clay together with skeletal fragments reflect erosion and deeper environments. The mainly uniform content and roundness of grains in the limestones point to a stable energy level of the basin. The transport of skeletal grains (brachiopods, ostracods, bryozoans, corals, algae, echinoderms, trilobites, gastropods, sponges) derived from several localized organic buildups and small reef mounds proceeded from waves and additionally, from tide movements. The occurrence of rugose coral, brachiopod, bryozoan and trilobite fragments indicates normal marine salinity (Wilson & Jordan 1983). Bioclasts-containing shelf sediments are mainly bioturbated. Different directions of burrows refer to subtidal conditions, while vertical burrows are more characteristic of hardened intertidal areas. Micritization of carbonates, borings, metal-compound staining and encrustation show periods of slow accumulation. The discontinuity surfaces and subtidal hardgrounds, marked by weathering and features of early diagenesis, point to periods of non-deposition probably in inner shelf environments. Stylolites, fractures and geopetal fillings as late diagenetic structures are observed. The end-Ordovician hiatus resulting from the pre-Silurian shallowing is connected with the Gondwana glaciation (Brenchley *et al.* 2003). This non-deposition period was followed by Early Llandovery glacio-eustatic rise of sea level and deposition of pure lime mud (Nestor & Einasto 1997).

The lower boundary of the **Llandovery** is marked by a wavy pyritized discontinuity surface in Hiiumaa sections. In the Männamaa (F-367) core variously argillaceous Silurian limestones with marlstone interbeds are represented by the Varbola and Tamsalu formations corresponding to the Juuru Stage (interval 29.0–46.5 m; Appendix 1, sheet 2). The lowermost microcrystalline and very finely crystalline limestones of the Koigi Member (interval 46.0–46.5 m; Appendix 3, D-4, D-5) on the Ordovician rocks are widespread in northern Estonia (Nestor 1997).

The Varbola Formation (interval 37.0–46.5 m) is represented by nodular and indistinctly bedded, very finely crystalline limestones (bioclasts 10–40%; Appendix 3, D-3) with calcitic marlstone interbeds. The Tamsalu Formation (interval 29.0–37.0 m) comprises limestones of the Tammiku Member, which are rich in shells of the brachiopod *Borealis borealis* (40–60% in some layers; Appendix 3, D-2), and limestones of the Hilliste Member, abounding in fragments of crinoids, corals and stromatoporoids (10–60%; Appendix 3, D-1).

The **Quaternary** cover in the Männamaa (F-367) core is 29.0 m thick (Appendix 1, sheets 1, 2), but only about 3 m of the core is available. The Upper Pleistocene tills and varved clay (Baltic Ice Lake) layers are covered by Holocene deposits. The boundaries of complexes were revealed by gamma logging (Appendix 4) and data from neighbouring sections.

DISTRIBUTION OF ORDOVICIAN CHITINOZOANS

A total of 196 samples from the Ordovician and lowermost Silurian of the Männamaa (F-367) core were processed and studied for chitinozoans (Appendix 5). The work was carried out at the Institute of Geology at Tallinn University of Technology (IG TUT) and financially partially supported by the Estonian Science Foundation (grants Nos 7640 and 7674). Chitinozoans (stored at the IGTUT) were collected by J. Nõlvak in three sets, in 1991, 1994 and 2007. The samples varied in size from 300 to 600 g, in special series (intervals 156.6–157.4 m and 164.45–165.16 m) from 50 to 200 g. In addition, Aasa Aaloe took samples to characterize the sedimentological features of rocks (Appendix 3). Almost all samples were productive and yielded a rich assemblage of acid-resistant microfossils (chitinozoans, acritarchs, scolecodonts, conodonts, foraminifers and others). Only four samples from the Ordovician–Silurian boundary beds were barren. Usually well to excellently preserved chitinozoan specimens were damaged by secondary dolomitization in the rocks of the Kunda and lower Lasnamägi stages (see Appendix 1, sheet 7). To achieve satisfactory results from borehole cores, especially from the sections of the North Estonian Confacies Belt (Fig. 4), separate series of samples of different sizes are needed. Samples of 200–300 g are too small for conodonts, foraminifers and lingulate brachiopods, but too large for acritarchs. Yet, larger samples taken from such condensed core sections like, for example, beds of the Kukruse Age and older in the Männamaa core, will represent a too long period of sedimentation and too mixed populations of microfossils.

Earlier data on chitinozoan distribution within some stratigraphically important intervals are partly published in Grahn *et al.* (1996) and Hints & Nõlvak (1999). In the Männamaa (F-367) section 99 chitinozoan taxa were identified. Their distribution is given in Appendix 6, where taxa under open nomenclature are designated as sp. 1 and sp. 2, which are identical to those found in the Kerguta (565) and other earlier published sections (see Nõlvak & Bauert 2006, pp. 9–11; app. 9). Almost all stratigraphically more important chitinozoan zones (Nõlvak *et al.* 2006, 2007) were established (Appendix 6), enabling reliable subdivision of the entire Ordovician succession from that palaeogeographically important area in northwestern Estonia.

The beds in the North Estonian Confacies Belt (Fig. 4) have some specific features: (1) the lithofacies belts, which are directed roughly sublatitudinally, thin out considerably westwards (Männil 1966; Jaanusson 1973, fig. 7), Lower Ordovician beds are locally absent and the Middle Ordovician succession is condensed; (2) in many levels the clay content of carbonate rocks is decreasing westwards, and less flattened specimens of chitinozoans are usually from limestones with very small amounts of terrigenous material; (3) hiatuses denote lack of deposits, but do not necessarily imply subaerial conditions. The Early Ordovician hiatus, which is fixed in the Gotska Sandön area (Jaanusson 1973, fig. 7), is followed also in the sections of the central part of Hiiumaa Island. Most probably there exists a narrow belt where sediments are absent (see Põldvere *et al.* in this volume). However, this gap is fulfilled and the whole succession changes relatively quickly to the northwest (e.g. in the Kõrgessaare core, unpublished data by L. Põlma; about 20 km from the Männamaa (F-367) drill hole) and south (Valgu (F-363) core; about 10 km from the Männamaa (F-367) drill hole). In the Lower Ordovician part of the Valgu (F-363) section, for example, 5 m thick glauconite-rich sandstones covered by 0.6 m thick glauconite-bearing limestones lie between sandstones of the Pakerort Stage and dolostones of the Kunda Stage, while sediments of the Varangu? and Volkhov stages are absent (Suuroja *et al.* 1991).

Contrary to acritarchs (see Uutela in this volume), no remains of chitinozoans were recovered from the upper Kallavere sandstones of the Pakerort Stage (below the 180.2 m level). It means that Early Ordovician chitinozoan fauna is unknown in the Männamaa (F-367) section.

Middle Ordovician

The stratigraphical break in the Lower Ordovician rocks of the Männamaa (F-367) section is succeeded by unique lithology of the Pakri Formation, represented by the oldest kerogenous limestones and dolostones in Estonia, with quartz sandstone patches, argillite pebbles and black fragile iron ooliths (Appendix 1, sheet 7). Such ooliths are very rare in the East Baltic. The Pakri beds contain besides the graptolite *Didymograptus pakrianus* Jaanusson also chitinozoans, among these *Cyathochitina hunderumensis* Grahn, Nõlvak *et* Paris, which is up to now known only from the lowermost Kunda Stage (Hunderumian Substage; see Grahn *et al.* 1996). This substage is considered to be missing in northern Estonia (Männil 1966; Jaanusson 1973) and Pakri beds are correlated with the middle part of the Kunda Stage. Thus, it indicates that pebbles from some older beds could be present in this layer and the chitinozoan association is mixed, or alternatively, this species has a wider vertical range than known earlier.

The Loobu Formation (dolostones and limestones) corresponds to the upper *Cyathochitina regnelli* Zone with poorly preserved *Lagenochitina esthonica* Eisenack and other species (Appendix 6, sheet 3), corroborating the Kunda Age as in the Taga-Roostoja (25A) and Kerguta (565) cores (Nõlvak 1999, app. 6; Nõlvak & Bauert 2006, app. 9). The absence of *Linochitina* sp. 1 from the Männamaa (F-367) section and its presence in the Kerguta (565) and Rapla cores show that the youngest Kunda beds are also in a hiatus, emphasized by discontinuity surfaces at a depth of 177.8 m and below.

The very condensed section of the Kandle Formation between lithologically very distinct gaps (upper part of the *C. regnelli* Zone is absent) is represented by limestones with yellowish-brown goethite ooliths. Rich and well-preserved chitinozoan fauna belongs to the *C. sebyensis* Subzone of the *L. striata* Zone. Specifically, specimens in the upper part of the *L. striata* (Eisenack) range have a brownish cover on the vesicle wall (marked as cf. in Appendix 6, sheet 3), but as other features are similar to those of typical forms, these specimens are not separated in the present review but tentatively referred to this species.

The interval of dolomitized limestones and dolostones at 175.7–177.0 m contains some very poorly preserved chitinozoans, therefore the lower boundary of the *C. clavaherculi* Subzone is not very precise (Appendix 6, sheet 3). The exact level of the Pae Member (Väo Formation of the Lasnamägi Stage) (Hints 1997), well recognized by dark to brownish-grey dolostones (thickness usually up to 0.5 m) in the Tallinn stratotype area, is also unclear in the Männamaa (F-367) core. Most probably it lies within the strongly dolomitized part (Appendix 2). Higher within the Väo Formation (lithologically very similar to the well-known North Estonian "building limestone"), about ten species appear in relatively rich and well-preserved chitinozoan assemblages, but among them no good marker for the lower boundary of the Uhaku Stage could be followed.

During the last decades this boundary has been defined by the appearance of the graptolite *Gymnograptus linnarssoni* (Moberg) or conodont *Eoplacognathus robustus* Bergström (Männil 1976, 1986; Nõlvak 1997; Nõlvak *et al.* 2006). However, for species level identifications these fossils were not recovered from the Männamaa (F-367) core, and at the moment the base of the Uhaku Stage cannot be reliably defined biostratigraphically. The same difficulties are encountered in the whole of the North Estonian Confacies Belt (Fig. 4). Despite their low frequency the named fossils are the only known criteria useful in the entire Baltoscandian basin. A hint could be given that this boundary lies within the complex of weakly phosphatized discontinuity surfaces, about 2–3 m below the "strong" hardgrounds at a depth of 170.0 m, near the appearance of *Conochitina* aff. *dolosa* Laufeld, which has been found up to now only from the Uhaku Stage, e.g. in the Kerguta (565) section (Nõlvak & Bauert 2006). The *C. clavaherculi* Subzone ranges also to the basal beds of the Uhaku Stage (Nõlvak & Grahn 1993).

Condensed slightly argillaceous rocks of the Kõrgekallas Formation provide a chitinozoan assemblage typical of the *Conochitina tuberculata* Subzone, except for rare specimens of *Conochitina tigrina* Laufeld, which are older than earlier finds (see Grahn *et al.* 1996). The boundary between the *L. striata* and *L. stentor* zones lies within the uppermost beds of the Kõrgekallas Formation, below its upper lithological boundary in the Männamaa (F-367) section (Appendix 6, sheet 3) and marks the base of the upper lithological complex (Erra Member in Männil 1986) in many North Estonian sections, including the Taga-Roostoja (25A) and Kerguta (565) cores (Nõlvak 1999; Nõlvak & Bauert 2006).

Of particular interest is the appearance of the *Nemagraptus gracilis* (Hall) specimen with cladial branches at a depth of 169.9 m within the *C. tuberculata* Subzone, but together with the uppermost finds of *L. striata* (Eisenack). Thus *N. gracilis* appears a little earlier than known up to now (Nõlvak & Goldman 2007) or has the same age with its earliest occurrence in the Savala core (in northeastern Estonia; Nõlvak & Goldman 2004, marked as the lowest *Nemagraptus* sp. in fig. 1). This shows that in spite of earlier optimistic suggestions (Nõlvak & Goldman 2004), very rare specimens, especially graptolites, occur often too sporadically in the East Baltic carbonate facies to be reliable local biostratigraphical markers. However, these species are very important global criteria in comparisons between basins (Nõlvak *et al.* 2007).

Upper Ordovician

The limestones of the Pihla Formation in the Männamaa (F-367) section correlate with the lower and middle parts of the Viivikonna Formation (Kiviõli and Maidla members, see Hints 1997) in the stratotype succession of the Kukruse Stage. The upper part of the Peetri Member, approximately above the level of the so-called Tapa deposit (= oil shale bed III) in East Estonia (see Põldvere & Saadre 2006), is in a gap marked by very strong discontinuity surfaces (Appendix 3, D-67). This idea (see also Suuroja *et al.* 1991, 1993) can be proved by the absence of *Pistillachitina* sp. 1, *Lagenochitina* sp. A aff. *capax* and *Cyathochitina* sp. (as *giraffa* nom. nud.; Grahn & Nõlvak in press) from the Pihla beds, which according to earlier data appear within the upper part of the Kukruse Stage (e.g. in the Peetri Member of the Taga-Roostoja (25A) and Kerguta (565) cores; Nõlvak 1999; Nõlvak & Bauert 2006). In the Männamaa (F-367) section these species appear in the basal Haljala beds (Appendix 6, sheet 3). The *Eisenackitina rhenana* Subzone of the *L. stentor* Zone supports the Kukruse Age assignment of beds in the interval 165.2–168.4 m, despite rare finds of the latter species. This species is often common also in younger Kukruse beds in other sections. It is well known that the large hiatus in the topmost Kukruse Stage will be southwards fulfilled with sediments having some specific faunas (chitinozoans, graptolites; Nõlvak 1972; Männil 1986; Nõlvak & Goldman 2007).

The gap, marked by discontinuity surfaces with over 25 cm deep bioerosional borings at the top of the Kukruse limestones at a depth of 165.2 m, is overlain by more argillaceous limestones with a remarkable assemblage of chitinozoans. The basal beds of the Tatruse Formation contain zonal *Armoricochitina granulifera* Nõlvak & Grahn and *Angochitina curvata* Nõlvak & Grahn, indicating the oldest sediments of the Haljala Age (Nõlvak & Grahn 1993). They occur together in a 5 cm thick sample (165.11–165.16 m), while the next sample (165.07–165.11 m) contains only *A. curvata* (Fig. 5). These zones are often very thin as in the Fjäcka section in Sweden (Nõlvak *et al.* 1999), and bed-by-bed sampling would be useful.

Detailed sampling (Fig. 5) was conducted below and above the layer affected by the **Kärdla meteorite impact** (164.8–164.9 m; see Põldvere *et al.* in this volume). Twenty samples had different sizes; the larger ones (400–500 g) were divided into smaller samples of at least 50 g. As suspected, the impact event itself had no influence on the species composition of chitinozoans, except for two samples from limestones with quartz grains and other ejecta-influenced matter (164.82–164.87 and 164.87–164.93 m). They were poor, the preservation of chitinozoan vesicles was worse than in the other samples and many larger specimens were crushed. In general, such sampling demonstrates that the species composition is rather stable and smaller samples contain very similar associations. More detailed information was needed to follow the precise distribution of stratigraphically important taxa, especially zonal forms, as was done in Grahn *et al.* (1996, fig. 9).

The well defined and widely distributed range zone of *Lagenochitina dalbyensis* (Laufeld), followed in almost all areas in the Baltoscandian Ordovician basin, occurs above the impact-influenced layers. Chitinozoan fauna is very similar to that of the Paluküla (383) and Soovälja (K-1) cores (Grahn *et al.* 1996, fig. 8; Nõlvak 2002, fig. 4), located inside the Kärdla impact crater, except for clearly reworked specimens in the latter section.

The absence of the succeeding *Belonechitina hirsuta* (Laufeld) Zone is noteworthy. The beds corre-

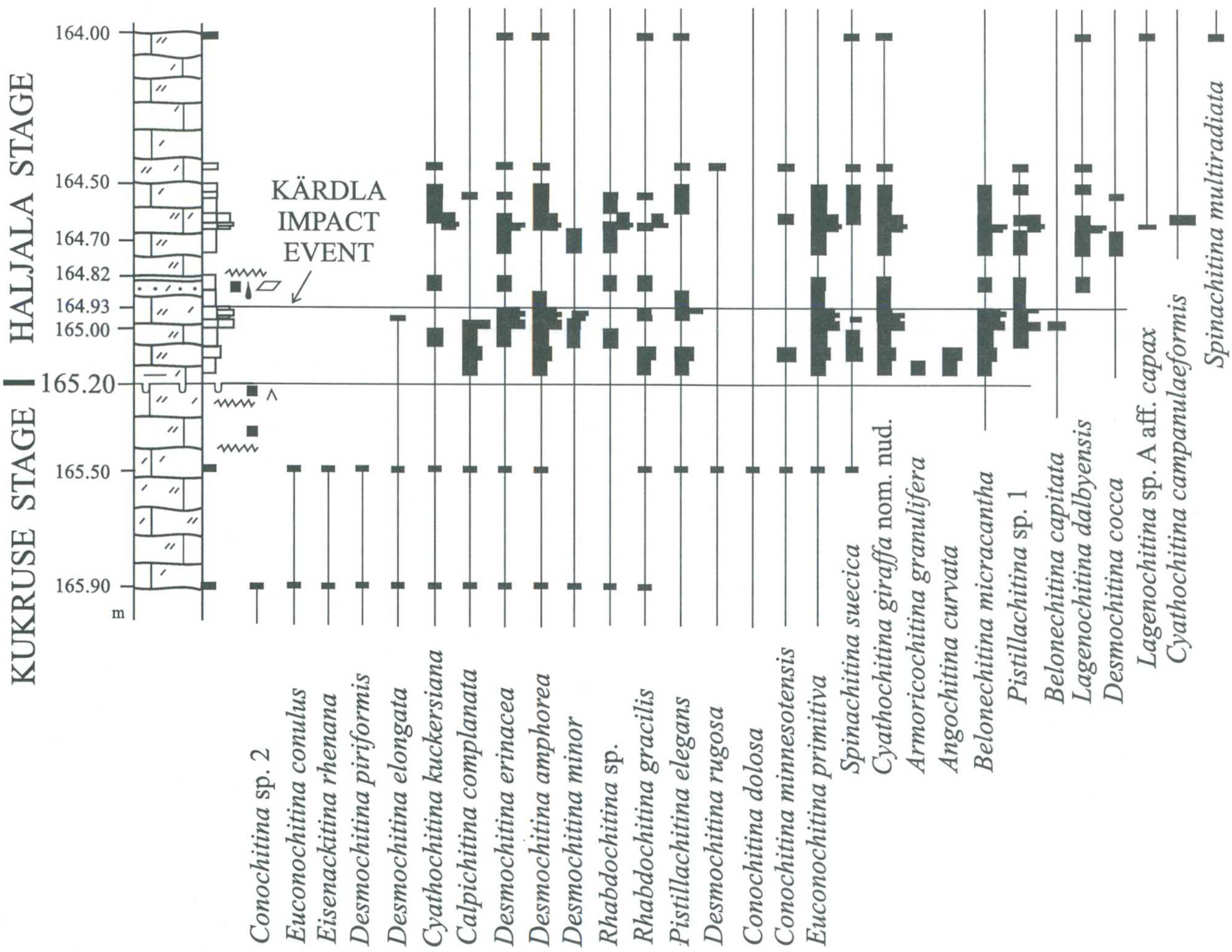


Fig. 5. Distribution of chitinozoans in the Kärdla impact event level of the Männamaa (F–367) core. Refer to Appendix 1 for lithology and Appendix 5 for sample depths.

sponding to that zone are not very widely distributed in the western condensed sections of North Estonia. This zone can be more clearly recognized in eastern sections (e.g. Kerguta (565); Nõlvak & Bauert 2006, app. 9) towards western Ingria, in southern sections (e.g. Valga (10); Nõlvak 2001, app.8) and in the Fjäcka section in Sweden (Nõlvak *et al.* 1999).

The succeeding *Spinachitina cervicornis* Zone is represented by the Haljala, Keila and lowermost Oandu stages. Chitinozoan associations are very diverse and abundant, especially desmochitinids, but species content is relatively stable. The boundary between the Idavere and Jõhvi substages is still problematic as clear criteria among acid-resistant microfossils are missing up to now. The graptolite *Amplexograptus baltoscandicus* (Jaanusson 1995) appears already within the Idavere Substage in the Peetri outcrop near Tallinn. However, exceptionally, within this biostratigraphically relatively stable interval of the Haljala to Keila stages, a highly valuable level for correlations, the Kinnekulle K-bentonite bed occurs and its lower boundary is defined as the base of the Keila Stage (Hints & Nõlvak 1999).

The **Kinnekulle K-bentonite** level was sampled bed-by-bed. A total of 16 samples of different sizes (partly duplicate) were (Fig. 6) investigated to recognize possible changes in chitinozoan associations below and above the 0.4 m thick K-bentonite layer. According to Jaanusson (1995) and Hints *et al.* (2003), the dynamics of ostracods, polychaete annelids and some shelly macrofauna across the Kinnekulle K-bentonite indicates some significant faunal changes. The distribution of chitinozoans is not so unequivocal. The effect of the volcanic event on probable zooplanktic chitinozoans and phytoplanktic prasinophycean algae *Leiosphaeridia* sp. was minimal, at least as far as the abundance of specimens is concerned. The thickness of the studied samples was more than 2 cm. *Leiosphaeridia* sp. and *Tasmanites* sp. are widely distributed, macroscopically easily recognized and good index fossils in the Haljala and Keila stages.

No great changes could be recognized in the number

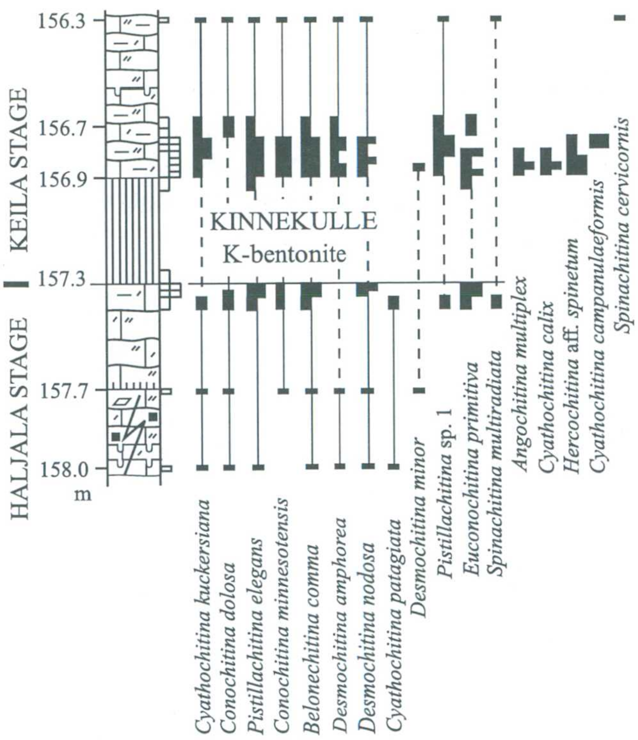


Fig. 6. Distribution of chitinozoans in the Kinnekulle K-bentonite level of the Männamaa (F-367) core. Refer to Appendix 1 for lithology and Appendix 5 for sample depths.

of chitinozoan species (Fig. 6). Only above the bentonite layer there appear two *Cyathochitina* species that have wide stratigraphical ranges (so-called *Lazarus*-species), and stratigraphically more important *Hercochitina* aff. *spinetum* Melchin & Legault (in the Kerguta (565) core incorrectly referred to as *H. lindstroemi* nom. nud.; Nõlvak & Bauert 2006, app. 9) together with stratigraphically valuable but rare zonal species *Angochitina multiplex* (Schallreuter). The described minor changes could be interpreted as not influenced by ash-fall. *Hercochitina* aff. *spinetum* has also been recognized from the beds below K-bentonite, e.g. in the Rapla core (Hints & Nõlvak 1999, fig. 4). In general, a chitinozoan species, which was rare in bigger samples, was rare also in the second series of smaller samples.

A relatively conspicuous change takes place in the topmost beds of the Keila Stage and is marked by a notable gap at a depth of 141.0 m (Appendix 6, sheet 2). It is indicated by lithology and faunal changes in many North Estonian sections. Several species disappear below this boundary level (Kaljo *et al.* 1996). In South Estonia the faunal change is less pronounced (e.g. in the Valga (10) core; Nõlvak 2001).

The boundary between the *Spinachitina cervicornis* and *Fungochitina spinifera* zones in the condensed Männamaa (F-367) section is within the Oandu Stage, more precisely near the lower boundary of the lithologically well-defined Tõrremägi Member, marked by discontinuity surfaces with burrows and eroded gullies. Most probably due to bioerosion, *Spinachitina cervicornis* (Eisenack) and *Fungochitina spinifera* (Eisenack) were found as mixed fauna together in the same sample at a depth of 138.90–138.95 m.

A clear change in sedimentation can be followed higher in the Männamaa (F-367) section: lithological subdivisions become thicker and the chitinozoan composition turns more stable. The specimens are excellently preserved, as for example in the crypto- to microcrystalline limestones of the Rägavere Formation (interval 117.4–138.2 m; Appendix 6, sheet 2) showing a relatively higher rate of sedimentation. These limestones correspond to the *Cyathochitina angusta* Zone. In the uppermost part of this formation, at a depth of 117.7 m, there occurs a 5 cm thick kukersite oil shale bed, used in some restricted regions as a lithostratigraphical marker near the boundary of the Rakvere and Nabala stages (Nõlvak 1987).

In the light of new data from the Männamaa (F-367) section, the age of the next interval at 113.2–117.4 m is problematic. Microcrystalline to very finely crystalline limestones poor in clay and with few marlstone interbeds are not typical of the lower part of the Paekna Formation in the North Estonian Confacies Belt and could represent such a type of rare sections where some part of the Tudu Member is probably of Nabala Age (see discussions in Kõrvel 1962; Männil 1966). Another question arises: is the problematic package lithologically more similar to the Rägavere Formation or to the lower part of the Paekna Formation (see Appendix 1, sheet 5)? However, *C. angusta* was not found in these beds (Appendix 6, sheet 2). In some sections (e.g. Kerguta (565) core; Nõlvak & Bauert 2006) this species even co-occurs with *Armoricochitina reticulifera* (Grahn), ranging into this higher zone. The appearance level of *A. reticulifera*, together with specific variable forms of the *Cyathochitina* group, marks one of the well-traced biostratigraphical horizons, used for correlations in the entire East Baltic area and corresponding to the lower boundary of the Nabala Stage. In the Männamaa (F-367) core *A. reticulifera* appears at 113.1 m. Thus, with regard to chitinozoans, the lower boundary of the Nabala Stage should be marked here by discontinuity surfaces at a depth of 113.2 m. The chitinozoan distribution is very similar in the Nabala (16) core and the Paekna quarry section in North Estonia (see Nõlvak & Meidla 1990, where *C. angusta* is referred to as *C. campanulaeformis* ssp. n).

As in many earlier investigated sections, a very clear lithological change at the lower boundary of the Vormsi Stage at 104.0 m (Appendix 6, sheet 2) is not reflected in the chitinozoan distribution in the Männamaa (F-367) core. Higher, based on the appearance of *Spinachitina coronata* (Eisenack), the Kõrgessaare beds can be subdivided into two parts as in the Lelle (D-102) core (Hints *et al.* 2007), but the appearance level of the zonal species *Tanuchitina bergstroemi* Laufeld and the total range of *Acanthochitina barbata* Eisenack are biostratigraphically more important. However, in the Männamaa core the former species appears exceptionally at a higher level than in some earlier investigated sections (see Nõlvak & Grahn 1993; Hints *et al.* 2007). The disappearance of *A. barbata* marks the top of the Vormsi Age beds, mostly coinciding with a sharp decrease in the clay content of limestones, but without any discontinuity surfaces.

The Moe and Adila formations have very poor intervals and chitinozoan assemblages are markedly scantier than in the lower beds (Appendix 6, sheet 1). The faunal change is clear near the upper boundary of the Moe Formation, below which many long-ranging species disappear (e.g. *Belonechitina*, *Lagenochitina*). The upper half of the Pirgu Stage is rich in discontinuity surfaces (about 18) and clearly condensed. This part needs much more detailed research than done in this review. Thus, zonation is somewhat uncertain. The zonal *Conochitina rugata* Nõlvak was found in only one sample, leaving zone boundaries open, and other zones, such as *Tanuchitina anticostiensis* Achab and *Belonechitina gamachiana* Achab (Hints *et al.* 2005; Nõlvak *et al.* 2006), were not recorded. The large pentamerid brachiopod *Holorhynchus giganteus* Kiaer (*det.* L. Hints) of Pirgu Age (Brenchley *et al.* 1997), one of the key elements among late Ordovician macrofaunas, was found at a depth of 54.1 m.

The *Conochitina taugourdeaui* Zone (Appendix 6, sheet 1) is distinct and well developed. This chitinozoan species is important in timing Hirnantian glaciation events (Brenchley *et al.* 2003; Kaljo *et al.* 2008). The base of the biozone marks the base of the Hirnantian Global Stage in many localities, which, however, is defined by the occurrence of the graptolite *Normalograptus extraordinarius* not found in the East Baltic (for a recent review see Kaljo *et al.* 2008). As usual, the biohermal limestones of the Tõrevere Member are barren of chitinozoans.

According to the samples available from the Männamaa (F-367) section, the older part of the Silurian with the *Ancyrochitina laevaensis* Zone seems to be absent. The basal part is very similar to higher levels of the Varbola Formation, e.g. in the Põltsamaa core (Interzone I in Nestor *et al.* 2003, fig. 3). It is interesting to note that a layer very similar to the *Borealis borealis* coquina lies at a depth of 37.6–37.9 m, which seems to be older than in many other sections.

In general, the changes in the chitinozoan succession of the Männamaa (F-367) section conform relatively well to the boundaries of most Middle and Upper Ordovician stratigraphical units, often marked with hiatuses.

DISTRIBUTION OF CAMBRIAN, ORDOVICIAN AND LOWERMOST SILURIAN ACRITARCHS

Five samples from the Lower Cambrian and Furongian (Upper Cambrian), 112 samples from the Ordovician and 14 samples from the lowermost Silurian part of the Männamaa (F-367) core were studied for acritarchs (Fig. 7; Appendix 7, 8). A filtering preparation method enabling the examination of slides under light microscope, described by Vidal (1988), was used. Samples were prepared in the laboratory of the Geological Survey of Finland, Otaniemi, and preparates are stored in the Geological Museum, University of Helsinki.

The well-preserved Männamaa (F-367) material is represented by 17 Cambrian, 72 Ordovician and 10 Silurian genera comprising a total of 276 species (Fig. 7; Appendix 7, 8): 15 Lower Cambrian, 8 Furongian and 252 Ordovician and Silurian species. Thirty species are long-ranging, with a lesser dating value (12%). Only two new species appear in the Silurian limestones (Fig. 8, Appendix 7). As many as 227 species (82%) have been identified already in the Rapla core in Estonia (NW part of the East European Platform; Uutela & Tynni 1991), while 25 species are known only from the Männamaa section. The distribution of biostratigraphically important taxa is given in Appendix 8, and in Figs 7 and 8.

The taxonomic nomenclature of the Männamaa (F-367) material follows the one used for the Rapla core (Uutela & Tynni 1991; Kaljo *et al.* 1996), although Sarjeant & Stancliffe (1994, 1996), Sarjeant & Vavrdová (1997), and Mullins (2007) proposed the assignment of some species to other genera (see Appendix 9). The acritarch distribution is restricted to the Baltic area only.

Compared to the Rapla core (Uutela & Tynni 1991), the most significant feature is the lesser number of small species. Acritarch assemblages seem to be more important than individual species to indicate differ-

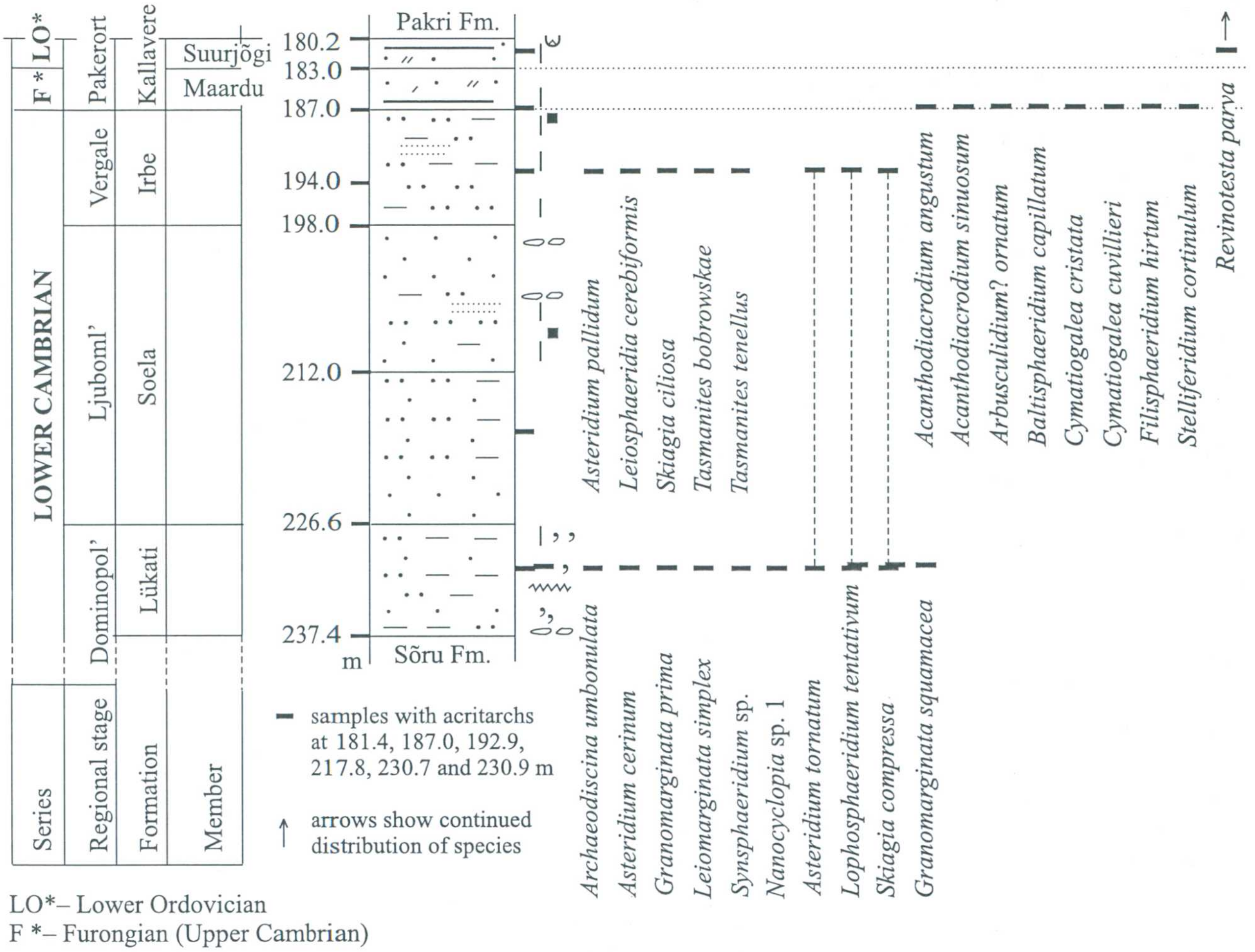


Fig. 7. Lower Cambrian and Lower Ordovician acritarchs of the Männamaa (F-367) core. Refer to Appendix 1 for key and to Appendix 9 for full names of the taxa.

ent stages. Additional acritarch studies from the Estonian area are needed to identify key assemblages for regional stages.

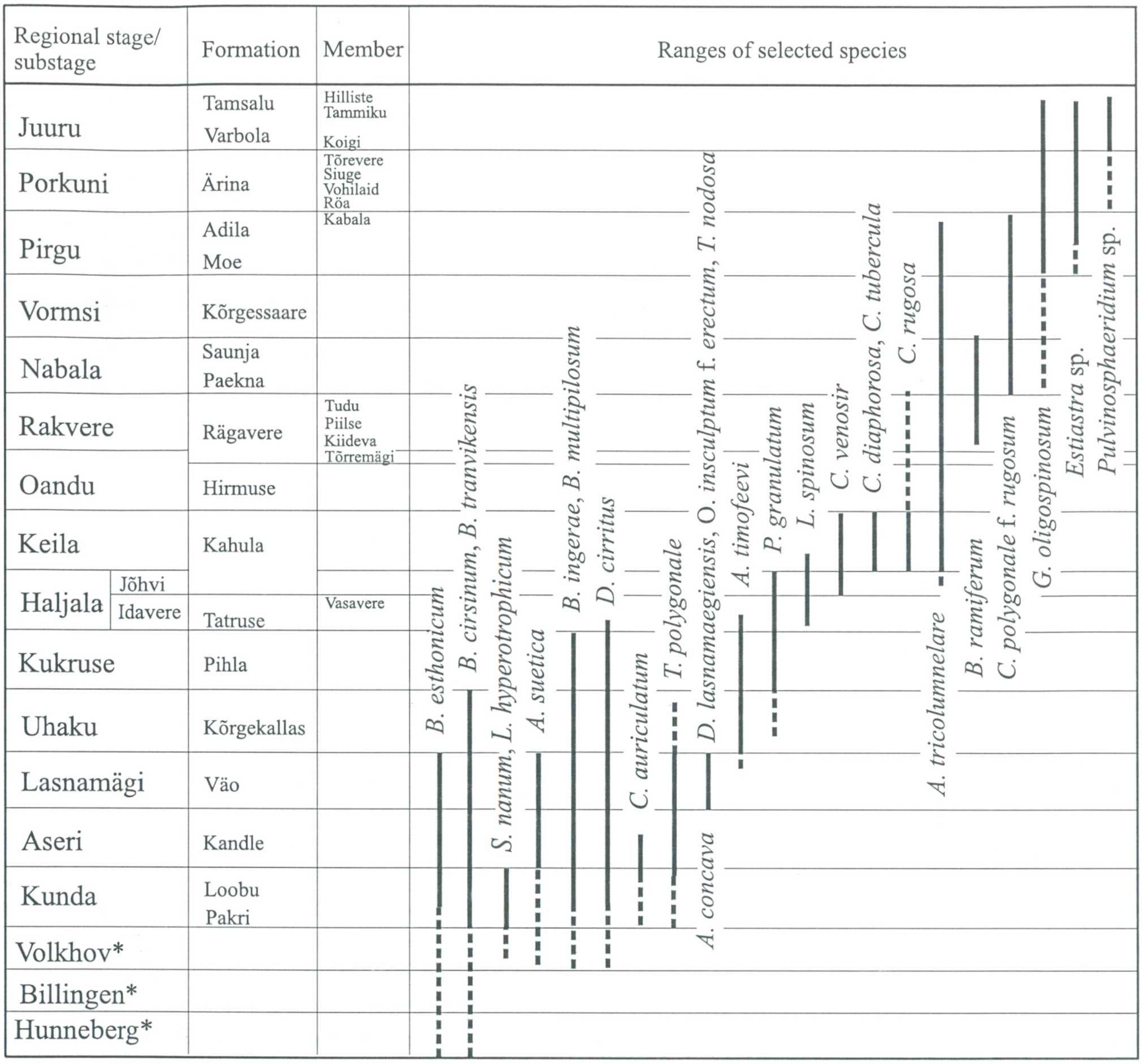
Only the upper part of **Lower Cambrian** silt- and sandstones was sampled for acritarchs (Fig. 7; Appendix 1, sheets 8–10). Ten species were identified in the **Dominopol' Stage** (Lükati Formation, 226.60–237.40 m; two samples). The only sample from the **Ljuboml' Stage** (Soela Formation, 198.0–226.60 m) was barren. The assemblage of the **Vergale Stage** (Irbe Formation, 187.00–198.00 m; one sample) contained eight species.

A rather poor **Lower Cambrian** assemblages of the Männamaa (F-367) section consists of long-ranging species typical of the Baltic area (Mens & Pirrus 1977; Volkova *et al.* 1983; Hagenfeldt 1989; Paalits 1995; Jankauskas 2002). *Lophosphaeridium tentativum* and *Asteridium tornatum* are more common in the Lükati Formation of the Dominopol' Stage, while the genera *Skiagia* and *Tasmanites* appear later in the Irbe Formation of the Vergale Stage (Fig. 7).

The **Furongian** sandstone is represented by the lower part of the **Pakerort Stage** (Maardu Member of the Kallavere Formation, 183.00–187.00 m; one sample). The sample yielded eight acritarch species (Fig. 7), including representatives of the oldest (*Stelliferidium* and *Cymatiogalea*) and youngest (*Acanthodiacrodium*) genera (Mens & Pirrus 1997). The genera *Acanthodiacrodium*, *Cymatiogalea* and *Dasydiacrodium* are also known from the Maardu Member (Kallavere Formation) of the Mäekalda section (Mens *et al.* 1989).

Only one specimen of *Revinotesta parva* was found from **Lower Ordovician** sandstones of the Pakerort Stage (Suurjõgi Member of the Kallavere Formation, 180.20–183.00 m; one sample) (Fig. 7). Its range reaches up to the Oandu Stage (Upper Ordovician; Appendix 8).

All younger Lower Ordovician rocks known from eastern and southern Estonian sections are missing in the surroundings of the Männamaa (F-367) section due to the erosional hiatus (see Nõlvak 1997).



Note: Rocks of the Varangu, Hunneberg, Billingen and Volkhov stages are missing in the Männamaa (F–367) section due to the erosional hiatus. In the Rapla core the Pakri Formation is replaced by the upper part of the Sillaoru Formation

Fig. 8. Distribution of selected Ordovician and Silurian acritarchs in the Männamaa (F–367) core (solid line), supplemented with data (dashed line) from Lithuanian (Paškevičienė 2003), Swedish (Hagenfeldt 1995) and Estonian (Rapla core; Uutela & Tynni 1991) sections.

Middle Ordovician limestones of the Männamaa (F–367) core comprise 168 acritarch species (Appendix 7). All productive samples yielded a rich assemblage of microfossils including well-preserved acritarchs.

The **Kunda Stage** (interval 177.80–180.20 m; three samples) is represented by the Pakri and Loobu formations in the Männamaa (F-367) core (Appendix 8). Sandy limestones (containing argillite pebbles) of the Pakri Formation occur in a limited area in northwestern Estonia west of Tallinn and are eastward replaced by the upper part of the Sillaoru Formation and the Loobu Formation (Meidla 1997). Two successive (from below) Sillaoru and Loobu formations are distinguished in the Kunda Stage in the Rapla core (Uutela & Tynni 1991).

Nine acritarch species appear in the Pakri Formation in the Männamaa (F-367) core (Appendix 7). The acritarch assemblage changes gradually in the Loobu Formation and is represented by 89 species typical of the Baltic area, with 34 species having a long range. Thirty-nine species, among them *Baltisphaeridium brevispinosum*, *B. cirsinum*, *B. esthonicum*, *B. ingerae*, *B. multipilosum*, *B. tranvikensis*, *Baltisphaeridium* sp. and *Dasydorus cirritus*, appear in the Rapla core already in the Volkhov Stage (Fig. 8; Uutela & Tynni 1991). The same situation is registered in Lithuanian sections (Paškevičienė 1999).

The range of *Baltisphaeridium anneliae* (Appendix 8) extends from the lowermost part of the Kunda Stage to the Kukruse Stage in the Rapla core (Uutela & Tynni 1991) and in the Dalby Limestone in Gotland (Górka 1987), but much higher up to the Oandu Stage in the Lithuanian sections (Paškevičienė 2001). *Baltisphaeridium flexuosum* known from the Kunda to Kukruse stages in the Rapla core (Uutela & Tynni 1991) appears in Lithuanian sections in the Volhkov Stage and is continuously present up to some levels in the Oandu and Rakvere stages (Paškevičienė 2001, 2003). *Solisphaeridium nanum* is found in the Männamaa (F-367) core only in the Kunda Stage like in the Rapla core (Uutela & Tynni 1991), but in Lithuanian sections appears earlier in the Volkhov Stage (Paškevičienė 2001). The appearance of *Goniosphaeridium mochtiensis* in the Loobu Formation coincides with Rapla data, but *Baltisphaeridium magnoporatum, Liliosphaeridium hyperotrophium* and *Peteinosphaeridium micranthum* have not been identified from the Rapla section (Uutela & Tynni 1991).

Liliosphaeridium hyperotrophium has been recorded in Lithuanian sections in the Volkhov (Paškevičienė 1998, 1999), Kunda and Lasnamägi stages (Paškevičienė 2003). *Baltisphaeridium magnoporatum* is known from the lower level of the Uhaku Stage in Grötlingbo core No. 1 (Kjellström 1971a) and Dalby Limestone in Gotland (Górka 1987), but also in the Oandu and Rakvere stages in Lithuania (Paškevičienė 2001). *Peteinosphaeridium micranthum* is found in the Volkhov and Kunda (Paškevičienė 1999), Lasnamägi and Uhaku (Paškevičienė 2002), and Oandu and Rakvere (Paškevičienė 2001) stages in Lithuania.

Thick-walled *Pachysphaeridium*-species (Appendix 7) have been identified in the Männamaa (F-367) core from the Kunda to Uhaku stages, in Lithuanian sections from the Volkhov to Uhaku stages (Paškevičienė 1999, 2002, 2003).

In the Rapla core *Baltisphaeridium verrucatum, Cycloposphaeridium auriculatum* and *Tranvikium polygonale* appear in the Sillaoru Formation (Uutela & Tynni 1991). The range of *C. auriculatum* in the Männamaa (F-367) section (Fig. 8; Appendix 8) is the same as in Lithuanian sections (Paškevičienė 1999). *Baltisphaeridium verrucatum* has previously been recorded in the level of the Lasnamägi Stage in Sweden (Kjellström 1971b) and in the Dalby Limestone in Gotland (Górka 1987). *Stelliferidium stelligerum* has not been found in the Rapla section, but in Lithuania it is recognized in the Uhaku Stage (Paškevičienė 2002).

The **Aseri Stage** (Kandle Formation, 177.00–177.80 m; three samples) is represented by 88 acritarch species, among these 43 long-ranging and 19 new species (Appendix 7). One of the new species is *Baltisphaeridium filosum* (Appendix 8), which appears in the Volkhov Stage in the Rapla core (Uutela & Tynni 1991) and in the Kunda Stage in Lithuanian sections (Paškevičienė 1999). *Ampululla suetica* (Appendix 8) is not found in the Rapla section (Uutela & Tynni 1991), but occurs in the level of the Volkhov and Kunda stages in Lithuanian sections (Paškevičienė 1998, 1999, 2002), as well as in Sweden (Righi 1991). *Liliosphaeridium kaljoi* has been identified in the Männamaa (F-367) section only in the Aseri Stage (Appendix 8), while in the Rapla core it ranges continuously from the Volkhov Stage to the Kunda Stage (Uutela & Tynni 1991), as in Lithuanian sections (Paškevičienė 1999). In the Männamaa (F-367) core *Polyancistrodorus phylloides* is present only in the Aseri Stage, but in the Rapla core also in the Lasnamägi Stage (Uutela & Tynni 1991). *Cycloposphaeridium auriculatum* disappears at the same level in the Männamaa (F-367) and Rapla sections. No dominant species are known from the Aseri Stage.

The **Lasnamägi Stage** (Väo Formation, 170.00–177.00 m; 12 samples) yielded the richest Middle Ordovician assemblage with 128 species, including 42 new species (Appendix 7). Similarly to the Rapla core (Uutela & Tynni 1991) *Arkonia concava, Dactylofusa lasnamaegiensis, Orthosphaeridium insculptum* f. *erectum* and *Timofeevia nodosa* were identified only in the Lasnamägi Stage (Fig. 8; Appendix 8). The most numerous species ranging throughout the stage are *Baltisphaeridium anneliae, B. flexuosum, B. ingerae, B. microspinosum, B. multipilosum, B. tranvikensis, Ordovicidium groetlingboensis, O. heteromorphicum* and *O. nudum*. Similar blooming of the genera *Baltisphaeridium* and *Ordovicidium* occurred in the Lasnamägi Stage in the Rapla core (Uutela & Tynni 1991) and other Baltic sections (Umnova 1975), as well as in the southeastern Baltic region (Paškevičienė 2002). Thick-walled species *Goniosphaeridium mochtiensis* and *Costatilobus bulbosus* are also common in the Männamaa (F-367) core (Appendix 7). Similarly to the Rapla core, *Tranvikium polygonale* and *Goniosphaeridium mochtiensis* disappear in the Lasnamägi Stage (Uutela & Tynni 1991), as well as *Ampululla suetica*, but in Lithuanian sections *G. mochtiensis* and *T. polygonale* have been recorded also from the Uhaku Stage (Paškevičienė 2002).

The **Uhaku Stage** (Kõrgekallas Formation, 168.40–170.00 m; five samples) in the Männamaa (F-367) core is represented by a rich acritarch assemblage of 114 species, including 19 new species (Appendix 7), among others *Axisphaeridium timofeevi, Ordovicidium groetlingboensis* f. *clavatum* and *B. constrictum* (Appendix 8). The last one is not present in the Rapla core (Uutela & Tynni 1991), but is found in Sweden in the Folkeslunda and Furudal sections (Kjellström 1971a, 1972, 1976). *Baltisphaeridium anneliae, B. ingerae, B. microspinosum, B. multipilosum, Ordovicidium groetlingboense, O. heteromorphicum* and *O. nudum* are still common (Appendix 8). Thirteen acritarch species disappear before and during the Uhaku Age. The most important of those are *Baltisphaeridium cirsinum* and *B. tranvikensis* (Appendix 7, 8), like in the Rapla core (Uutela & Tynni 1991).

In the **Upper Ordovician** the acritarch assemblage of the Männamaa (F–367) core changes gradually (Fig. 8; Appendix 7, 8). From the **Kukruse Stage** (Pihla Formation, 165.20–168.40 m; seven samples) 107 species have been identified (Appendix 7). Eight species appear in the Kukruse Stage. The most important new species is *Peteinosphaeridium breviradiatum*, which has been recorded from Lithuanian sections in the Latorp (=Hunneberg) Stage (Paškevičienė 1998), and from Folkeslunda beds (on the level of the lower part of the Uhaku Stage) in Gotland (Kjellström 1971a) and Dalby Limestone (Górka 1987). *Baltisphaeridium anneliae, B. microspinosum, Ordovicidium groetlingboense* and *O. nudum* are still common (Appendix 8). Nine species disappear, among others *Baltisphaeridium accinctum, B. anneliae, B. filosum, B. ingerae, B. magnoporatum* and *B. multipilosum*. In Lithuania, *B. anneliae* and *B. brevispinosum* have been recorded later in the Oandu Stage, *B. accinctum, B. magnoporatum* and *B. multipilosum* even in the Rakvere Stage (Paškevičienė 2001).

The base of the **Haljala Stage** (**Idavere Substage**; Tatruse Formation, 160.20–165.20 m; 11 samples) is represented by 124 acritarch species, 17 of which are new (Appendix 7). Similarly to the Rapla core, the first appearance of *Lacunosphaeridium spinosum* in the Männamaa (F–367) section is registered (Fig. 8; Appendix 8; Uutela & Tynni 1991). Species of the genera *Baltisphaeridium* and *Ordovicidium* are less numerous than previously, although *Baltisphaeridium hirsutoides, B. microspinosum, B. nanninum, B. parvigranosum* and *B. pauciverrucosum* are still common, as well as *Ordovicidium groetlingboense, O. eleganthulum* and *O. nudum*. Numerous *Multiplicisphaeridium*-species appear (Appendix 7). Six species disappear: *Aremoricanium deflandrei, Axisphaeridium timofeevi, Dasydorus cirritus, Polyancistrodorus bryoides, Dasydorus* sp. 1 and *Micrhystridium inconspicuum aremoricanium*.

The upper part of the **Idavere Substage** (Vasavere Member of the Kahula Formation, 158.60–160.20 m; three samples) differs from the lower part (Tatruse Formation) in a smaller number (83) of species (Appendix 7). The *Baltisphaeridium* and *Ordovicidium* species common in the Tatruse Formation are present in the Vasavere Member. No new species appear in this part of the substage but *Baltisphaeridium flexuosum, Costatilobus bulbosus, Dilatisphaera nanofurcata* and *Polyancistrodorus magnispinosus* disappear (Appendix 8).

The **Jõhvi Substage** of the **Haljala Stage** (157.30–158.60 m; three samples) is represented by 87 species (Appendix 7). Only the lowermost sample is rich in acritarchs. Five species appear in this stage, among others *Cheleutochroa venosa* and *Gorgonisphaeridium frequens* (Appendix 8). The latter has not been identified in the Rapla core (Uutela & Tynni 1991), but in Sweden it is found in the Dalby Limestone (Górka 1987). *Multiplicisphaeridium lichenoides* and *Peteinosphaeridium granulatum* disappear during Jõhvi time (Fig. 8; Appendix 8).

The richest acritarch sample in the Männamaa (F–367) section comes from the level of 156.8–156.9 m of the **Keila Stage** (Kahula Formation, 141.00–157.30 m; eight samples). A total of 132 species have been found in the Keila Stage, whereas 28 species appear for the first time (Appendix 7). Like in the Rapla section (Uutela & Tynni 1991), 16 species have been identified only in the Keila Stage, among others *Arkonia semigranulata, Cheleutochroa diaphorosa, C. rugosa, C. tubercula, Costatilobus? trifidus, Cymatiosphaera latimurata, Orthosphaeridium* sp., *Veryhachium asymmetrospinosum* and *Vulcanisphaera minor*.

In Lithuania *A. semigranulata* is also known in the Lasnamägi and Uhaku stages (Paškevičienė 2002). *Cheleutochroa rugosa* and *C. venosa* have been recorded also in the Oandu and Rakvere stages in Lithuania (Paškevičienė 2001). Thirty-eight species disappear during Keila Age, e.g. *Cheleutochroa venosior, Multiplicisphaeridium* aff. *palmitella, Ordovicidium groetlingboensis* f. *clavatum, Orthosphaeridium latispinosum* and *Polygonium delicatum* (Fig. 8; Appendix 8). *Veryhachium*-species are the most common in the Keila Stage of the Männamaa (F–367) section.

The Hirmuse Formation of the **Oandu Stage** (interval 138.80–141.00 m; three samples) yielded 40 species (Appendix 7). Samples are poor in acritarchs. *Baltisphaeridium onniense* and *Micrhystridium* sp. 1 appear in the Hirmuse Formation (Appendix 8), while *Multiplicisphaeridium gotlandicum* disappears earlier than in the Rapla core (Uutela & Tynni 1991). The Tõrremägi Member (138.20–138.80 m; one sample) of the Rägavere Formation in the upper part of the Oandu Stage contains a poor assemblage of 29 acritarch species (Appendix 7). Two probably new species *Baltisphaeridium* sp. 1 and *Baltisphaeridium* sp. 2 are found.

Leiosphaeridia keilaensis that disappears here has a longer range in the Rapla section (Uutela & Tynni 1991).

The lower part of the **Rakvere Stage** (Kiideva and Piilse members of the Rägavere Formation, 126.40–138.20 m; four samples) is represented by 55 species (Appendix 7). The appearing species *Baltisphaeridium ramiferum* has a longer range in the Männamaa (F-367) core than in the Rapla core (Fig. 8; Uutela & Tynni 1991). Six species disappear: *Baltisphaeridium pauciverrucosum*, *B. verrucatum*, *Micrhystridium brevispinosum*, *Orthosphaeridium densiverrucosum*, *Dictyotidium reticulatum* and *Labyrinthosphaeridium curvatum* (Appendix 7, 8). In the upper part of the Rakvere Stage (Tudu Member of the Rägavere Formation, 117.40–126.40 m; four samples) two new species were found in the assemblage of 32 species (Appendix 7), while two species disappeared: *Gorgonisphaeridium antiquum* and *Tylotopalla* sp. (Appendix 8).

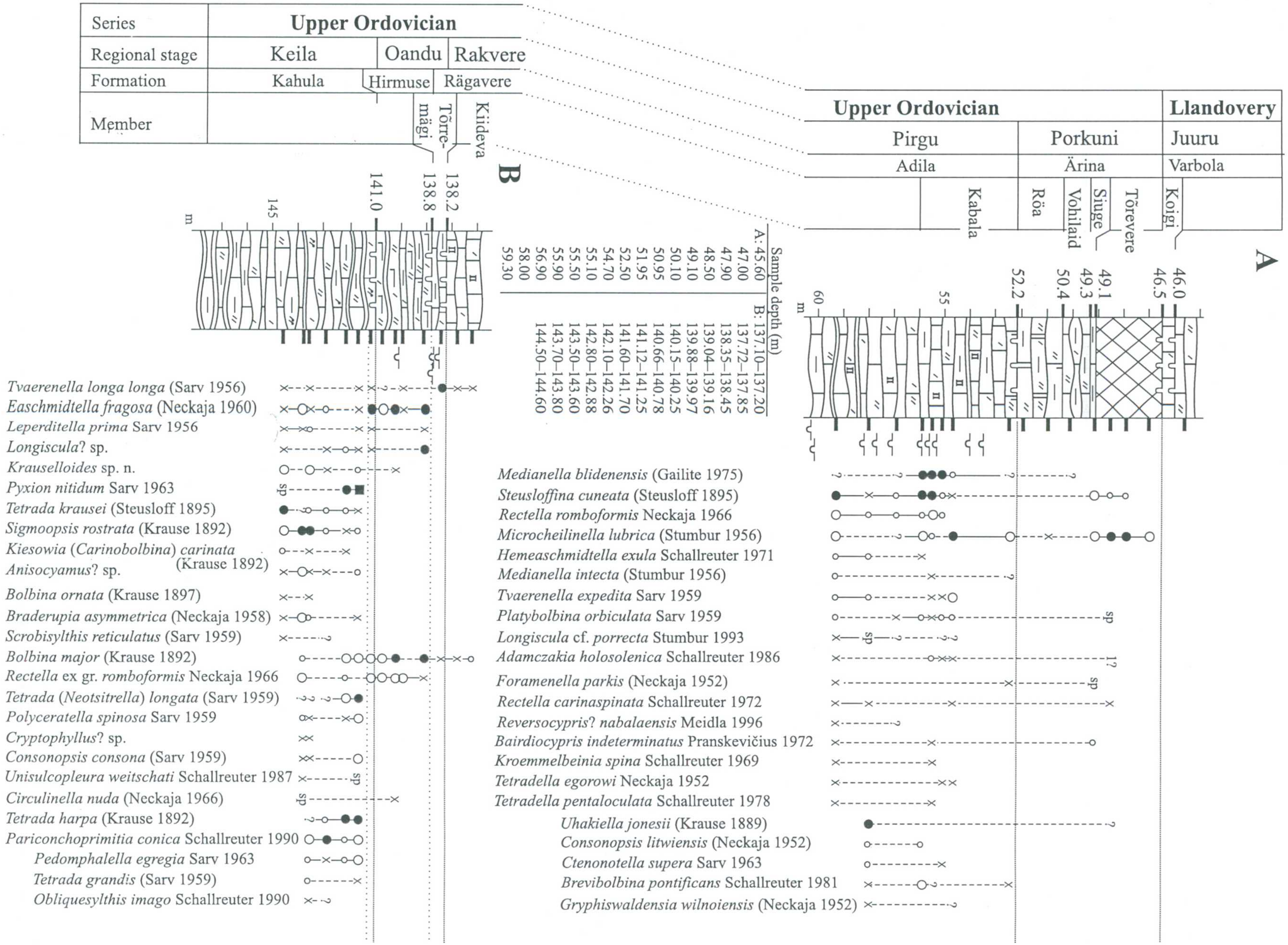
The lower part of the **Nabala Stage** (Paekna Formation, 108.00–117.40 m, four samples) is represented by 32 acritarch species (Appendix 7). Two species appear here, whereas *Ordovicidium aequifurcatum* occurs only in the Paekna Formation of the Nabala Stage, but *Goniosphaeridium polygonale* f. *rugosum* ranges up to the Adila Formation of the Pirgu Stage (Appendix 8). *Baltisphaeridium nanninum* and *B. perclarum* disappear in the lower part of the Nabala Stage. The upper part of the Nabala Stage (Saunja Formation, 104.00–108.00 m; two samples) is the second poorest interval next to the Porkuni Stage in the Upper Ordovician part of the Männamaa (F-367) core. A total of 16 acritarch species were found, and no new species appear in this interval (Appendix 7), *Baltisphaeridium digitiforme*, however, disappears (Appendix 8). In the Rapla core *B. digitiforme* reaches only the Rakvere Stage (Uutela & Tynni 1991).

In the **Vormsi Stage** (Kõrgessaare Formation, 87.00–104.00 m; nine samples) 68 acritarch species were found; 17 species disappear (Appendix 7). Three new species *Leiofusa brevispinosa*, *Baltisphaeridium heitzelinii*, *Multiplicisphaeridium verrucosum* appear here, whereas the last two occur only in this stage. *Baltisphaeridium*? *bramkaense*, *B. oligopsakium*, *B. pustulatum* and *Rhopaliophora pilata* disappear (Appendix 8).

In the lower part of the **Pirgu Stage** (Moe Formation, 68.20–87.00 m; 13 samples) 84 acritarch species were identified. Eight new species appear in the Moe Formation (Appendix 7), e.g. *Goniospaheridium oligospinosum* (Appendix 8), which appears in the Rapla core slightly later, at the end of the Adila Formation (Uutela & Tynni 1991), while in Lithuanian sections it is present also in the Rakvere Stage (Paškevičienė 2001). *Cheleutochroa elegans*, *Lophosphaeridium regulare*, *Micrhystridium curvatum* and *Multiplicisphaeridium cornigerum* are found only in the Moe Formation. Fourteen species disappear in the Männamaa (F-367) core (Appendix 7). The upper part of the Pirgu Stage (Adila Formation, 52.20–68.20 m; 11 samples) is represented by 74 species (Appendix 7). Three new species appear in the Adila Formation. All of them are large in size, e.g. *Estiastra* sp., which appears in the Moe Formation in the Rapla core (Fig. 8; Uutela & Tynni 1991). Large *Goniosphaeridium* sp. 1 was previously unknown (Appendix 8). Fifty species disappear in the Adila Formation of the Männamaa (F-367) core (Appendix 7).

Four successive members (from below): Röa, Vohilaid, Siuge and Tõrevere (Appendix 8) are distinguished in the **Porkuni Stage** (Ärina Formation, 46.50–52.20 m; five samples). Three samples were barren (Appendix 7). The Röa Member (50.40–52.20 m; one sample) is very poor, containing four long-ranging species. The Vohilaid Member (49.30–50.40 m) was not sampled. The Siuge Member (49.10–49.30 m; two samples) yielded an assemblage of nine species. In the lower sample *Estiastra* sp. and *Goniosphaeridium oligospinosum* are common (Fig. 8; Appendix 8), the upper sample is barren. The two acritarch samples from the Tõrevere Member (46.50–49.10 m) were barren.

The **Llandovery** Series of the **Silurian** is represented by limestones of the **Juuru Stage** in the Männamaa (F-367) core (Appendix 8). Two formations are distinguished: Varbola and Tamsalu. The lowermost part of the Varbola Formation (Koigi Member, 46.00–46.50 m; one sample) is very poor in acritarchs; only three long-ranging species are found (Appendix 7). The upper part of the Varbola Formation contains 25 species, with *Pulvinosphaeridium* sp. and *Veryhachium oligospinoides* being common (Fig. 8; Appendix 8). The sample from 36.80 m in the lower part of the Tamsalu Formation (Tammiku Member, 34.00–37.00 m; four samples) was rich in acritarchs and yielded an assemblage of 12 species, including long-ranging and large species like *Estiastra* sp., *Goniosphaeridium oligospinosum*, *Multiplicisphaeridium digitatum* and *Veryhachium oligospinoides* (Fig. 8; Appendix 8). *Pulvinosphaeridium* sp. is common. The upper part of the Tamsalu Formation (Hilliste Member, 29.00–34.00 m; two samples) is characterized by an assemblage very similar to that of the Tammiku Member, however *Multiplicisphaeridium digitatum* and *Veryhachium oligospinoides* are both missing (Appendix 8). In Gotland *M. digitatum* (syn. *Hoeglintia digita*) reaches up to the Wenlockian Mulde/Halla Formation (Le Herissé 1989).


Series
Upper Ordovician
Regional stage
Keila
Oandu
Rakvere
Formation
Kahula
Hirmuse
Rägavere
Member
Tõrre-mägi
Kiideva
B
141.0
138.8
138.2
145
m
Sample depth (m)
A: 45.60 B: 137.10–137.20
47.00 137.72–137.85
47.90 138.35–138.45
48.50 139.04–139.16
49.10 139.88–139.97
50.10 140.15–140.25
50.95 140.66–140.78
51.95 141.12–141.25
52.50 141.60–141.70
54.70 142.10–142.26
55.10 142.80–142.88
55.50 143.50–143.60
55.90 143.70–143.80
56.90 144.50–144.60
58.00
59.30
Upper Ordovician
Llandovery
Pirgu
Porkuni
Juuru
Adila
Ärina
Varbola
Kabala
Röa
Vohilaid
Siuge
Tõrevere
Koigi
A
52.2
50.4
49.3
49.1
46.5
46.0
60
55
m
Tvaerenella longa longa (Sarv 1956)
Easchmidtella fragosa (Neckaja 1960)
Leperditella prima Sarv 1956
Longiscula? sp.
Krauselloides sp. n.
Pyxion nitidum Sarv 1963
Tetrada krausei (Steusloff 1895)
Sigmoopsis rostrata (Krause 1892)
Kiesowia (Carinobolbina) carinata (Krause 1892)
Anisocyamus? sp.
Bolbina ornata (Krause 1897)
Braderupia asymmetrica (Neckaja 1958)
Scrobisylthis reticulatus (Sarv 1959)
Bolbina major (Krause 1892)
Rectella ex gr. romboformis Neckaja 1966
Tetrada (Neotsitrella) longata (Sarv 1959)
Polyceratella spinosa Sarv 1959
Cryptophyllus? sp.
Consonopsis consona (Sarv 1959)
Unisulcopleura weitschati Schallreuter 1987
Circulinella nuda (Neckaja 1966)
Tetrada harpa (Krause 1892)
Pariconchoprimitia conica Schallreuter 1990
Pedomphalella egregia Sarv 1963
Tetrada grandis (Sarv 1959)
Obliquesylthis imago Schallreuter 1990
Medianella blidenensis (Gailite 1975)
Steusloffina cuneata (Steusloff 1895)
Rectella romboformis Neckaja 1966
Microcheilinella lubrica (Stumbur 1956)
Hemeaschmidtella exula Schallreuter 1971
Medianella intecta (Stumbur 1956)
Tvaerenella expedita Sarv 1959
Platybolbina orbiculata Sarv 1959
Longiscula cf. porrecta Stumbur 1993
Adamczakia holosolenica Schallreuter 1986
Foramenella parkis (Neckaja 1952)
Rectella carinaspinata Schallreuter 1972
Reversocypris? nabalaensis Meidla 1996
Bairdiocypris indeterminatus Pranskevičius 1972
Kroemmelbeinia spina Schallreuter 1969
Tetradella egorowi Neckaja 1952
Tetradella pentaloculata Schallreuter 1978
Uhakiella jonesii (Krause 1889)
Consonopsis litwiensis (Neckaja 1952)
Ctenonotella supera Sarv 1963
Brevibolbina pontificans Schallreuter 1981
Gryphiswaldensia wilnoiensis (Neckaja 1952)

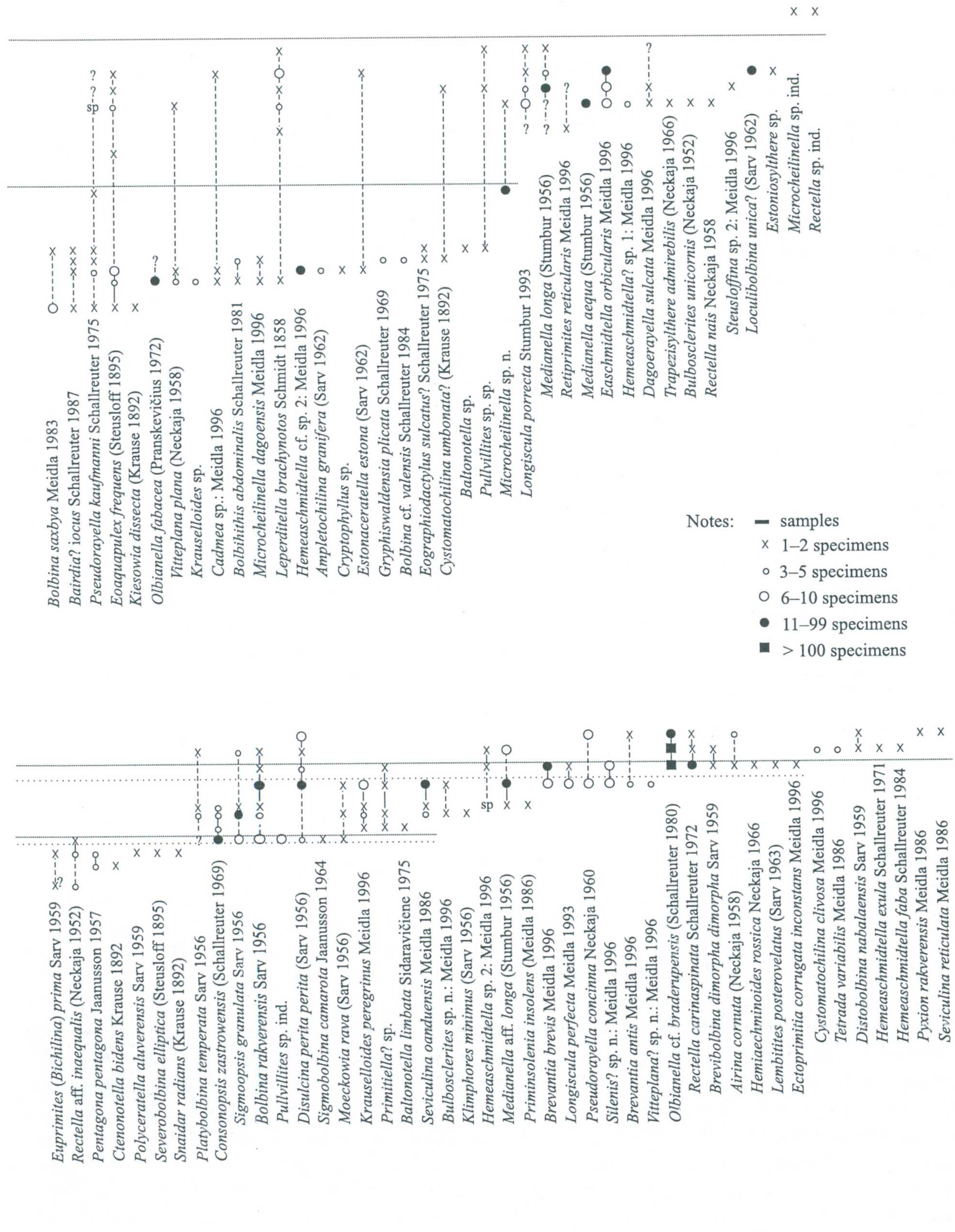


Fig. 9. Distribution of the Upper Ordovician and lowermost Llandovery ostracods in the Männamaa (F-367) section. (A) Pirgu, Porkuni and Juuru stages, (B) Keila, Oandu and Rakvere stages. Refer to Appendix 1 for lithology.

DISTRIBUTION OF UPPER ORDOVICIAN OSTRACODS

The distribution of ostracods in the Männamaa (F-367) core section was analysed in two intervals (Fig. 9): from the upper Keila to lower Rakvere stages (14 samples, all fossiliferous) and in the Ordovician–Silurian boundary beds (16 samples, one of them unfossiliferous). Most of the limestone samples contained abundant and well-preserved ostracod fauna. However, ostracods were rather rare and poorly preserved in grain-rich layers, where a number of broken and strongly deformed carapaces remained unidentified. Dolomitization, affecting the preservation of fossils, has apparently destroyed most of ostracods in dolomites of the Röa Member.

The lowermost Late Ordovician sample from the interval 144.5–144.6 m is dominated by *Tetrada krausei*, *Sigmoopsis rostrata* and an undescribed metacope *Krauselloides* sp. nov. The total number of taxa recognized in this sample is twelve (Fig. 9). All these species have previously been recorded by L. Sarv from this stratigraphic interval and the assemblage looks typical of the middle–upper part of the Keila Stage (Põlma *et al.* 1988, pp. 59–68).

The fact that rare specimens of some taxa which are normally abundant in the Oandu–Rakvere interval (*Bolbina major, Platybolbina temperata, Klimphores minimus* and some other representatives of the so-called Late Ordovician ostracod fauna; see Meidla 1996, p. 11) do appear already in the upper part of the Keila Stage, several metres below the stage boundary, has repeatedly been mentioned in publications (Sarv 1959, p. 194; Meidla 1996, p. 151). In the Männamaa core *Bolbina major* was identified in the sample at 143.7–143.8 m (Fig. 9). Similar early appearance of *B. major* is observed in the Orjaku and Laiamäe-259 cores (Meidla 1996, figs 7, 9).

The topmost part of the interval 141.6–142.9 m (three samples), attributed to the Keila Stage, displays a gradual change in the assemblage structure. The rich and diverse ostracod assemblage is dominated by *Pyxion nitidum*, *Tetrada harpa* (referred to as *Tallinnopsis ovalis* by L. Sarv in Sarv 1959 and Põlma *et al.* 1988), *Tetrada (Neotsitrella) longata*, *Pedomphalella egregia* and *Pariconchoprimitia conica*. The listed taxa, except for the last one, are widespread in the upper part of the Keila Stage (e.g. Orjaku and Virtsu-360 cores in Meidla 1996; Pagari core in Põlma *et al.* 1988). The uppermost sample (141.6–141.7 m) shows the highest diversity for the Keila–Rakvere interval, comprising 24 species/subspecies.

One of the greatest changes in the Ordovician ostracod succession occurs at the lower boundary of the Oandu Stage, in the Männamaa (F-367) core in the interval 141.25–141.60 m (Fig. 9). The sample from the interval 141.12–141.25 m also marks a dramatic alteration in the ostracod fauna. All previously listed dominant taxa disappear and new species start to dominate (*Easchmidtella fragosa, Bolbina major, Tvaerenella longa longa, Sigmoopsis granulata* and *Consonopsis zastrowensis*). The first three of these species are common also in the underlying strata, but the appearance of the last two, together with the less frequent *Disulcina perita perita*, *Bolbina rakverensis* and *Sigmobolbina camarota*, marks the emergence of a new evolutionary assemblage. This abrupt change in a very narrow interval is most likely due to a gap in the studied section, like in many North Estonian sections that have been investigated so far (Põlma *et al.* 1988; Meidla 1996).

The late Ordovician ostracod fauna appears in the basal Hirmuse Formation in many North Estonian localities. In the Männamaa (F-367) core the sudden change in the ostracod composition described above occurs 12–25 cm below the lower boundary of the formation at a depth of 141.0 m. This boundary interval is bioturbated but evidences of faunal mixing seem to be lacking. The topmost beds of the Kahula Formation contain mixed fauna because of heavy bioturbation also in the Laeva-18 core (see Meidla 1996, p. 161 and fig. 13) and core No. 7909 (Põlma *et al.* p. 79 and fig. 37), but in the Männamaa (F-367) core displacement of the particular interval (the piece of core where the sample was taken) cannot be ruled out completely.

The composition of the ostracod assemblage of the Hirmuse Formation of the Männamaa (F-367) core is fairly stable (Fig. 9). The dominant species are changing (*Disulcina perita perita*, *Bolbina rakverensis* and metacopes become more frequent) only in its uppermost part (sample 139.04–139.16 m). An exception is the topmost sample of the Oandu Stage, which comes from the Tõrremägi Member of the Rägavere Formation. This sample (from 138.35–138.45 m), similarly to the two following samples from the Kiideva Member of the Rägavere Formation, is heavily dominated by *Olbianella* cf. *braderupensis*. The ostracod record from the basal Rakvere Stage is mostly similar to that of the topmost Oandu Stage, as pointed out already in Meidla 1996 (p. 167). The lower boundary of the Rägavere Formation is usually lithologically well defined, like it is also in the Männamaa (F-367) core, at a depth of 138.8 m (see Fig. 9). This level is distinct also in the ostracod range charts, as it comprises a notable facies shift. Only minor evidence of the faunal change at the base of the Rakvere Stage, about a metre above the formation boundary, is available. That boundary is generally tied to a distinct hardground surface and this makes the present concept of the Rakvere Stage topostratigraphic rather than chronostratigraphic (the boundary is drawn at a distinct marker level which is poorly expressed in the faunal record). Some rare ostracod species (*Retiprimites reticularis*, *Ctenonotella supera*, *Ectoprimitia corrugata inconstans*) have previously been reported from the lower part of the Rägavere Formation but not from its basal Tõrremägi Member (Meidla 1996, p. 167). However, in the Männamaa (F-367) core *Ectoprimitia corrugata inconstans* is found in the Tõrremägi Member as well.

The investigated interval of the Ordovician–Silurian boundary beds begins in the upper Adila Formation, which typically revealed a diverse assemblage dominated by *Steusloffina cuneata* and *Medianella blidenensis* (Fig. 9). Noteworthy is the occurrence of *Brevibolbina pontificans* and *Bolbihithis abdominalis*, which are found in the topmost Pirgu Stage (in the topmost Adila Formation or the topmost Halliku Formation) in several sections of North and Central Estonia, e.g. Puhmu-567, Aidu-427 and Virtsu-360 cores (see Meidla 1996). In the Männamaa (F-367) section ostracod diversity drops in the topmost Adila Formation. The sample from a depth of 52.5 m is dominated by metacopes *Microcheilinella* sp. nov. and *Microcheilinella lubrica*, whereas other suborders are not represented.

The three lower samples of the Porkuni Stage were taken from dolomitized limestones and dolostones (Fig. 9), and contain no ostracods or only rare specimens of long-ranging taxa (*Microcheilinella lubrica*, *Leperditella brachynotos*, *Eoaquapulex frequens*). The appearance of *Medianella aequa*, *Longiscula porrecta*, *Bulbosclerites unicornis* and *Dagoerayella sulcata* at a depth of 49.1 m (and higher above), together with the increased abundance of some other long-ranging metacope taxa (*Microcheilinella lubrica*, etc.), marks the appearance of the assemblage characteristic of the Ärina Formation in several Estonian localities (Puhmu-567 core, Siuge quarry, Porkuni quarry and Iida karst cave in Meidla 1996, fig. 34, table 8). The highest sample in this series is thought to come from the basal Silurian strata, but as it contains only poorly preserved material of probably long-ranging taxa, no distinct Silurian affinities can be pointed out.

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ORDOVICIAN CARBON ISOTOPES

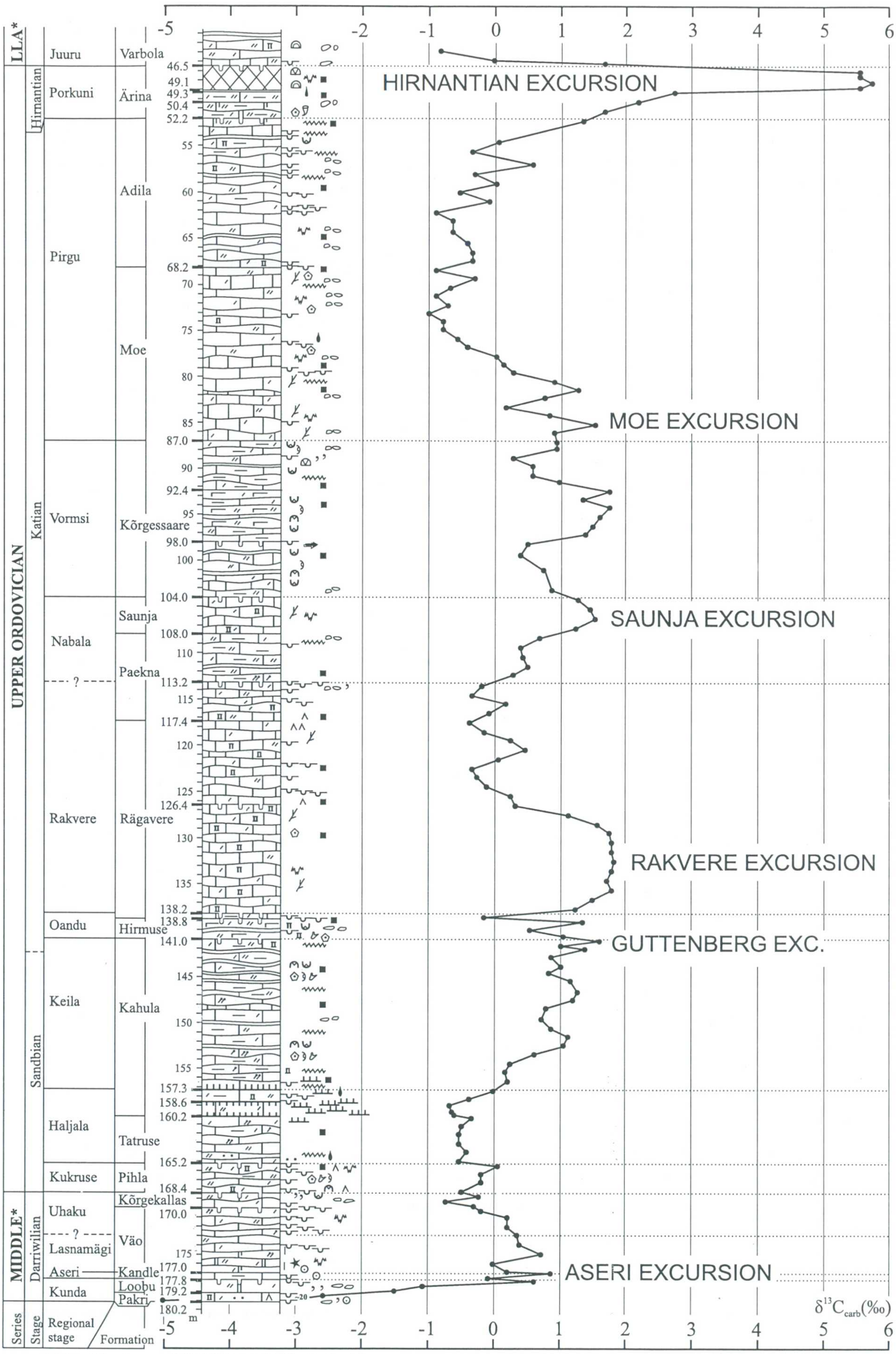
For the analysis of stable carbon and oxygen isotope composition core 150 samples were collected at approximately 1 m intervals from the Middle and Upper Ordovician section of the Männamaa (F-367) core (Fig. 10; Appendix 10). Preliminary results of carbon isotope composition in the Männamaa section were published by Ainsaar *et al.* (2004a).

Whole-rock samples were crushed and material for isotopic analyses was selected avoiding obvious veins or burrows. Powdered carbonate material was reacted with 100% phosphoric acid at 75 °C and analysed for carbon and oxygen stable isotopes using the Finnigan MAT 251 mass spectrometer in the Department of Geosciences at University of Bremen. Samples were measured relative to the VPDB standard. The reproducibility of the internal standard sample was 0.07‰ for $\delta^{18}O$ and 0.05‰ for $\delta^{13}C$. Data on oxygen isotopes are listed in the Appendix 10, but not discussed here, as whole-rock material is not considered sufficiently reliable to indicate true Ordovician sedimentary conditions.

Fluctuations in the stable isotope composition ($\delta^{13}C$) of oceanic dissolved inorganic carbon (DIC) are considered to be indicators of global or regional environmental changes. Unless the marine carbonates are diagenetically altered, their carbon isotope composition is expected to reflect original composition of DIC in seawater. Relatively good preservation of Middle and Upper Ordovician, and Silurian carbonate rocks in Baltoscandia makes this region unique for chemostratigraphical and palaeoenvironmental isotope studies of this period.

Secular variations of $\delta^{13}C$ in marine carbonates have become an important tool in stratigraphy, especially in the correlation of sections from the facies that formed in different biotic and sedimentary environments. Based on the data of more than twenty sections, seven Ordovician positive carbon isotope excursions have been described in the Baltoscandian area (Ainsaar *et al.* 2004b, 2007; Kaljo *et al.* 2004, 2007). All excursions, except for the end-Ordovician Hirnantian excursion, have relative $\delta^{13}C$ values around 1–2‰. The studies have demonstrated that the isotope events can be correlated across the different lithologies over the Baltoscandian palaeobasin and some excursions (Hirnantian excursion, Guttenberg excursion) even between different continents.

The Middle Ordovician carbonate succession in the Männamaa (F-367) section begins with a sedimenta-



LLA*– Llandovery; MIDDLE*– Middle Ordovician

Fig. 10. The Ordovician and lowermost Silurian bulk carbonate carbon stable isotope profile of the Männamaa (F-367) core. Refer to Appendix 1 for lithology and Appendix for sample depths.

ry gap, as the sandy limestone of the Pakri Formation (Kunda Regional Stage of the Darriwilian Stage) lies directly on the sandstone of the Kallavere Formation (Pakerort Regional Stage of the Tremadocian Stage; see Appendix 1, sheets 7, 8). The anomalously low $\delta^{13}C$ values from the Pakri Formation (–5 to –2.6‰; Fig. 10; Appendix 10) are probably due to diagenetic depletion of original marine values in the contact zone of siliciclastic and carbonate rocks. The carbon isotopic values reach the normal Ordovician level in the upper part of the Kunda Stage only.

The first of the Ordovician positive excursions, the Aseri excursion (Middle Darriwilian excursion by Meidla *et al.* 2004) has been recorded in Baltoscandia in the stratigraphic interval from the uppermost Kunda to lower Lasnamägi stages, with maximum values in the Aseri Stage (Fig. 10; Ainsaar *et al.* 2007). The value 0.85‰ from the Kandle Formation in the Männamaa core, which is relatively high for this part of the section, may represent the Aseri excursion (Fig. 10). However, the $\delta^{13}C$ values in units of low sedimentation and early cementation (thin hardground-bounded intervals) may be secondarily depleted (Ainsaar *et al.* 2007).

The early Katian Guttenberg excursion (GICE; Mid-Caradoc excursion by Ainsaar *et al.* 1999) has been described from the upper part of the Keila Stage in many sections of Baltoscandia (Ainsaar *et al.* 2004a). This positive excursion has been found in different continents and it has a global nature (Saltzman *et al.* 2003; Young *et al.* 2005). In the Männamaa (F-367) section most of the peak of the GICE seemingly falls into a stratigraphic gap between the Keila and Oandu stages, but rising relatively high $\delta^{13}C$ values (up to 1.6‰) below the stage boundary probably represent the beginning of the Guttenberg excursion (Fig. 10).

The next Katian positive excursions are differently represented in the isotope curve of the Männamaa (F-367) section (Fig. 10). The Rakvere excursion (the first Late Caradoc excursion by Kaljo *et al.* 2004) is well recognized from the lower part of the Rägavere Formation. The Saunja excursion (the second Late Caradoc excursion by Kaljo *et al.* 2004) is prominent in the Saunja Formation. The Moe excursion (Early Ashgill excursion by Kaljo *et al.* 2004) could be recognized in the interval with some elevated isotopic values in the lower part of the Moe Formation. The last of the Katian excursions, the Paroveja excursion (Mid-Ashgill excursion by Kaljo *et al.* 2007) is missing in the Männamaa section, probably due to sedimentary gaps in the Pirgu and Porkuni boundary beds. Relatively high $\delta^{13}C$ values in the middle part of the Kõrgessaare Formation of the Männamaa (F–367) section can only be compared with those of the Orjaku section (Kaljo *et al.* 2004) and have not been recorded in the Vormsi Stage in other areas or facies zones.

The end-Ordovician Hirnantian excursion (HICE), a prominent glaciation-driven isotopic event, is found in many sections in the Baltic region (Kaljo *et al.* 2001; Brenchley *et al.* 2003) and is known worldwide. Comparison of the Männamaa (F–367) curve to other curves clearly demonstrates that despite very high $\delta^{13}C$ peak values (up to 5.7‰), the upper part of the excursion is still missing because of a stratigraphic gap in the upper Porkuni Stage caused by glacioeustatic sea level drop (Kaljo *et al.* 2001). Due to this gap, the isotopic curve falls back to the prevalent (background) level (around 0‰) right at the Ordovician–Silurian boundary.

The Ordovician carbon isotope excursions have probably different origins. Some of the excursions (Aseri, Guttenberg, Hirnantian) can be correlated with sedimentary gaps in the middle shelf (e.g. Männamaa) and may be related to sea level falls. Others occur in pure micritic carbonates (Rakvere, Saunja, Paroveja) and seem to be related to sea level highstands or transgressions and need different environmental interpretations. According to Saltzman & Young (2005) and Saltzman (2005), the Katian isotope excursions signal the transition of the Earth climate to the icehouse period and end the long greenhouse period. This may also explain more frequent occurrence of isotopic excursions in the Upper Ordovician of Baltoscandia.

The study was supported by the Estonian Science Foundation (grants Nos 6207 and 6460), and Paleostudies Programme at the University of Bremen.

UPPER ORDOVICIAN ALTERED VOLCANIC ASH BEDS

Twelve altered volcanic ash interbeds from the Haljala and Keila stages of the Männamaa (F–367) core were sampled (Fig. 11; Table 1). Geochemical analyses were performed by the standard X-ray fluorescence (XRF) method at the Institute of Geology at Tallinn University of Technology. The methods of major and trace element analyses applied in the study are described in detail in Kiipli *et al.* (2008a). The study was supported by the Estonian Science Foundation (grant No. 7605).

The number of volcanic ash beds in the Männamaa (F–367) core is relatively large compared to other Estonian sections (Kiipli *et al.* 2006). High concentrations of K_2O, ranging between 7.7 and 13.7%, indicate

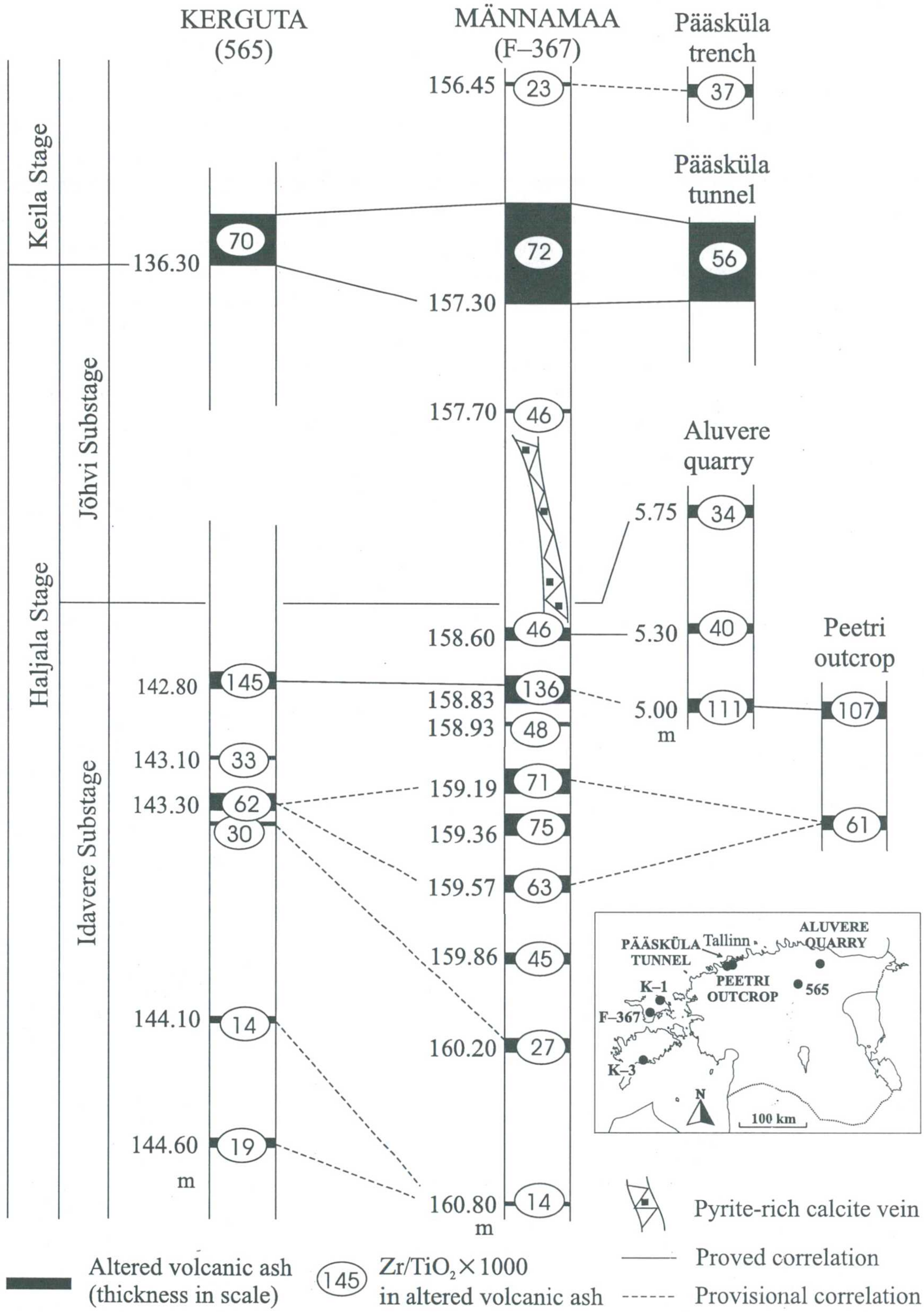


Fig. 11. Correlation of the Upper Ordovician volcanic ash beds in schematic columns of the Kerguta (565) and Männamaa (F–367) cores, supplemented by data from the Pääsküla trench and tunnel (Hints et al. 1997), Aluvere quarry and Peetri outcrop (Rõõmusoks 1970, pp. 190–193 and 226). The sketch map of the locality shows also Kuressaare (K–3) and Soovälja (K–1) drill holes, named in the text.

Table 1. XRF data of the volcanic beds of the Männamaa (F-367) core

Sample depth (m)	156.45	157.30	157.70	158.60 A	158.60 B	158.83	158.93	159.19	159.36	159.57	159.86 A	159.86 B	160.20	160.80 A	160.80 B
Bed thickness (cm)	1	40	1	4		13	1	9	11	7	6		5	1	
K-bentonite bed interval (m) and names after Bergström et al. (1995)	156.44–156.45 Grimstorp	156.90–157.30 Kinnekulle	157.69–157.70 Sinsen	158.60–158.64 Grefsen		158.70–158.83 Grefsen	158.92–158.93 Grefsen	159.10–159.19 Grefsen	159.25–159.36 Grefsen	159.50–159.57 Grefsen	159.80–159.86 Grefsen		160.15–160.20 Grefsen	160.80–160.81 Grefsen	
Colour of sampled rock	yellow	light grey	yellow	yellow	grey	light grey	yellow, hard	light grey	yellowish-grey	light grey	yellow	light grey	mixed, multi-	light grey	dark grey

Content of major elements (%):

SiO_2	54.23	59.67	55.90	59.21	59.60	63.26	52.01	59.72	59.72	60.36	56.93	59.07	54.85	59.09	48.26
TiO_2	0.55	0.25	0.70	0.33	0.32	0.21	0.38	0.43	0.27	0.73	0.74	0.88	0.56	1.89	1.06
Al_2O_3	15.05	20.38	17.49	17.82	18.73	17.89	15.06	16.90	18.91	21.00	17.99	20.04	14.80	16.61	13.76
Fe_2O_3 total	8.85	2.65	8.66	5.53	2.05	1.13	11.38	0.86	3.43	2.69	5.46	2.92	6.00	2.07	4.45
MnO	0.012	0.008	0.015	0.008	0.010	0.004	0.009	0.017	0.002	0.003	0.007	0.005	0.013	0.014	0.033
MgO	1.52	4.15	3.37	2.15	2.55	1.79	2.78	1.05	5.17	3.93	3.07	3.45	1.31	1.41	1.74
CaO	4.97	0.39	1.32	0.90	2.49	0.75	2.47	3.60	0.49	0.47	1.79	1.09	7.47	4.46	12.43
K_2O	10.53	9.03	8.49	11.10	11.10	13.69	8.30	13.34	7.91	8.20	9.29	8.97	9.71	11.36	7.71
P_2O_5	0.07	0.05	0.07	0.02	0.07	0.02	0.05	0.13	0.02	0.05	0.04	0.05	0.12	0.12	0.07
BaO	0.021	0.016	0.025	0.016	0.017	0.004	0.017	0.645	0.002	0.002	0.009	0.008	0.011	0.021	0.011
LOI 920 °C	4.25	3.80	5.05	4.41	3.48	1.22	7.73	2.36	4.50	4.15	4.86	4.02	4.48	4.16	12.33
SUM	100.06	100.40	101.09	101.51	100.43	99.97	100.21	99.05	100.43	101.59	100.18	100.50	99.33	101.21	101.86
S	4.29	0.18	2.55	2.14	0.51	0.14	4.91	0.46	0.10	0.26	2.34	0.74	2.76	0.67	1.13

Content of trace elements (ppm):

As	60	6	87	55	10	9	79	11	9	<8	28	14	28	22	23
Bi	< 10	< 10	< 10	< 10	< 10	< 10	< 10	< 10	< 10	< 10	< 10	< 10	< 10	< 10	< 10
Br	< 3	< 3	< 3	< 3	< 3	< 3	< 3	< 3	< 3	< 3	< 3	< 3	< 3	< 3	< 3
Ce	< 60	< 60	< 60	< 60	< 60	< 60	< 60	< 60	< 60	< 60	< 60	< 60	< 60	< 60	< 60
Cr	35	7	54	30	20	18	32	<10	<10	31	39	26	56	61	104
Cu	< 100	< 100	< 100	< 100	< 100	< 100	< 100	< 100	< 100	< 100	< 100	< 100	< 100	< 100	< 100
Ga	7	24	17	17	19	18	15	10	28	26	19	25	13	10	12
La	< 40	< 40	< 40	< 40	< 40	< 40	< 40	< 40	< 40	< 40	< 40	< 40	< 40	< 40	< 40
Mn	78	48	141	54	63	14	81	106	<15	16	53	36	113	107	261
Mo	9	< 3	< 3	< 3	< 3	< 3	4	< 3	< 3	< 3	< 3	< 3	9	< 3	< 3
Nb	12	12	16	17	14	28	12	18	15	30	27	23	12	23	14
Ni	28	19	19	21	24	13	26	21	15	21	42	39	34	26	32
Pb	28	6	32	36	15	6	42	7	6	13	21	32	33	23	28
Rb	71	111	112	89	89	71	89	57	121	114	101	90	78	75	77
Se	< 4	< 4	4	< 4	< 4	< 4	< 4	3	< 4	< 4	< 4	< 4	3	< 4	< 4
Sr	88	68	50	45	57	30	74	100	74	50	65	79	126	70	142
Th	8	14	22	17	16	21	14	12	18	27	25	23	10	13	7
Tl	< 12	< 12	< 12	< 12	< 12	< 12	< 12	< 12	< 12	< 12	< 12	< 12	< 12	< 12	< 12
U	< 8	< 8	< 8	< 8	< 8	< 8	< 8	< 8	< 8	< 8	< 8	< 8	< 8	< 8	< 8
V	42	15	87	24	18	< 20	43	49	12	57	72	73	70	181	159
Y	6	16	14	6	8	28	6	29	2	38	31	28	13	19	19
Zn	36	14	28	12	12	3	23	< 4	7	5	9	8	20	14	24
Zr	129	182	323	139	163	282	183	305	205	458	389	338	150	247	159

Note: LOI – loss on ignition.

that all 12 analysed samples are from K-bentonites. Some of these interbeds contain 3.6–12.4% CaO, showing substantial addition of sedimentary carbonate component to the volcanogenic material. Supplementary XRD measurements exhibited illite–smectite, K-feldspar, pyrite, gypsum and jarosite as main minerals. The first three minerals were formed in primary sedimentary–diagenetic processes. Gypsum and jarosite, however, are secondary minerals, which originate from pyrite and indicate that the core has been subjected to weathering processes during storing.

In general the K-bentonite beds in the Männamaa (F–367) core are similar to Ordovician volcanic ash beds known from other Estonian sections (Kiipli & Kallaste 2002; Kiipli *et al.* 2006). However, several interbeds of the section have high contents of sulphur and iron (Table 1). This is probably due to hydrothermal late diagenetic processes as vertical calcite veins rich in pyrite, penetrating the limestone layers, are found between volcanic beds at 157.7–158.6 m. The veins are up to 3 cm thick and have clear contacts with limestone.

The trace elements in ash beds (Table 1) can be grouped into three associations: (1) Zr, Nb, Th, Y, Ga, (2) Ti, V, Cr, Mn, Ni, Sr and (3) S, Fe, As, Mo, Pb, Zn. Elements of the first association are typical of acidic magmatic rocks and originate from volcanic ash. The second association correlates well with CaO, indicating admixture of sedimentary carbonate and terrigenous material. The third association includes several siderophile elements and is typical of pyrite.

Correlation of K-bentonites of the Männamaa (F–367) section with those of previously investigated sections is based on the Zr/TiO_2 concentration ratio (Fig. 11). Zr and Ti exhibit low mobility in sedimentary environment and their ratio well characterizes the source magma (Kiipli *et al.* 2008b). These elements were also chosen because they occur in sufficiently high concentrations to be analysed precisely by XRF (Kiipli *et al.* 2008a).

The Zr/TiO_2 ratio in the Kinnekulle K-bentonite (most widespread in the Upper Ordovician of Baltoscandia; Bergström *et al.* 1995) on the lower boundary of the Keila Stage is similar in the Männamaa (F–367) and Kerguta (565) sections (Fig. 11). A lower value was calculated for the Pääsküla tunnel sediments (North Estonia; Hints *et al.* 1997), possibly because the sample was taken from the upper part of the volcanic ash bed (thickness 27 cm), while in other sections samples were taken from the middle part of the Kinnekulle K-bentonite. Vertical changes in the composition within volcanic ash layers are common (Fisher & Schmincke 1984).

Another well correlatable K-bentonite bed occurs in the Haljala Stage, in the upper part of the Idavere Substage (Vasavere Member; Appendix 1, sheet 6). In the Männamaa (F–367) section it lies at a depth of 158.83 m and the Zr/TiO_2 ratio is 0.136. Very high Zr/TiO_2 values in this K-bentonite bed, ranging from 0.107 to 0.145, have been recorded in other North Estonian sections (Fig. 11). This correlation indicates that two K-bentonites are present above the described bed in the uppermost part of the Idavere Substage in Aluvere quarry (northeastern Estonia; Rõõmusoks 1970), but a gap occurs in the Peetri outcrop section (North Estonia; Rõõmusoks 1970), and in the Kerguta (565) and Männamaa (F–367) cores.

The deepest recognizable K-bentonite at a depth of 160.80 m in the Männamaa (F–367) section has a low Zr/TiO_2 ratio (Fig. 11) and can be correlated with beds at 144.1 m or 144.6 m in the Kerguta (565) section. Such low values are characteristic of K-bentonites of the lower part of the Vasavere Member (Kiipli *et al.* 2006).

The Na content of sanidine was established by XRD in four samples of the Männamaa (F–367) section, from depths of 156.45, 157.70, 158.60 and 158.93 m. The samples at 156.45 and 158.93 m samples revealed a weak sanidine reflection due to a high content of authigenic K-feldspar. The samples from 157.70 m (Jõhvi Substage) and 158.60 m (the upper part of the Idavere Substage) revealed a sufficiently strong reflection for the calculation of the Na-component in sanidine: 23.0±1.5 and 23.3±1.5 mol%, respectively. These values coincide with previous data and confirm the correlation of the sample at 157.70 m with the Sinsen K-bentonite in the Kuressaare section (K–3; depth 369.2 m) and of the lower one with K-bentonite in the Grefsen Series in the Soovälja (K–1; depth 177.45 m) section (Kiipli & Kallaste 2002, 2005).

Five of the 12 K-bentonite beds analysed from the Männamaa (F–367) section have been correlated over the North Estonian area (Fig. 11). For other provisional correlations further geochemical study of representative sections and support from lithological and palaeontological data are needed.

CHEMICAL COMPOSITION AND PHYSICAL PROPERTIES OF THE ROCK

The Ordovician (Lower, Middle, Upper) and lowermost Silurian (Llandovery) section of the Männamaa (F-367) core (Appendix 1) is represented by primary and dolomitized carbonate (variously argillaceous limestones, dolomitic limestones, dolostones, calcitic and dolomitic marlstones) and siliciclastic rocks. A total of 70 rock samples were studied by gravimetric and titration chemical analysis, whereas 54 samples were measured for porosity and density by the water saturation method (Appendix 11).

Methods

The chemical parameters were determined by gravimetric (insoluble residue) and titration (CaO, MgO, FeO and Fe_2O_3total) chemical analysis in the laboratory of the Institute of Geology at Tallinn University of Technology (IGTUT). Physical properties of the rock were analysed on cylinders 25.4 mm in diameter and 27–28 mm high in the IGTUT using water saturation during one week at room temperature and normal pressure. Effective porosity, wet and grain density were calculated by formulas published in Shogenova *et al.* (2006). Chemical and physical parameters were interpreted together using regression and correlation analysis by the Statistica 7 software (StatSoft). The significance of the correlation coefficients was determined by the program employing standard statistical criteria such as F-test.

Composition of rock samples

The insoluble residue (IR), MgO and CaO contents were used to discriminate the rock lithology (Fig. 12; Appendix 11). Distinction of rock types is based on the classification of carbonate rocks used in Estonia (Vingisaar *et al.* 1965; Nestor 1990; Kleesment & Shogenova 2005) and on international classifications (Jackson 1997; Miall 2000; Selley 2000). The rocks were subdivided into nine lithological groups based on their chemical composition (Table 2; Fig. 12).

"Pure" and argillaceous limestones predominate in the investigated section (Appendix 1), while dolomitization was detected only in the Lower Ordovician rocks (Kallavere Formation), in the lower part of the Middle Ordovician (Pakri to Väo formations) and in some Upper Ordovician formations (partly in the Hir-

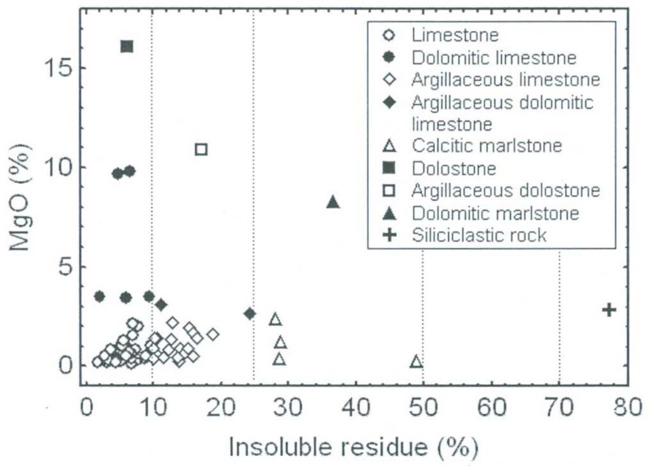


Fig. 12. MgO content versus insoluble residue content.

Table 2. Lithological groups of the rock in the Männamaa (F-367) core

Lithological group	Rock name	Number of samples	Insoluble residue (%)	$CaMg(CO_3)_2$ (%)
1	Limestone ("pure")	36	< 10	< 10
2	Dolomitic limestone	5	< 10	10–50
3	Argillaceous limestone	19	10–25	< 10
4	Argillaceous dolomitic limestone	2	10–25	10–45
5	Calcitic marlstone	4	25–50	$CaCO_3 > CaMg(CO_3)_2$
6	Dolostone	1	< 10	> 65
7	Argillaceous dolostone	1	10–25	> 50
8	Dolomitic marlstone	1	25–50	$CaCO_3 < CaMg(CO_3)_2$
9	Siliciclastic rock	1	> 70	< 30

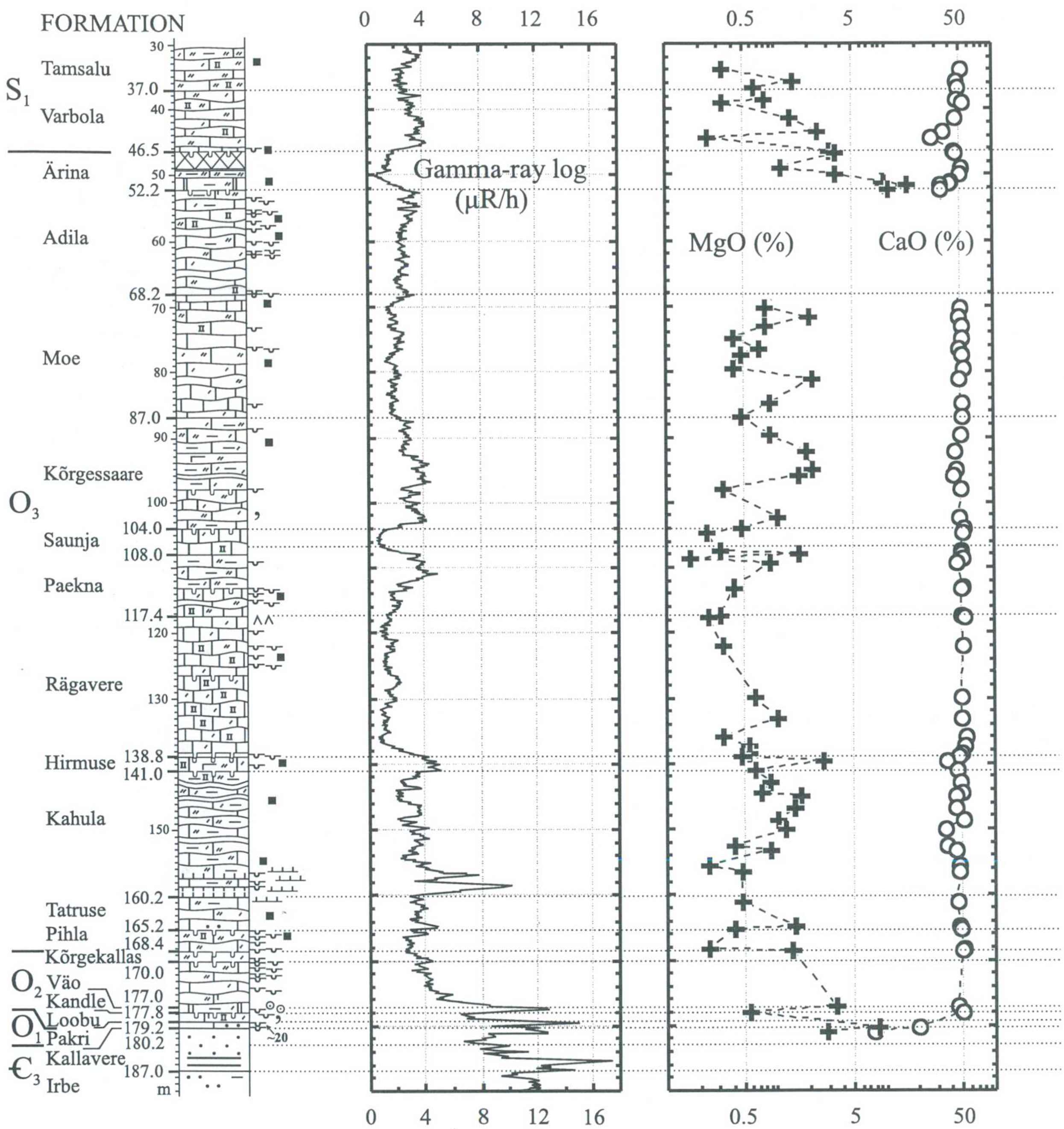
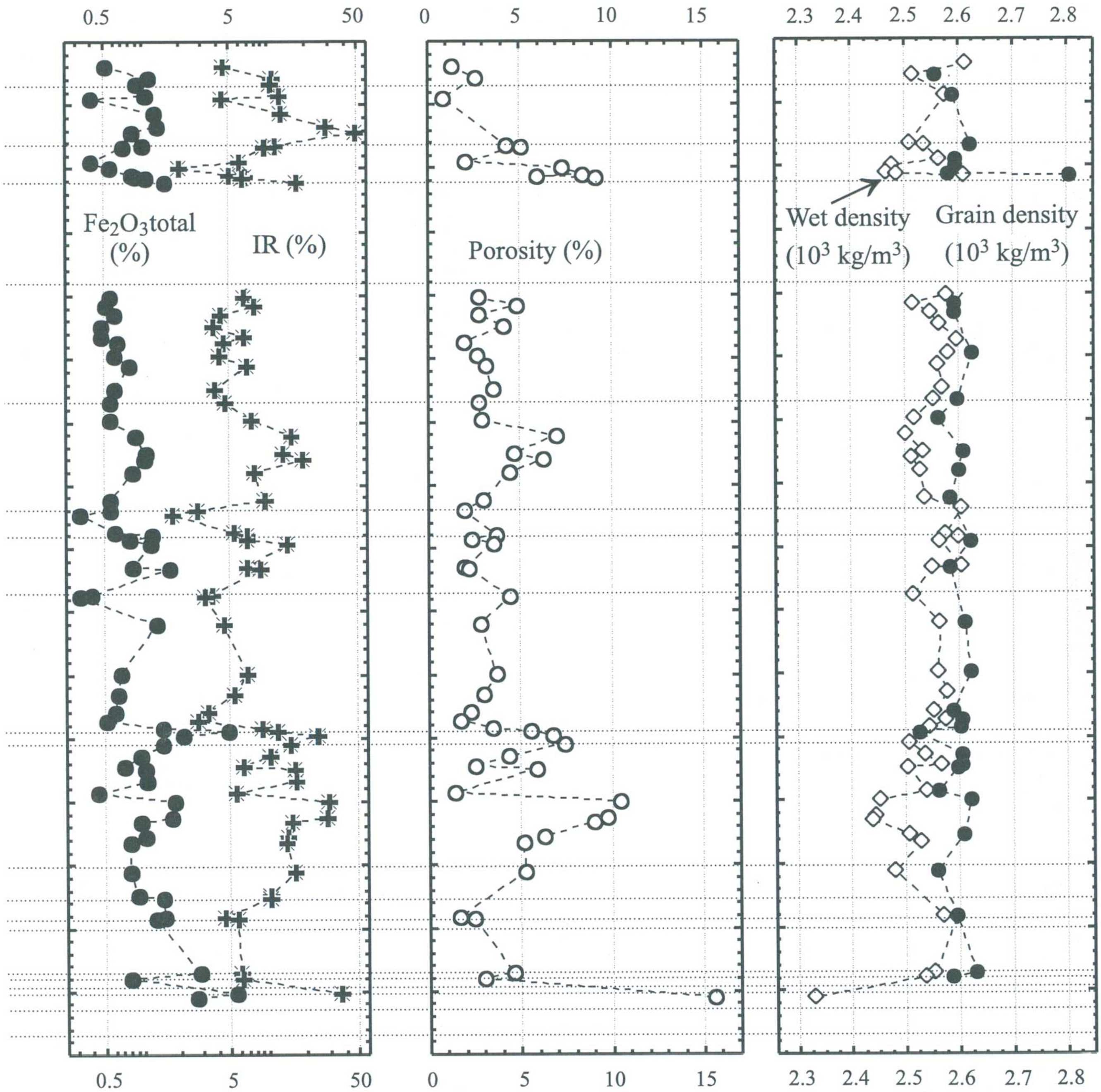


Fig. 13. Gamma-ray log, chemical composition and physical parameters of the Männamaa (F-367) core. Є$_3$ – Furongian (Upper Cambrian); O$_1$ – Lower Ordovician; O$_2$ – Middle Ordovician; O$_3$ – Upper Ordovician; S$_1$ – Llandovery. Refer to Appendix 1 for lithology and distribution of the regional stages.

muse, Adila and Ärina formations; see Fig. 13 and Appendix 1). Siliciclastic rocks (sandstone) are common in the Lower Ordovician section only.

The total iron (Fe_2O_3total) content of most of the studied rocks correlates with IR content, with the common correlation coefficient (*R*) 0.49; correlation for carbonate rocks is only 0.47 (Figs 13, 14; Appendix 11). The correlation coefficient for the Llandovery (Silurian) rocks is 0.8, except for one sample of calcitic marlstone having 48.98% IR and only 0.84% total iron, which is lower than expected (Appendix 11). Slight deviations in the correlation were registered also for some Upper Ordovician limestone samples (Pihla, Rägavere and Paekna formations). The lowest total iron content in the Llandovery "pure" limestones is 0.40–0.52%, in the Upper Ordovician limestones 0.32–0.60% (Fig. 13). The highest iron content of "pure" limestones reaches up to 1.44–1.64% in the Pihla, Rägavere and Paekna formations and could be explained by pyrite admixture.



Total iron content is 0.84–1.32% in the Llandovery (Juuru Stage) argillaceous limestones and calcitic marlstones, while in Ordovician argillaceous limestones it is in the range of 0.88–1.76% and reaches 2.08% and 4.76% in two samples of the Hirmuse Formation (Oandu Stage). The total iron content 0.72–0.88% of dolomitic limestones of the Ärina Formation (Porkuni Sage) is as low as that of "pure" limestones, but 2.84% in dolomitic limestone of the Kandle Formation (Aseri Stage). Dolostone of the Ärina Formation contains 1.08% of Fe_2O_3total (Appendix 11).

The highest total iron contents for the given IR (Figs 13, 14; Appendix 11) were determined in oolith-bearing dolomitic limestone of the Kandle Formation (2.84%), argillaceous limestone of the Hirmuse Formation (4.76%) and pyrite-rich dolomitic marlstone of the Kallavere Formation (5.44%). The high iron value of the Kallavere Formation is explained by high clay content and pyrite admixture, and is accompanied by the highest FeO content in this rock (0.78%).

In general, FeO content correlates with Fe_2O_3total content with $R = 0.76–0.77$ (Fig. 14B). The Fe_2O_3/FeO ratio varies widely in the studied rocks, being the lowest (2.8 and 4.6) in two argillaceous limestones (depths

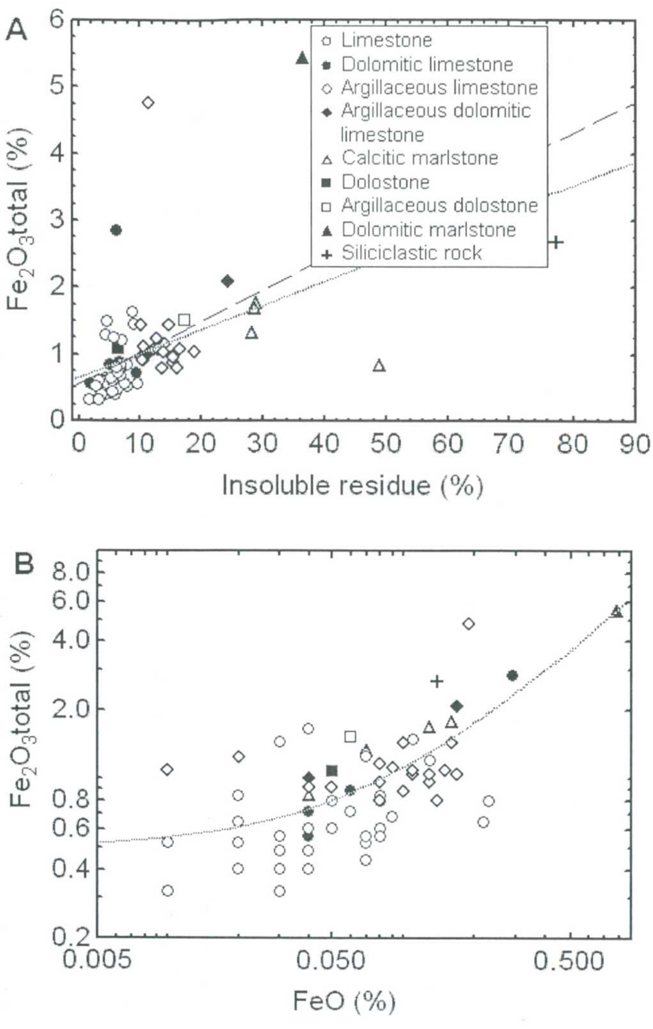


Fig. 14. (A) Fe_2O_3total versus insoluble residue content. Correlation coefficient R = 0.49 for all rocks (70 samples; dotted regression line), R = 0.47 for carbonate rocks (69 samples; dashed regression line). (B) Fe_2O_3total versus FeO content, both in log-decimal scale. Correlation coefficient R = 0.76 for all rocks (70 samples; dotted regression line), R = 0.77 for carbonate rocks (69 samples).

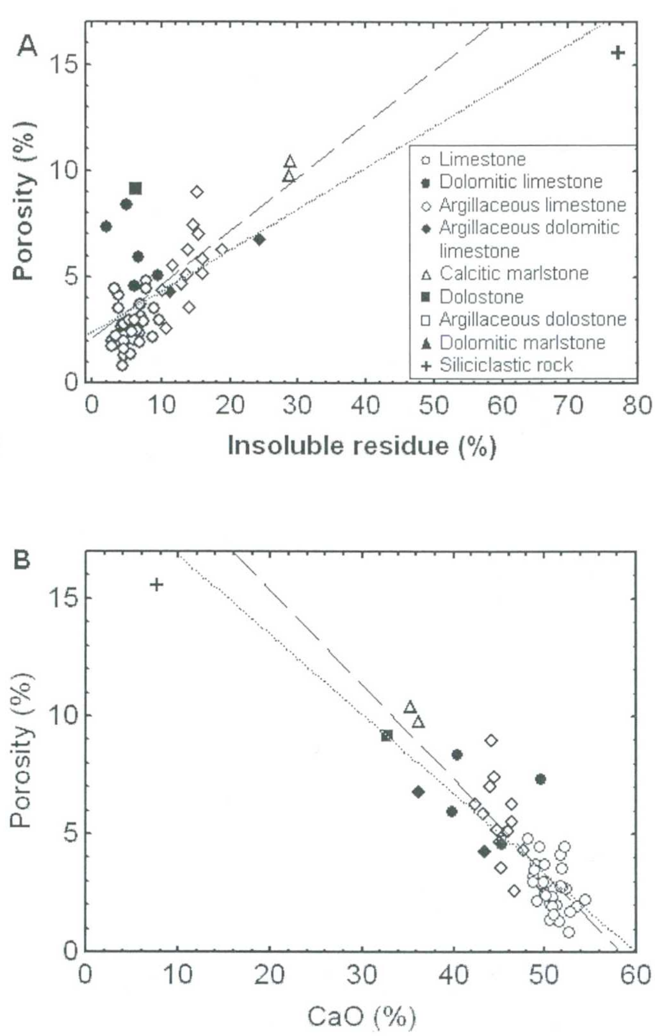


Fig. 15. (A) Porosity versus insoluble residue content. Correlation coefficient R = 0.77 for all rocks (56 samples; dotted regression line), R = 0.67 for carbonate rocks (55 samples; dashed regression line). (B) Porosity versus CaO content. Correlation coefficient R = −0.88 for all rocks (56 samples; dotted regression line), R = −0.84 for carbonate rocks (55 samples; dashed regression line).

161.2 m and 177.9 m, respectively). The FeO content changes from 0.01% to 0.78%, being less than 0.1% in the upper part of the Männamaa (F-367) section (Moe, Ärina, Varbola and Tamsalu formations). In the other parts of the section it is in the range of 0.02–0.23% but reaches 0.29% in the Kandle Formation and 0.78% in the Kallavere Formation (Pakerort Stage).

Porosity and density

All studied samples of the Männamaa (F-367) core show significant positive correlation (R = 0.67–0.77) between porosity and IR content (Figs 13, 15). The samples with positive porosity–IR correlation are characterized by primary porosity associated with sedimentation processes. The porosity that does not correlate with clay content is called secondary and could be associated with diagenetic processes (Shogenova *et al.* 2003, 2005, 2006, 2007). The most significant scatter observed on the porosity–IR plot is caused by two dolomitic limestone samples and one dolostone sample (depths 49.9, 51.1 and 51.4 m, respectively) from the Ärina Formation (Porkuni Stage; Fig. 15A), supporting their secondary porosity.

The lowest porosity (0.8–4.8%) and highest wet density (2560–2640 kg/m^3) were measured for "pure" limestones. In argillaceous limestones the porosity was 2.58–8.97% and wet density 2440–2510 kg/m^3, in dolomitic limestones respectively 4.6–8.4% and 2470–2550 kg/m^3, in calcitic marlstones 9.8–10.4% and 2440–2450 kg/m^3, and in one dolostone sample 9.1% and 2610 kg/m^3.

Among carbonates dolomitized rocks of the Ärina Formation (Porkuni Stage) in the upper part of the section and argillaceous rocks of the lower part of the

Kahula Formation (Keila Stage) are the most porous. The latter rocks have the lowest bulk density among the studied carbonate samples. Carbonate cemented sandstone from the Kallavere Formation (Pakerort Stage) has the porosity of 15.6% and density of 2330 kg/m^3. Grain density of the rocks is in the limits of 2560–2640 kg/m^3 for all rock types except for one dolostone with the grain density of 2810 kg/m^3

Gamma-ray log

The highest natural gamma radioactivity anomalies in the Ordovician and Silurian section of the Männamaa (F-367) core (Fig. 13) were determined for sandstones of the Kallavere Formation (Pakerort Stage). These can be explained by high potassium content of sandstones and high phosphorite content of shells, which are able to adsorb uranium. The next peak was registered in the Kandle Formation (Aseri Stage) including iron ooliths and is explained by the adsorption of uranium by iron minerals (Shogenova 1989). Natural radioactivity anomalies are also caused by several K-bentonite layers in the Vasavere Member of the Kahula Formation (Haljala Stage; Appendix 1, sheet 6). In the other parts of the sections gamma-ray (GR) log readings permit discrimination between "pure" limestones (the lowest log readings) and more argillaceous carbonate rocks (increased log readings).

In general, the GR log correlates with insoluble residue content and porosity (Fig. 13). As the Männamaa (F-367) core is represented mainly by primary carbonate rocks, the GR log (excluding anomalies), insoluble residue and porosity mainly correlate with the primary clay content of the rocks. The influence of dolomitization is observed locally (Kallavere and Ärina formations).

Conclusions

The examined samples of the Männamaa (F-367) drill core represent mainly Ordovician and Silurian primary carbonate rocks. Usually "pure" limestones are intercalated by argillaceous limestones and calcitic marlstones. Dolomitized rocks are common in the Kallavere (diagenetic dolomite cementation), Loobu, Kandle, Väo (only the lower part), Hirmuse, Adila (topmost part) and Ärina formations.

The lowest GR log readings, IR content, porosity, FeO and Fe_2O_3total contents and the highest bulk density were determined for limestones of the Rägavere (Rakvere Stage), Saunja (Nabala Stage) and Moe formations (Pirgu Stage). The GR log readings and IR content were low also in partly dolomitized rocks of the Ärina Formation (Porkuni Stage), but total iron content and porosity were somewhat higher.

Higher GR log readings, IR content, porosity and Fe_2O_3total content were measured for argillaceous limestones of the Kahula, Paekna, Kõrgessaare and Varbola formations (Fig. 13).

The increase in the iron content of "pure" limestones to 1.44–1.64% in the Pihla, Rägavere and Paekna formations could be explained by pyrite admixture. The decrease in the iron content of some argillaceous rock samples is mainly due to increased supplement of quartz, potassium feldspar and other Fe-poor minerals.

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APPENDIX 1

Description of the Männamaa (F-367) core

The description is given in a standardized form. The table is divided into nine columns based on the type of information.

STANDARD UNITS — Chronostratigraphic and geological time units.

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

CORE BOX NO./FIGURES — Numbers of boxes, location of the intervals of core illustrated on compact disc in read-only memory (Palaeoproterozoic, Lower Cambrian, Furongian (Upper Cambrian), Ordovician (Lower, Middle, Upper), Silurian (Llandovery) and Quaternary photo-log in Appendix 2, and detailed core photos marked as D-1...77 in Appendix 3).

DEPTH/SAMPLES — Depth of the boundaries and sample levels: A, acritarchs; Ch, chitinozoans; F, X-ray fluorescence samples; Is, stable isotope analyses ($\delta^{13}C$ and $\delta^{18}O$); K, chemical and physical properties; O, ostracods; S, spectral analyses; T, thin sections; X, X-ray diffractometry.

LITHOLOGY — For legend see the next page. The core section is given alternately at scales of 1:200 and 1: 500.

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.

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) and medium-crystalline (0.1–1.0 mm). The percentage of allochems (mainly bioclasts and clastic material) is also indicated. Clastic fractions (size of particles; in italics) are described as follows: clay (< 0.005 mm), silt (0.005–0.05 mm), sand (0.05–2.0 mm), gravel (2–10 mm) and pebbles (10–100 mm). Grain size limits for igneous rocks (in italics) are: fine-grained (< 1 mm), medium-grained (1–5 mm) and coarse-grained (5–30 mm).

Appendix 1 continued

LEGEND

limestone (in general)

argillaceous limestone

dolomitized limestone

sandy (a) and silty (b) limestone

dolostone

argillaceous dolostone

biohermal limestone

calcitic marlstone

claystone

silty claystone

siltstone

clayey siltstone

sandstone

shale

K-bentonite bed, on (a) or under (b) the boundary

biotite, sillimanite and cordierite gneisses

migmatite granites

weathered igneous rocks

cataclasis and mylonitization of igneous rocks

skeletal limestones: grains 10–25% (a) and grains 25–50% (b)

crypto- and microcrystalline limestone

fine bioclasts, pyritized

coarse bioclasts, pyritized

horizontal bedding: thin (a), medium (b) and thick bedding (c)

wavy bedding

nodular

thin intercalation

horizontal, thin bedding (a) and inclined bedding (b) in sand-, silt- and claystones

discontinuity surface

4 number of discontinuity surfaces between the upper and the lower surface

slickenside

veins

stylolites

caverns (vugs)

burrows

pyritic mottles

ooliths

clastic material

silicification

glauconite grains

kerogen

pyrite

calcite

micas (in general)

bitumen

mottled, red-coloured and yellow streaks

tabulate corals

stromatoporoids

rugosae

brachiopods

trilobites

ostracodes

echinoderms (crinoids)

bryozoans

calcareous algae

gastropods

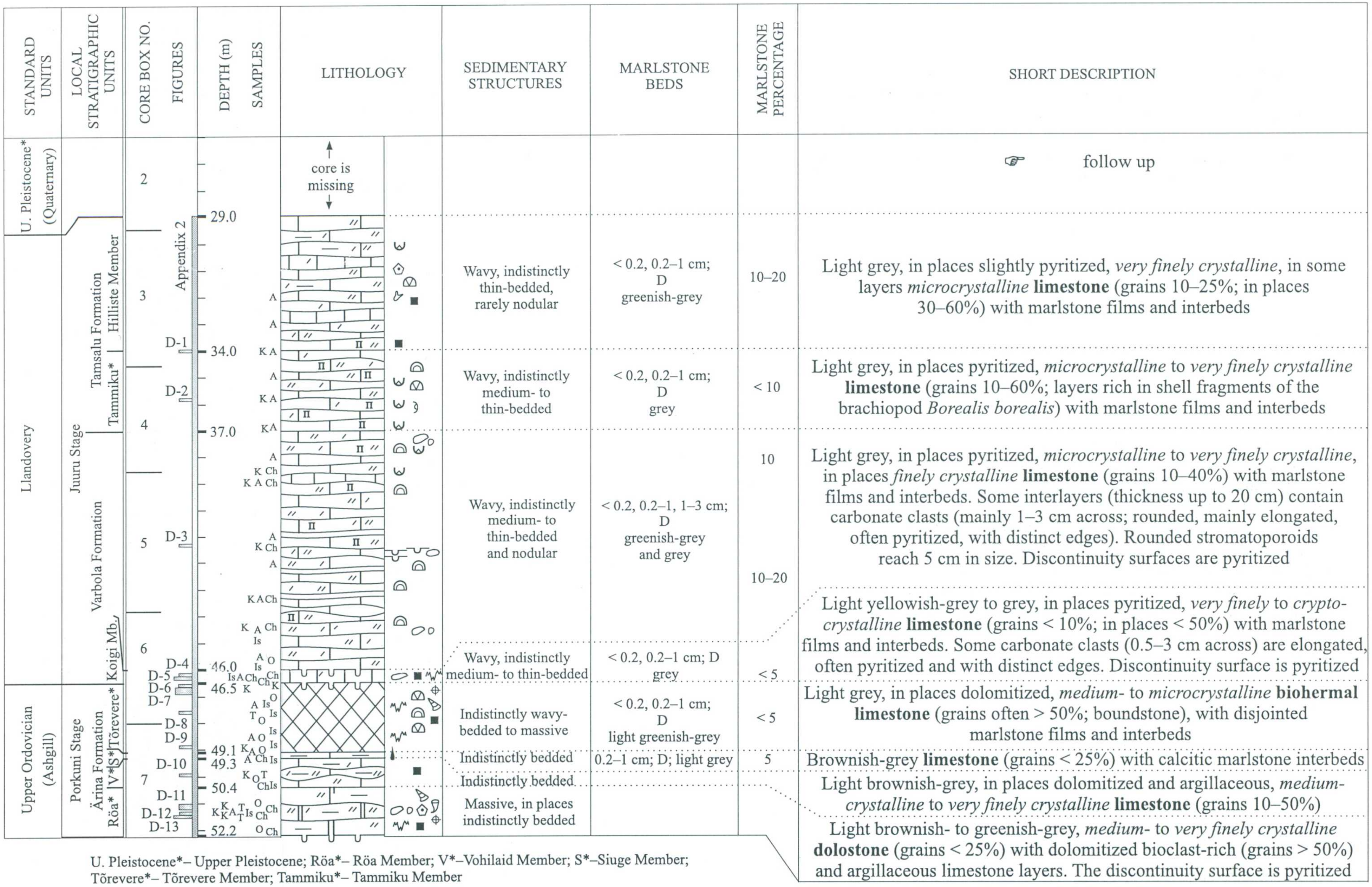
cephalopods

APPENDIX 1, SHEET 1

DESCRIPTION OF THE MÄNNAMAA (F–367) CORE

Location: 58° 50' 18" N, 22° 37' 42" E. Length of the core 358.3 m. Elevation of the top 17.0 m above sea level.

STANDARD UNITS	LOCAL STRATIGRAPHIC UNITS	CORE BOX NO.	FIGURES	DEPTH (m)	SAMPLES	LITHOLOGY (SCALE 1:200)	SEDIMENTARY STRUCTURES	MARLSTONE BEDS	MARLSTONE PERCENTAGE	SHORT DESCRIPTION
Holocene (Quaternary)			Appendix 2	0.0		core is missing; core is missing	(Core yield 25%)			Cultivated soil cover underlain by gravel. Carbonate pebbles (1–10 cm across) make up about 80%, the rest are of igneous rocks. The lower boundary of the complex was revealed by gamma logging
Upper Pleistocene (Quaternary)		2		12.0		core is missing				Varved clay revealed by gamma logging
				20.0		core is missing				Till with pebbles and cobbles, revealed by gamma logging

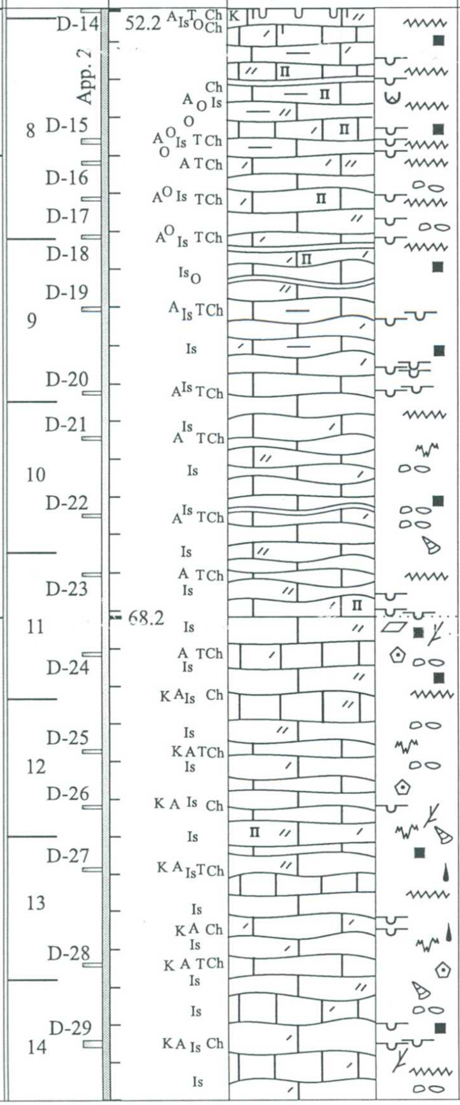


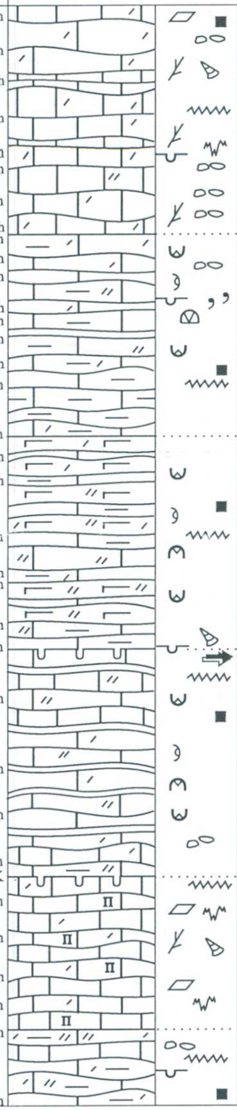
U. Pleistocene*– Upper Pleistocene; Röa*– Röa Member; V*–Vohilaid Member; S*–Siuge Member; Tõrevere*– Tõrevere Member; Tammiku*– Tammiku Member

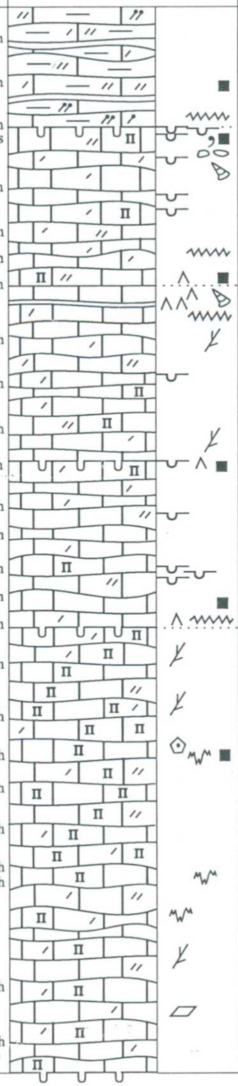
MÄNNAMAA (F-367) DRILL CORE

STANDARD UNITS	LOCAL STRATIGRAPHIC UNITS	CORE BOX NO. / FIGURES / DEPTH (m) / SAMPLES / LITHOLOGY	SEDIMENTARY STRUCTURES	MARLSTONE BEDS	MARLSTONE PERCENTAGE	SHORT DESCRIPTION
Upper Ordovician (Ashgill)	Pirgu Stage; Adila Formation; Kabala Member	see log	Wavy, indistinctly thin- and medium-bedded with nodular intervals	< 0.2, 0.2–2 (3) cm; IND (D) grey and greenish-grey	5–20	Light grey, the upper 2.5 m light yellowish- to brownish-grey, the uppermost part dolomitized, in places greenish-grey and pyritized, *microcrystalline* to *very finely crystalline* **limestone** (grains 10–25%, in places < 10% or > 50%) with argillaceous limestone and marlstone (bioclasts up to 20%) interbeds. Carbonate clasts (0.5–3.0 cm across) containing intervals are up to 20 cm thick. At 54.1 m the pentamerid brachiopod *Holorhynchus giganteus* is found. Discontinuity surfaces are pyritized, rock impregnation reaches in places 5–10 cm below the surface
Upper Ordovician (Ashgill)	Pirgu Stage; Moe Formation	see log	Wavy, thick-bedded, in places nodular and indistinctly thin- to medium-bedded intervals	< 0.2, 0.2–1 (2–5) cm; D dark grey and brownish-grey	< 5	Light brownish-grey, *finely* to *very finely crystalline*, in places *medium-* to *finely crystalline*, in the uppermost part *microcrystalline* to *very finely crystalline* **limestone** (grains 10–30%, in places < 10% and < 50%) with marlstone interbeds. Carbonate clasts (0.5–4.0 cm across) are observed in up to 10 cm thick intervals. Fragments of calcareous algae *Palaeoporella*? (=*Dasyporella*) are found. Discontinuity surfaces are pyritized

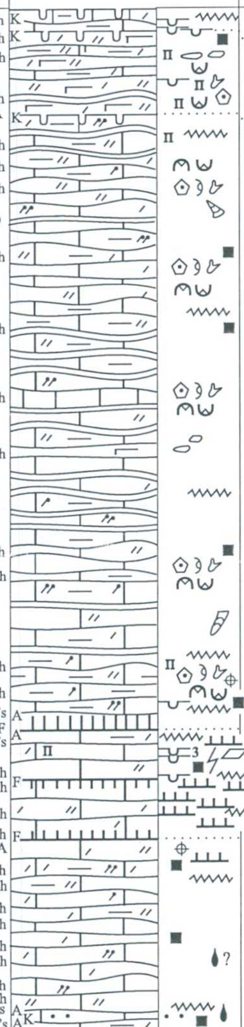
CORE BOX NO.	FIGURES	DEPTH (m)	SAMPLES	LITHOLOGY



STANDARD UNITS	LOCAL STRATIGRAPHIC UNITS	CORE BOX NO. / FIGURES	DEPTH (m) / SAMPLES	LITHOLOGY	SEDIMENTARY STRUCTURES	MARLSTONE BEDS	MARLSTONE PERCENTAGE	SHORT DESCRIPTION
Upper Ordovician (Ashgill)	Pirgu Stage, Moe Formation	15, 16; D-30, D-31					< 5	☞ follow up
	Vormsi Stage, Kõrgessaare Formation	16, 17; D-32; Appendix 2	87.0		Wavy, indistinctly thin- and medium-bedded, rarely thick-bedded and nodular	< 0.2, 0.2–2 cm; IND (D) dark grey	5–10	Light grey, slightly argillaceous, *microcrystalline* to *very finely crystalline* **limestone** (grains 10–30%) with interbeds of highly argillaceous limestone and marlstone (bioclasts up to 30%). The discontinuity surface is pyritized
		18; D-33	92.4		Wavy and horizontal, indistinctly thin- and medium-bedded, in places nodular	0.2–10 cm; IND dark greenish-grey	20–40	Intercalation of **calcitic marlstone** (bioclasts in places up to 50%) and greenish-grey, medium to highly argillaceous, *microcrystalline* to *very finely crystalline* **limestone** (grains 10–25%). Phosphatized discontinuity surfaces lie on the lower boundary
		19, 20; D-34, D-35, D-36	98.0		Wavy, indistinctly thin- and medium-bedded, in places nodular	0.2–2 (4) cm; IND and D dark brownish-grey	5–10	Light grey and yellowish-grey, *very finely crystalline* to *microcrystalline* **limestone** (grains 10–25%, in places < 10%, often pyritized) with marlstone (bioclasts up to 30%) interbeds. A phosphatized and pyritized discontinuity surface lies on the lower boundary
(Caradoc)	Nabala Stage, Saunja Fm.	21; D-37, D-38, D-39	104.0		Wavy, indistinctly thin- and medium-bedded	< 0.2, 0.2–0.5 cm; D dark brownish-grey	1–2	Light greyish-beige, *cryptocrystalline* to *microcrystalline*, in patches *very finely crystalline* **limestone** (grains < 10%, in places < 25%) with rare calcitic marlstone interbeds. Calcite-filled primary and secondary veins are found
	Paekna Fm.	22; D-40, D-41	108.0					☞ follow down

STANDARD UNITS	LOCAL STRATIGRAPHIC UNITS	CORE BOX NO.	FIGURES	DEPTH (m)	SAMPLES	LITHOLOGY	SEDIMENTARY STRUCTURES	MARLSTONE BEDS	MARLSTONE PERCENTAGE	SHORT DESCRIPTION
Upper Ordovician (Caradoc)	Nabala Stage; Paekna Formation	22	D-42	113.2	Is, Ch, A, Is, Ch, Is, KT, K, Ch, Is		Wavy, indistinctly thin- and medium-bedded, rarely indistinctly nodular	(< 0.2), 0.2–4 cm; IND (D) dark greenish-grey	5–20	Light greenish-grey, slightly argillaceous, *very finely crystalline* **limestone** (grains in places 25–50%) with **marlstone** (bioclasts up to 50%) interbeds. At 108.5–109.1 m lies a beigish-grey, burrowed *micro-* to *crypto-crystalline* limestone interbed. Discontinuity surfaces are pyritized
	?; Paekna Formation	23	D-43, D-44	117.4	A, Is, Ch, A, Is, Ch, Is, Ch, KK, Is, Ch		Wavy, indistinctly thin- and medium-bedded	< 0.2, 0.2–1 cm; D dark greenish-grey	< 5	Light grey, *microcrystalline* to *very finely crystalline* **limestone** (grains 10–25%) with **marlstone** (bioclasts up to 10%) interbeds. Discontinuity surfaces are pyritized
	Rakvere Stage; Rägavere Formation; Tudu Member	24, 25	D-45, D-46, D-47; Appendix 2	126.4	Is, Ch, A, Is, Ch, Is, A, Ch, Is, K, Ch, Is, Ch, Is, Ch, A, Is, Ch, Is, Ch, A, Is, Ch		Wavy, indistinctly thin- and medium-bedded, very rarely thick-bedded	< 0.2, 0.2–0.5 cm; D greenish-grey	< 5	Light beigish-grey, *crypto-* to *microcrystalline*, in places very finely crystalline **limestone** (grains 10–25%) with rare **marlstone** interbeds. The uppermost 0.5 cm contains kerogenous interlayers, at 117.45 and 117.70 m lie dark brown distinct kukersite oil shale interbeds (thickness respectively 1 cm and 5 cm). Discontinuity surfaces are pyritized
	Rakvere Stage; Rägavere Formation; Piilse Member; Kiideva Mb.	26, 27, 28, 29	D-48, D-49	138.2	Is, Ch, Is, Ch, Is, K, A, Ch, Is, Ch, Is, Ch, Is, Ch, K, Ch, Is, A, Is, Is, K, A, Ch, Is, K, O, Ch, A, Is, O		Wavy, indistinctly thin- and medium-bedded	< 0.2, 0.2–0.5 (1) cm; D grey	< 5	Light grey, with small pyrite mottles (especially at 128.0–133.0 m), in places with beige shade, *crypto-* to *microcrystalline* **limestone** (grains < 10%, in places 30%) with rare **marlstone** interbeds. In places calcite-filled veins occur

MÄNNAMAA (F-367) DRILL CORE



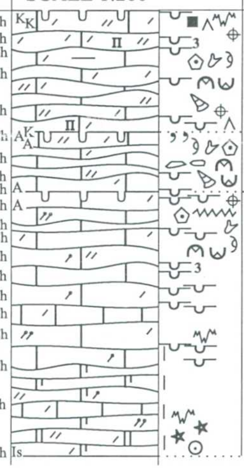
STANDARD UNITS	LOCAL STRATIGRAPHIC UNITS	CORE BOX NO.	FIGURES	DEPTH (m)	SEDIMENTARY STRUCTURES	MARLSTONE BEDS	MARLSTONE PERCENTAGE	SHORT DESCRIPTION
Upper Ordovician (Caradoc)	Oandu St.; Hirmuse*; R*; T*	29; D-50, D-51, D-52		138.2; 138.8	Wavy, indistinctly medium- and thin-bedded	< 0.2, 0.2–0.5 cm; D and IND greenish-grey	5	Light grey, slightly argillaceous, *very finely crystalline* to *microcrystalline* **limestone** (grains 10–25%, rarely < 40%) with rare **marlstone** interbeds. Discontinuity surfaces are pyritized
		D-53		141.0	Wavy, indistinctly medium- and thin-bedded	0.2–3 cm; D and IND dark greenish-grey	40	Intercalation of **calcitic marlstone** (bioclasts in places up to 40%) and light greenish-grey, in places dolomitized, slightly to highly argillaceous, *microcrystalline* to *very finely crystalline* **limestone** (grains 10–30%). Clay content increases downwards. Discontinuity surfaces are pyritized
	Keila Stage; Kahula Formation	30; D-54, D-55, D-56; 31; D-57, D-58, D-59; 32; D-60, D-61; 33; D-62			Indistinctly nodular and thick- to medium-bedded, with micro- to thin-bedded intervals (thickness up to 10 cm)	< 0.2, 0.2–5 cm; IND dark greenish-grey and greenish-grey	30–50; 20; 30–40; 30–50	Intercalation of **argillaceous limestone** and **calcitic marlstone**. **Limestone** (grains 25–60%) is light grey and light greenish-grey, mainly medium to highly argillaceous, *microcrystalline* to *very finely crystalline*. Grain content increases upwards, in places bioclasts are accumulated in up to 5 cm high conic bodies with distinct edges. At 144.0–146.0, 148.0–148.8 and 154.0–155.0 m interlayers of slightly argillaceous, often *microcrystalline* limestone are common. **Marlstone** (bioclasts in places up to 40%) prevails in the intervals 141.0–142.6, 146.2–147.4, 149.0–152.6 and 155.0–156.9 m, where calcite and clay content changes in thin layers and patches. At 156.44 m and on the lower boundary lie greenish-grey K-bentonite beds (thickness respectively 1 and 40 cm)
							10–20; 20–30	Light greenish-grey, *very finely crystalline* **limestone** (grains 25–50%) with rare marlstone interbeds. At 157.7 m lies a 2 cm thick K-bentonite bed. At 157.7–158.6 m is a vertical calcite vein (thickness 1–2 cm) with pyrite aggregates. Discontinuity surfaces are pyritized
	Jõhvi*	D-63; 34	Appendix 2	157.3; 158.6	Indistinctly medium- and thick-bedded	0.2–0.5 cm; IND greenish-grey	< 5	Light grey and greenish-grey, *very finely crystalline* **limestone** (grains in places 25–50%) with K-bentonite* and marlstone (contains spicules of the sponge *Pyritonema subulare*) interbeds. K-bentonite beds (the lower boundary sharp) have two or three layers of different colour (dark to light greenish-grey, yellowish-grey) and cementation
	Haljala Stage; Vasa*			160.2	Horizontal and wavy, medium-bedded	0.2–5 cm; D and IND dark greenish-grey	< 10	
	Idavere Substage; Tatruse Formation	D-64; 35; 36; D-65; D-66		165.2	Wavy, indistinctly thin- and medium-bedded, in the uppermost part thick-bedded	< 0.2, 0.2–1 (2) cm; IND (D) greenish-grey	< 5	Light greenish-grey, *very finely crystalline* **limestone** (grains 25–50%, in places > 50%) with marlstone interbeds. At 164.8–164.9 m silty limestone (in the lowermost part bituminous) with a siltstone interbed (Kärdla Formation) is found, covered with burrowed rock. A wavy, pyritized discontinuity surface lies on the lower boundary

←KÄRDLA IMPACT EVENT

Jõhvi*– Jõhvi Substage; Hirmuse*– Hirmuse Formation; R*– Rägavere Formation; Vasa*– Vasavere Member; T*–Tõrremägi Member

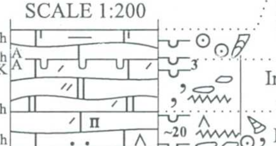
K-bentonite* beds of the Vasavere Member (Idavere Substage, Haljala Stage): 158.60–158.64 m; 158.70–158.83 m; 158.92–158.93 m; 159.10–159.19 m; 159.25–159.36 m; 159.50–159.57 m; 159.80–159.86 m; 160.15–160.20 m.

SCALE 1:200

STANDARD UNITS	LOCAL STRATIGRAPHIC UNITS	CORE BOX NO. / FIGURES	DEPTH (m) / SAMPLES	LITHOLOGY	SEDIMENTARY STRUCTURES	MARLSTONE BEDS	MARLSTONE PERCENTAGE	SHORT DESCRIPTION
Upper Ordovician (Caradoc)	Kukruse St. Pihla Fm.	D-67, 36, D-68	165.2		Indistinctly thin- to medium-nodular, in the uppermost part thick-bedded	< 0.2, 0.2–0.5 cm; D grey and brownish-grey	< 2	Light grey and brownish-grey, in some thin layers slightly kerogenous, *microcrystalline* to *very finely crystalline* **limestone** (grains 10–30%, in places 30%) with calcitic marlstone interbeds. Pyritized discontinuity surfaces are often excavated and impregnation reaches up to 30 cm
Middle Ordovician (Llanvirn)	Uhaku Stage Kõrgekallas Fm.	D-69, 37, D-70, D-71	168.4, 170.0		Indistinctly medium-bedded, in the middle part thin-bedded and nodular	< 0.2, 0.2–0.5 cm; D greenish-grey	< 5	Light grey and greenish-grey, in places slightly argillaceous, *microcrystalline* to *very finely crystalline* **limestone** (grains 10–30%) with marlstone interbeds. Discontinuity surfaces are pyritized and phosphatized
	Lasnamägi Stage ? Väo Formation	38, 39	177.0		Horizontal and wavy, indistinctly thick-bedded, with thin- to medium-bedded intervals (thickness 5–10 cm)	< 0.2, 0.2–0.3 cm; D grey	< 5	Light grey, in places with brown spots, *microcrystalline* to *very finely crystalline* **limestone** (grains 10–25%) with rare marlstone interbeds. At 174.8–175.4 and 176.0–177.0 m occur grey dolomitized limestone and dolostone with brownish-red patches. Discontinuity surfaces (impregnation weak) are phosphatized and pyritized. Rare calcareous ooliths are found on the lower boundary

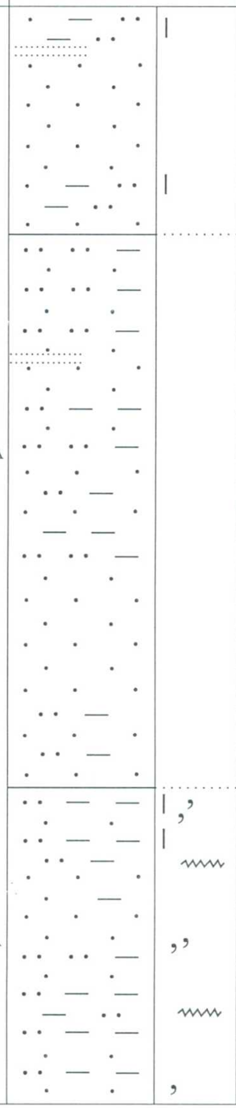
Appendix 2

SCALE 1:200

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 Kandle Fm.	D-72, D-73	177.0, 177.8		Indistinctly thick-bedded with thin-bedded intervals	< 0.2 (0.2–0.3) cm; D grey	1–2	Light grey and grey, in places dolomitized and slightly argillaceous, *very finely crystalline* **limestone** (grains 10–30%) with rare marlstone interbeds. Discontinuity surfaces are limonitized, the lowermost two are phosphatized. Lenses with iron ooliths (in places up to 30%) are found
	Kunda Stage Loobu Fm.	39, D-74	179.2		Indistinctly medium- and thick-bedded	< 0.2 (0.3) cm; IND grey	1–2	Dark grey, with brown patches, *finely crystalline* **dolostone** (grains 10–30%) with rare marlstone interbeds. The uppermost 0.2 m is grey *very finely crystalline* limestone. Discontinuity surfaces and carbonate clasts are phosphatized
	Pakri Fm.	D-75, 40	180.2		Indistinctly bedded	< 0.2 cm; IND grey	1–2	Light grey, with brown patches, *very finely crystalline* **limestone** (grains 10–30%) with indistinct argillaceous and kerogenous or sandy lenses, and rare marlstone (shale) beds. The lowermost part contains kerogenous dolostone layers, argillite pebbles (up to 5 cm across), iron ooliths and sandstone patches with bioclasts. Discontinuity surfaces are pyritized

STANDARD UNITS	LOCAL STRATIGRAPHIC UNITS	CORE BOX NO.	FIGURES	DEPTH (m)	SAMPLES	LITHOLOGY	SEDIMENTARY STRUCTURES	MARLSTONE BEDS	MARLSTONE PERCENTAGE	SHORT DESCRIPTION
Lower Ord* (Tremadoc)	Pakerort Stage, Kallavere Formation, Suurjõgi*	D-76, D-77	Appendix 2	180.2	KT, K, A		Inclined, mainly thin-bedded (Core yield 55%)			Light grey, medium-cemented, *very fine-grained* to *fine-grained* **quartz sandstone** with brachiopod fragments. Above 181.0 m occur dark brown argillite, marlstone and bioclast-rich interbeds (thickness up to 1 cm)
Furongian*	Pakerort Stage, Kallavere Formation, Maardu Mb.	40		183.0			Medium- to thin-bedded, in places inclined (Core yield 40%)			Light grey, medium-cemented, *very fine-grained* **quartz sandstone** with brachiopod fragments and dark brown argillite (shale) interbeds (at 185.0–187.0 m 30–40% of the section, thickness in the upper- and lowermost parts up to 20 cm)
Lower Cambrian	Vergale Stage, Irbe Formation	41		187.0	A, A		Horizontal, bioturbated, medium- to thin-bedded with lenses (Core yield 45%)			Medium-cemented **silt-** and **sandstone** with interbeds and lenses of greenish-grey **clayey siltstone** and **silty claystone**. In places violetish-grey clayey siltstone interbeds (thickness 1–2 cm) occur. Clay content changes vertically. Burrows filled with sand penetrate the bedding. At 188.0–188.4 m pyrite aggregates are present
Lower Cambrian	Vergale Stage, Irbe Formation			194.0			Horizontal, medium- to thin-bedded (Core yield 50%)			Light grey, medium-cemented **siltstone** with greenish-grey clayey siltstone interbeds. The lowermost 5 cm is violetish-grey clayey siltstone
Lower Cambrian	Ljuboml' Stage, Soela Formation	42		198.0			Horizontal, massive (Core yield 35%)			Light grey, medium- and weakly cemented *fine-grained* **quartz sandstone** with coarse sand grains. Rare pebbles and interbeds of greenish-grey clayey siltstone are present

Furongian*– Furongian (Upper Cambrian); Lower Ord*– Lower Ordovician; Suurjõgi*– Suurjõgi Member

STANDARD UNITS	LOCAL STRATIGRAPHIC UNITS	CORE BOX NO.	FIGURES	DEPTH (m)	SAMPLES	LITHOLOGY	SEDIMENTARY STRUCTURES	MARLSTONE BEDS	MARLSTONE PERCENTAGE	SHORT DESCRIPTION
Lower Cambrian	Ljuboml' Stage Soela Formation	42	Appendix 2							☞ follow up
		43		212.0	A		Not observable (Core yield 20%)			Light grey, weakly cemented, *very fine-grained* to *fine-grained* **quartz sandstone** with greenish-grey, clayey siltstone interbeds. Intervals with increased clay content and the lower boundary were revealed by gamma logging
	Dominopol' Stage Lükati Formation			226.6	A A		Not observable (Core yield 40%)			Intercalation of greenish-grey **clayey siltstone**, **silty claystone** and light grey, weakly (rarely strongly) cemented, in places silty, *fine-grained* to *very fine-grained* **sandstone** layers. Claystone contains silty films and trace fossils. Glauconite grains and *Volborthella tenuis* fragments are observed. At 226.6–227.2 m is a violetish-red and ochre-yellow brownish-red mottled greenish-grey weathering crust. The lower boundary (in neighbouring sections marked by a conglomerate: claystone with siltstone pebbles) was revealed by gamma logging

STANDARD UNITS	LOCAL STRATIGRAPHIC UNITS	CORE BOX NO.	FIGURES	DEPTH (m)	SAMPLES	LITHOLOGY	SEDIMENTARY STRUCTURES	MARLSTONE BEDS	MARLSTONE PERCENTAGE	SHORT DESCRIPTION
Lower Cambrian	Lükati Fm.	43	Appendix 2	237.4		SCALE 1:200				☞ follow up
	Dominopol' Stage Sõru Formation			237.4 240 250 260		SCALE 1:500 core is missing				Greenish-grey, weakly cemented, **clayey siltstone** (prevails in the upper part) and light grey *fine-grained* **quartz sandstone** (predominates in the lower part) with interbeds of clay- and siltstone were revealed by gamma logging and by data obtained from neighbouring sections
	Lontova Stage Voosi Formation	44	Appendix 2	265.6 270 280 290 298.0			Not observable (Core yield 10%)			Light grey and whitish-grey, weakly to medium cemented, mostly *fine-grained* **quartz sandstone** with greenish-grey silty claystone interbeds (thickness mainly up to 2 cm). At 265.6–271.5 and 280.5–282.0 m (depths specified by gamma logging) claystone layers predominate, in places with mica flakes. Glauconite grains are not found. In the lower part sandstone is better sorted and comprises kaolinite patches. The lower boundary (in neighbouring sections marked by a conglomerate bed) was revealed by gamma logging

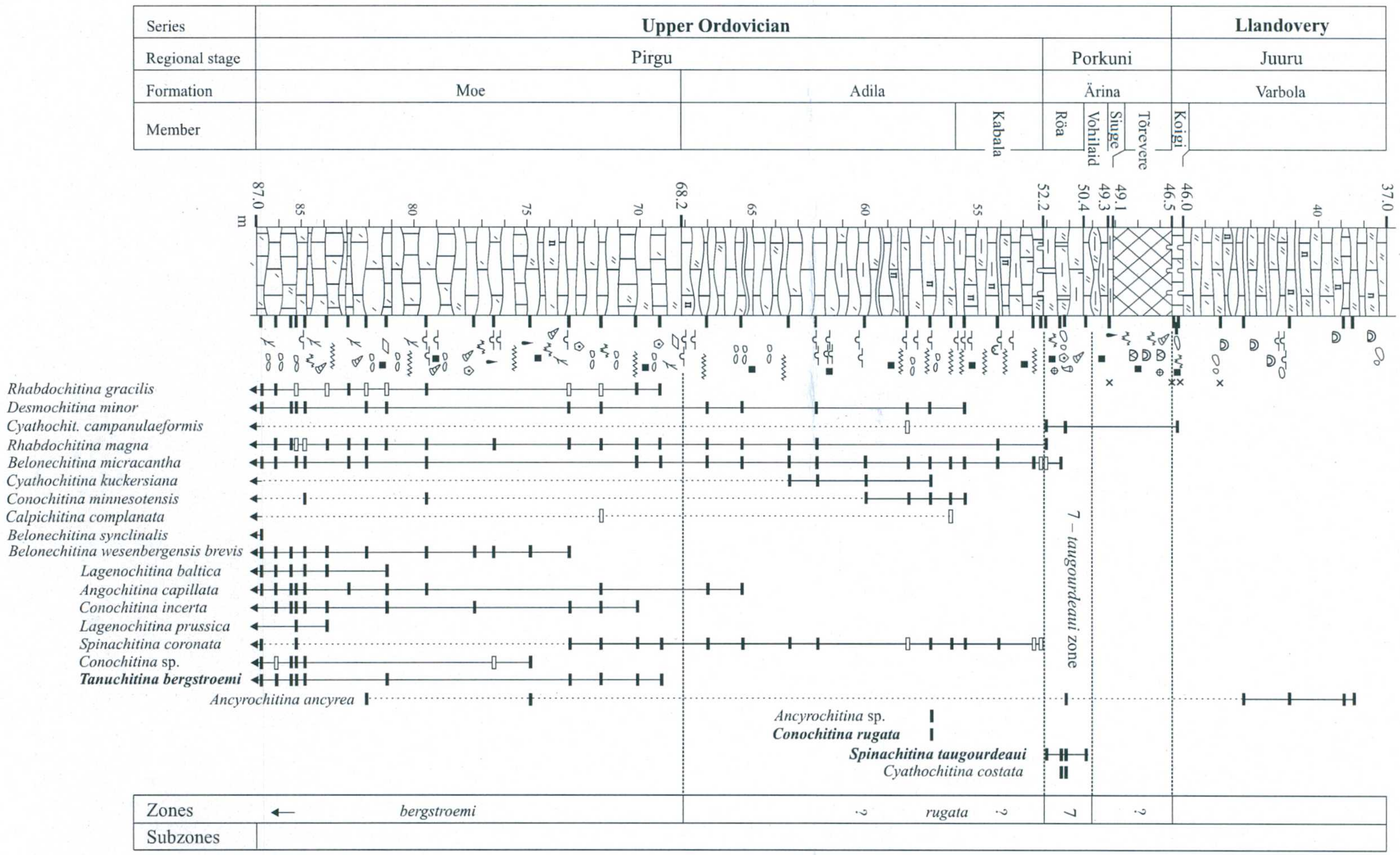
SCALE 1:500

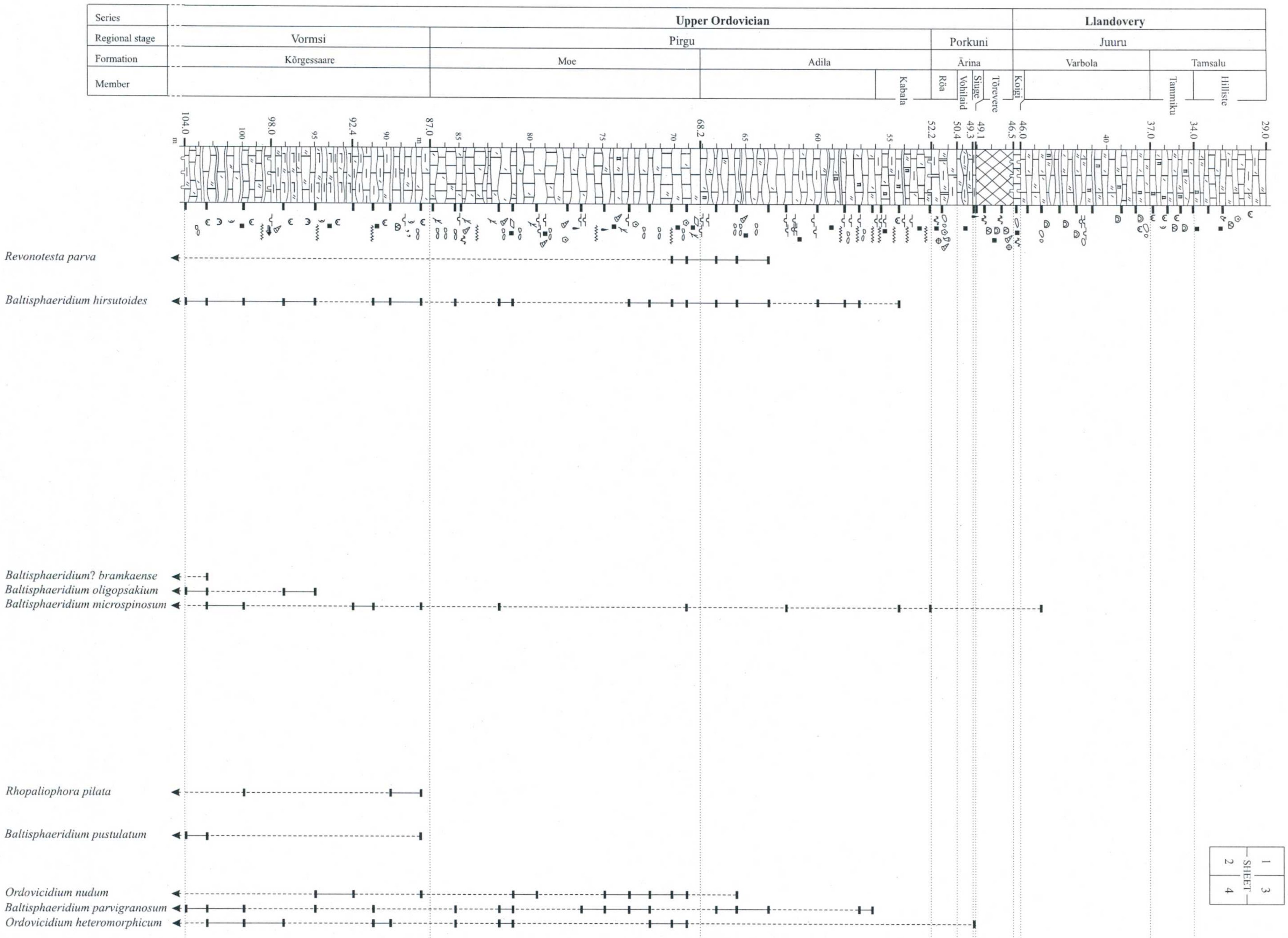
STANDARD UNITS	LOCAL STRATIGRAPHIC UNITS	CORE BOX NO.	FIGURES	DEPTH (m)	SAMPLES	LITHOLOGY	SEDIMENTARY STRUCTURES	MARLSTONE BEDS	MARLSTONE PERCENTAGE	SHORT DESCRIPTION
Palaeoproterozoic	West Estonian block	44	Appendix 2	298.0–307.8 (300)	S S S		Dip 20–40° (Core yield 15%)			Brownish-violet, weathered, in places migmatized and mylonitized, *fine-grained* **sillimanite-biotite-gneiss**, rich in slickensides
		45		307.8–316.0 (310)	S S S S S S S		Dip 20–40° (Core yield 60%)			Mottled, the lowermost 1 m reddish-grey, in places weathered, migmatized, often finely folded and cataclastic, *fine-* to *medium-grained* **sillimanite-cordierite-gneiss**
				316.0–321.8 (320)	S S S		Dip 20–30° (Core yield 60%)			Pinkish-red, cataclastic, *medium-* to *fine-grained* **migmatite granite**. Thin veins of secondary minerals occur
		46		321.8–324.8	ST S T		Dip 20–40°			Weathered, migmatized, cataclastic, *medium-* to *fine-grained* **sillimanite-biotite-gneiss** with cordierite and **migmatite granite**
				324.8–331.8 (330)	S S ST S S		Dip 20–40° (Core yield 85%)			Pinkish-red, migmatized, *medium-* to *fine-grained* **biotite-gneiss** with sillimanite. Rare slickensides and thin veins of secondary minerals occur
		47		331.8–343.0 (340)	ST S S S S S ST S S		Dip 20–40°			Pinkish-red, *medium-grained*, rarely *coarse-grained* **migmatite granite** with relicts of *fine-* to *medium-grained* **sillimanite-cordierite-gneiss**. Slickensides and thin veins of secondary minerals occur
		48		343.0–345.5	S ST		Dip 20–40°			Migmatized, *medium-* to *fine-grained* **sillimanite-cordierite-gneiss** and **migmatite granite**
				345.5–347.6	S S					Pinkish-red, migmatized, *medium-* to *fine-grained* **migmatite granite** with **sillimanite-cordierite-gneiss** relicts
		49		347.6–358.3 (350)	S S KSTT S S ST S ST S		Dip 30–40°			Cataclastic, *fine-* to *medium-grained* **migmatite granite** and migmatized **biotite-gneiss**. Slickensides and thin veins of secondary minerals (carbonate, chlorite, epidote) occur

APPENDIX 6, SHEET 1

Distribution of Ordovician and lowermost Silurian chitinozoans in the Männamaa (F–367) core

(Jaak Nõlvak, Institute of Geology at Tallinn University of Technology)

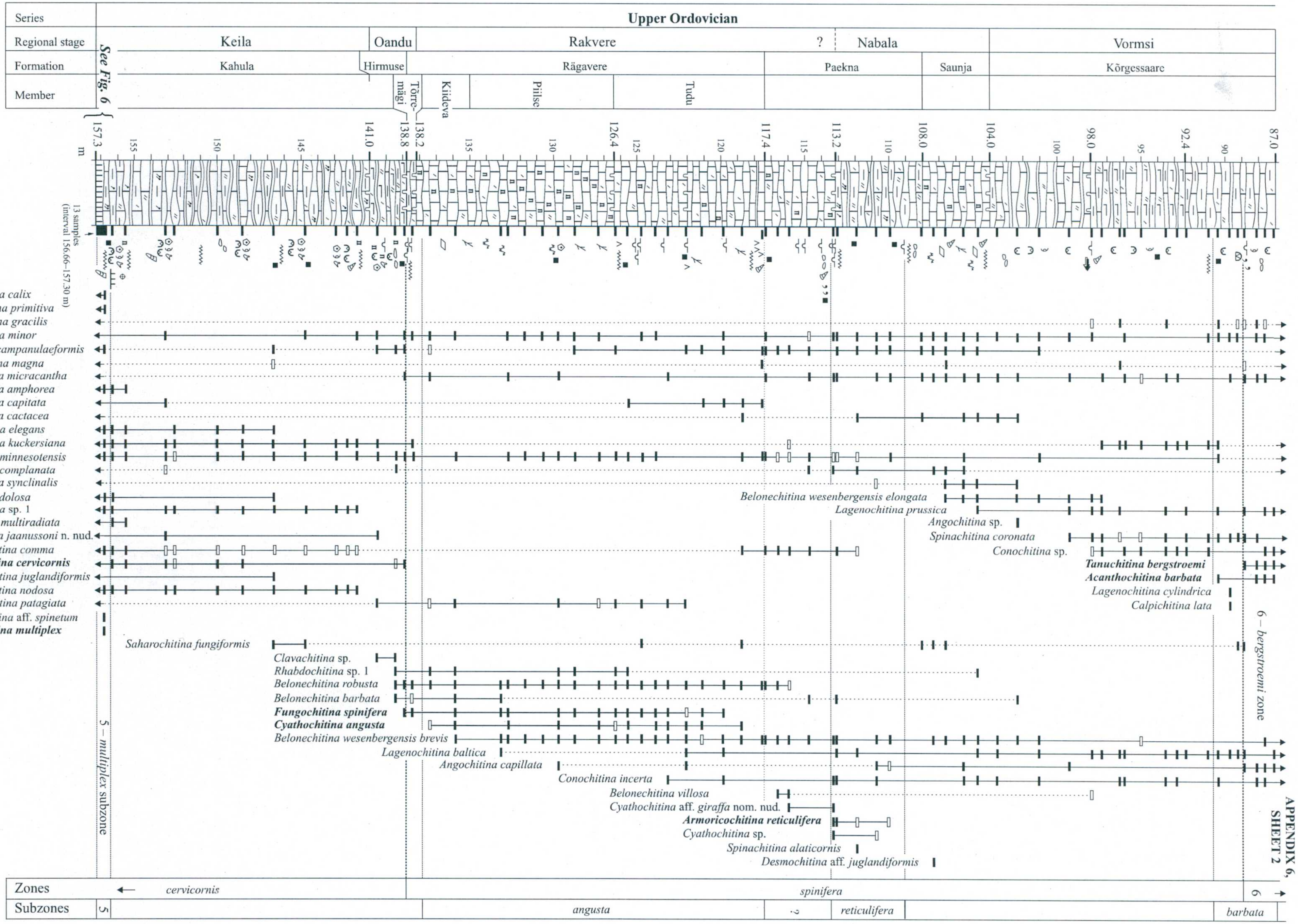




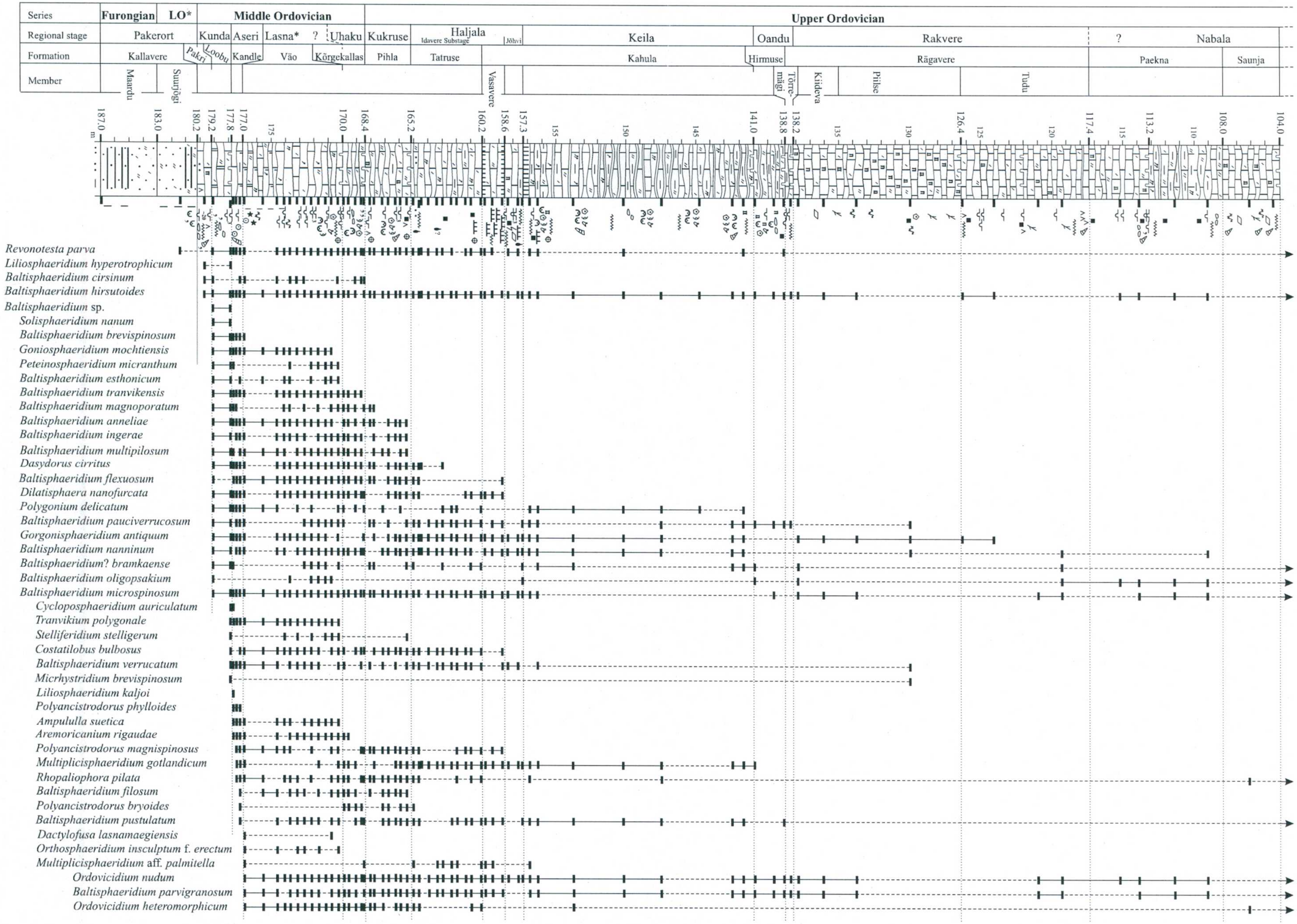
APPENDIX 8, SHEET 1

Distribution of selected Ordovician and lowermost Silurian acritarchs in the Männamaa (F–367) core

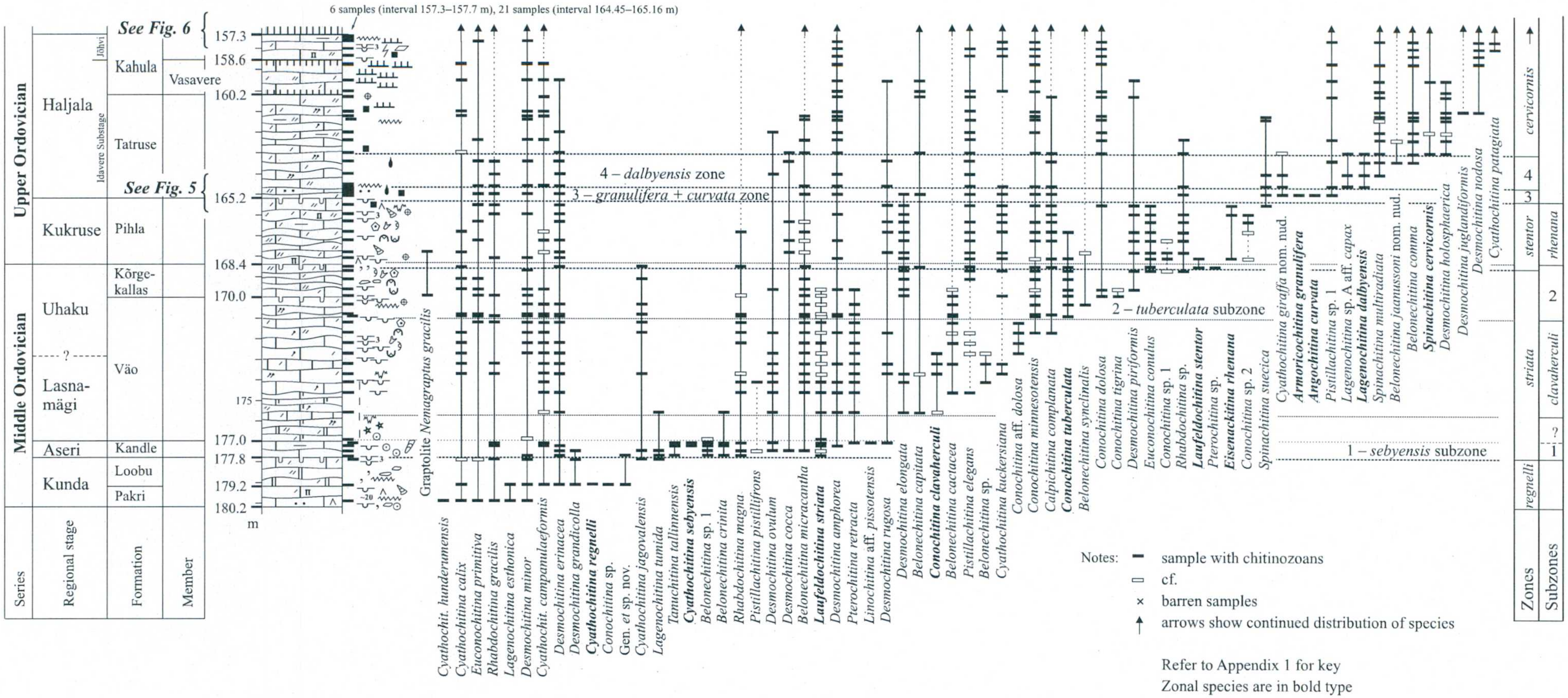
(Anneli Uutela, University of Helsinki)

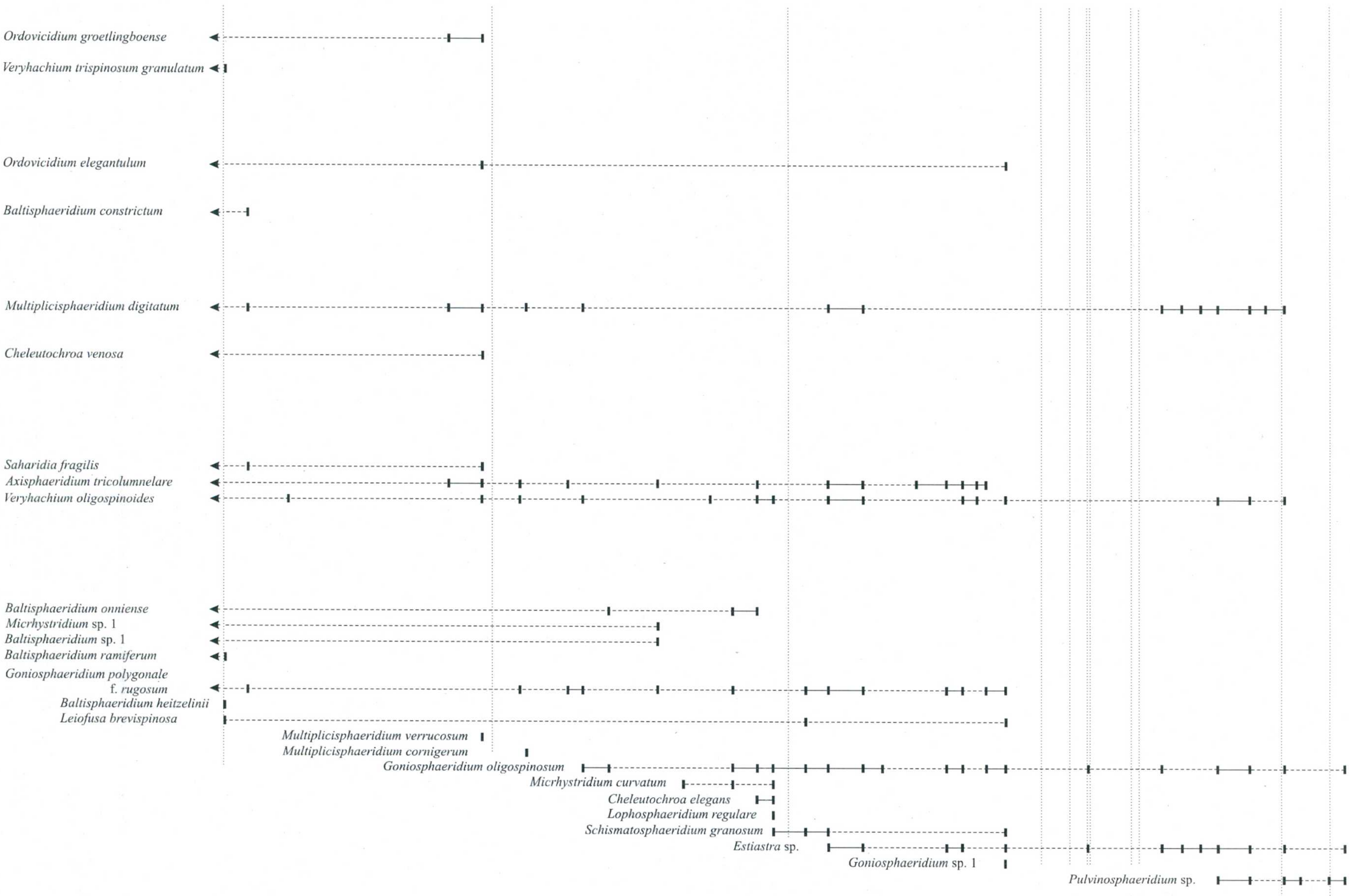


APPENDIX 6, SHEET 2

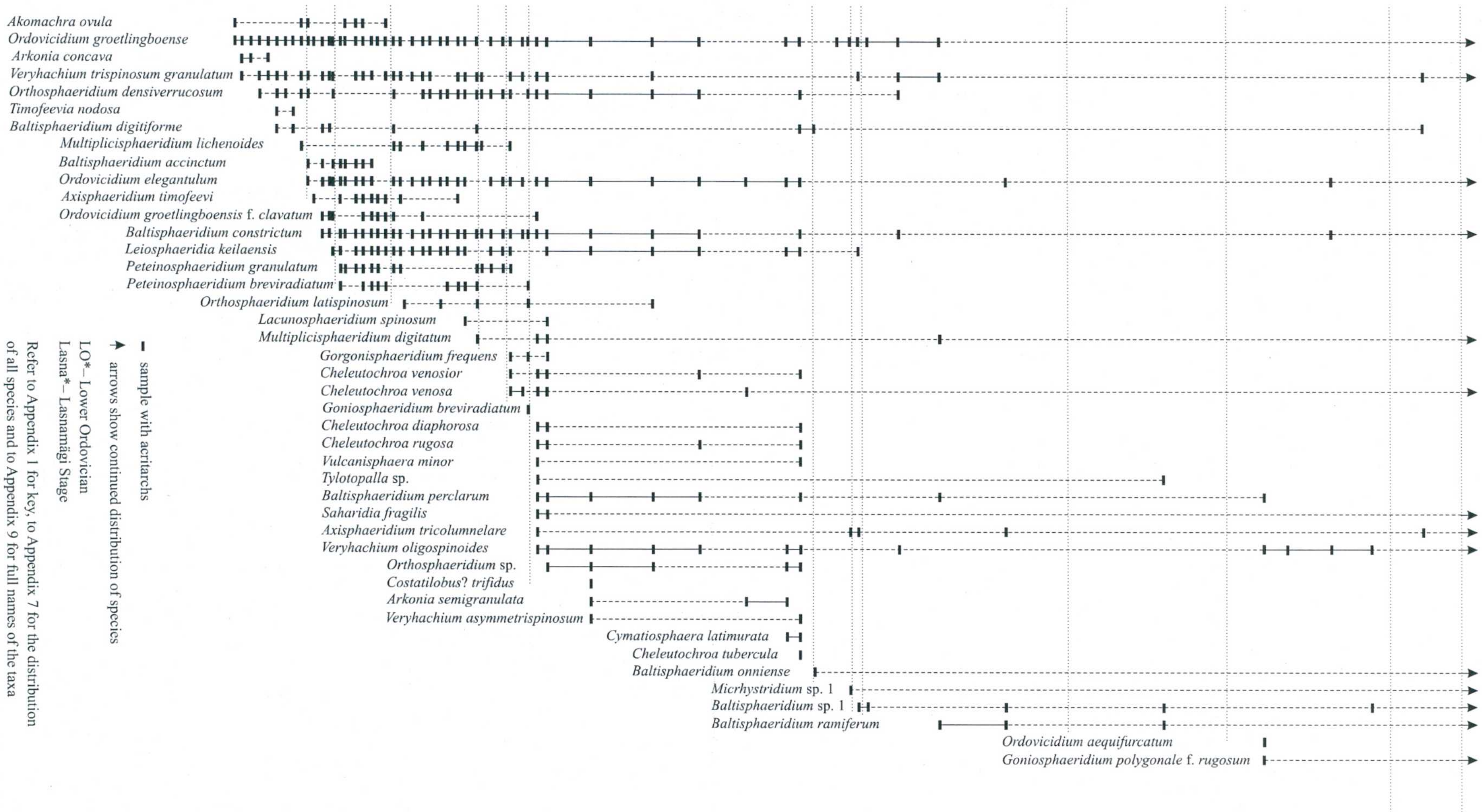


APPENDIX 8, SHEET 2


See Fig. 6
See Fig. 5
6 samples (interval 157.3–157.7 m), 21 samples (interval 164.45–165.16 m)
Upper Ordovician
Middle Ordovician
Haljala
Kukruse
Uhaku
Lasnamägi
Aseri
Kunda
Jõhvi
Idavere Substage
Kahula
Vasavere
Tatruse
Pihla
Kõrgekallas
Väo
Kandle
Loobu
Pakri
Series
Regional stage
Formation
Member
157.3
158.6
160.2
165.2
168.4
170.0
175
177.0
177.8
179.2
180.2
m
Graptolite Nemagraptus gracilis
4 – dalbyensis zone
3 – granulifera + curvata zone
2 – tuberculata subzone
1 – sebyensis subzone
Notes: sample with chitinozoans
cf.
barren samples
arrows show continued distribution of species
Refer to Appendix 1 for key
Zonal species are in bold type
Zones
Subzones
cervicornis
stentor
rhenana
striata
clavaherculi
regnelli
4
3
2
1
?



APPENDIX 8, SHEET 3



APPENDIX 8, SHEET 4

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)
Ruhnu (500) drill core (Bulletin 5; 2003)
Mehikoorma (421) drill core (Bulletin 6; 2005)
Kerguta (565) drill core (Bulletin 7; 2006)
Tsiistre(327) drill core (Bulletin 8; 2007)

Forthcoming issue:
Viki drill core