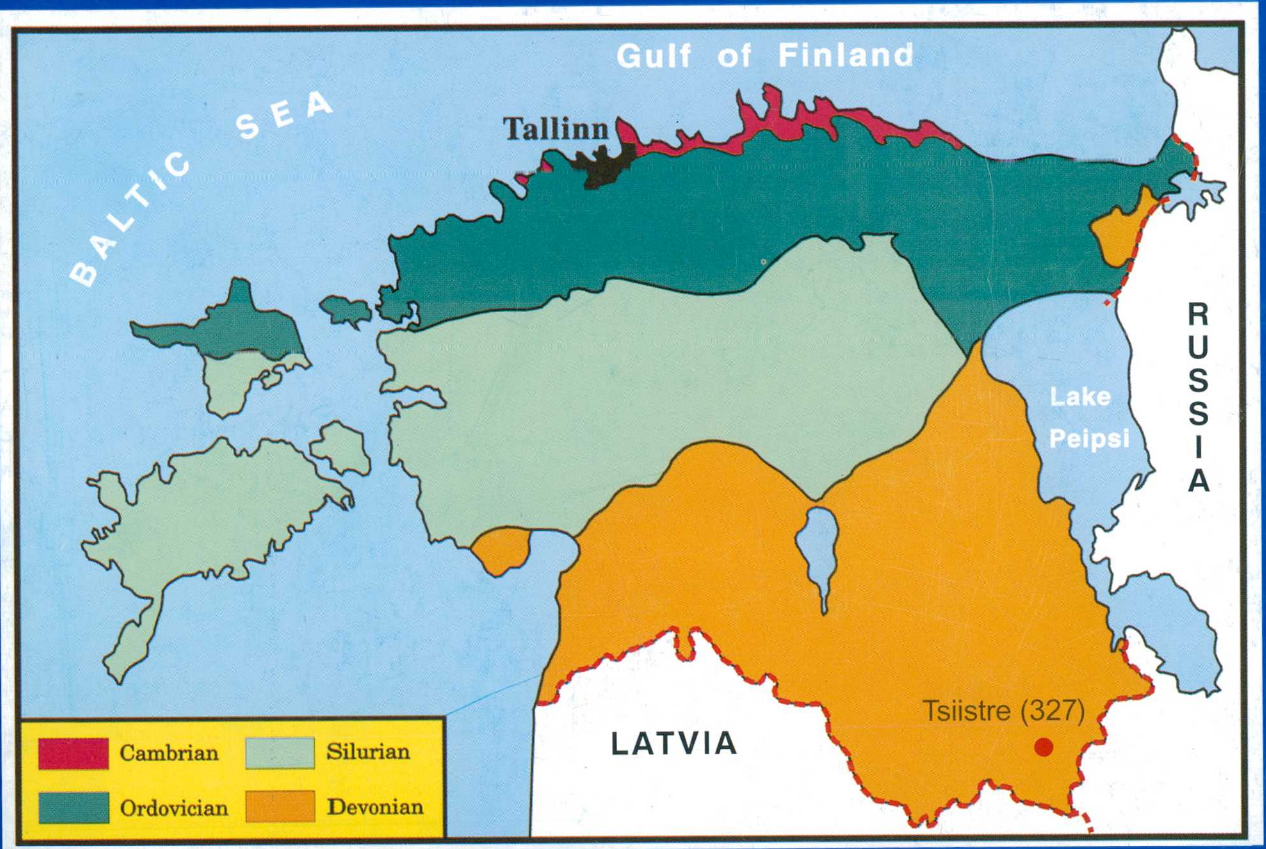
EESTI GEOLOOGIAKESKUS
GEOLOGICAL SURVEY OF ESTONIA

ESTONIAN GEOLOGICAL SECTIONS

BULLETIN 8

TSIISTRE (327) DRILL CORE



TALLINN 2007

Estonian Geological Sections
Ilmub 1998 aastast

Eesti Geoloogiakeskuse ajakiri.
Eelretsenseeritav, ilmub ebaregulaarselt.

Estonian Geological Sections
Published since 1998

Journal of the Geological Survey of Estonia,
peer-reviewed, published irregularly.

Toimetus: Kadaka tee 82, 12618, Tallinn
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Kaanekujundus: Heikki Bauert
CD kujundus: Martin Terav
Trükk: Ortwil OÜ

Editor: Anne Põldvere
Reviewers: Dimitri Kaljo & Jüri Plado
English text revision: Anne Noor
Layout: Toomas Ild
Cover design: Heikki Bauert
CD design: Martin Terav
Printed by Ortwil Ltd.

ISBN 978-9985-815-64-9 (trükis)
ISBN 978-9985-815-65-6 (CD-ROM)
ISSN 1406-3476

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CONTENTS

Introduction. *Anne Põldvere* 4
Core description and terminology. *Anne Põldvere, Anne Kleesment, Kalju Kajak, Kaisa Mens.* 5
General geological setting and stratigraphy. *Anne Põldvere, Anne Kleesment, Kalju Kajak, Kaisa Mens* 5
Distribution of Furongian (Upper Cambrian) organic-walled microfossils. *Ivo Paalits* 9
Devonian. *Anne Kleesment* 10
Distribution of Devonian fossils. *Elga Mark-Kurik* 19
Chemical composition and physical properties of the rock. *Alla Shogenova, Kazbulat Shogenov, Lauri J. Pesonen, Fabio Donadini* 21
References 30
Appendix 1. Description of the Tsiistre (327) core 35

APPENDIXES ON CD-ROM

Appendix 2. Photos of selected parts and descriptions of thin sections of the Tsiistre (327) core
Appendix 3. Photos of selected intervals of the Tsiistre (327) core
Appendix 4. Heavy and light minerals in the Devonian and topmost Cambrian rocks of the Tsiistre (327) core
Appendix 5. Grain-size distribution in the Devonian and topmost Cambrian rocks of the Tsiistre (327) core
Appendix 6. CaO, MgO, insoluble residue and loss on ignition in Devonian and lowermost Ordovician rocks of the Tsiistre (327) core
Appendix 7. XRD data of the Devonian rocks (fraction < 0.005 mm) of the Tsiistre (327) core
Appendix 8. Chemical analyses and XRF data of the Tsiistre (327) core
Appendix 9. Photos of selected Furongian (Upper Cambrian) organic-walled microfossils from the Tsiistre (327) core
Appendix 10. Physical properties of rocks from the Tsiistre (327) core

INTRODUCTION

The present issue of *Estonian Geological Sections* deals with the Tsiistre (327) core (also known as the Mära core). The Tsiistre (327) drill hole (57° 40′ 23″ N, 27° 11′ 31″ E) is located in southeastern Estonia in the NW part of the East European Platform, near Tsiistre village about 22 km to the southeast of the town of Võru (Fig. 1). The 533.7 m deep drill hole, which penetrates the Cambrian (39.0 m), Ordovician (8.7 m) and Devonian (441.0 m) sedimentary rocks and 45.0 m thick loose Quaternary deposits (Fig. 2), was made during complex geological-hydrogeological mapping (at a scale of 1:200 000) of southeastern Estonia. The source material for the present study is available in an unpublished mapping report (Väärsi *et al.* 1964) stored in the Depository of Manuscript Reports of the Geological Survey of Estonia (GSE), Kadaka tee 82, Tallinn. The results of earlier investigations (Kleesment *et al.* 1981; Ljarskaja & Kleesment 1981; Ljarskaja *et al.* 1981; Viiding *et al.* 1981; Sildvee *et al.* 1985; Sildvee & Vaher 1995; Kajak 1997; Kleesment & Mark-Kurik 1997) are used in this work together with newly obtained data. The core is housed in the depository of the Geological Survey of Estonia in the town of Keila, North Estonia.

The original macrolithological characterization, based on the laboratory study of the drill core, was compiled by Kalju Kajak (GSE; Väärsi *et al.* 1964). In the course of geological mapping (Väärsi *et al.* 1964) and later in the 1960s and 1970s, 95 mineralogical and 70 grain-size analyses of Cambrian and Devonian sedimentary rocks were conducted in collaboration with scientists of the Institute of Geology at Tallinn University of Technology (IGTUT). The contents of CaO, MgO, insoluble residue and loss on ignition were measured in 33 samples of Ordovician and Devonian rocks. X-ray diffractometry (XRD) was performed on 86 Devonian samples. All results of laboratory analyses were included into the description of the core.

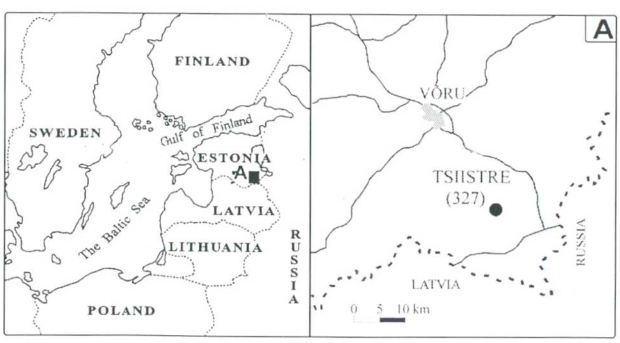


Fig. 1. Location of the Tsiistre (327) drill hole.

The Tsiistre (327) core was restudied in 2006. The lithology of Cambrian rocks was supplemented by unpublished data of Kaisa Mens (IGTUT). Ivo Paalits (Museum of Geology, University of Tartu) studied microfossils in 11 samples and improved the stratigraphic subdivision of the Cambrian section. The lithology of the Ordovician part was provided by Anne Põldvere (GSE). Anne Kleesment (IGTUT) described the Devonian rocks, using also the materials collected by Herbert Viiding in the 1960s. Elga Mark-Kurik (IGTUT)

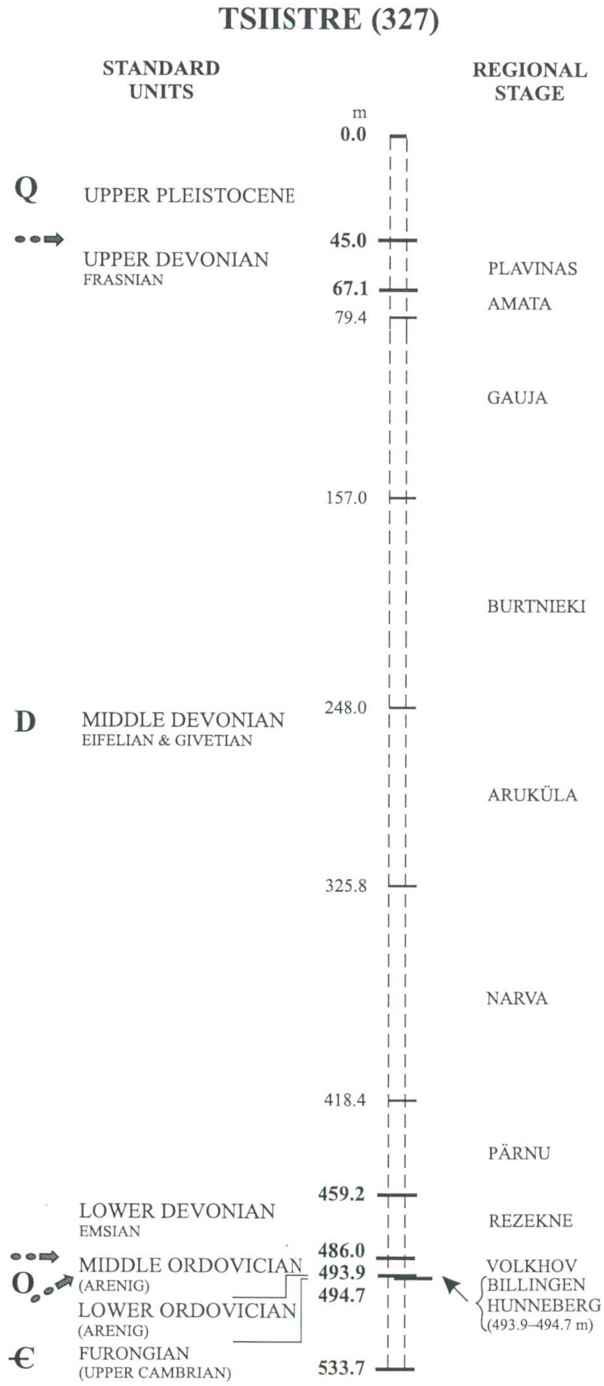


Fig. 2. Generalized stratigraphy of the Tsiistre (327) core. € – Cambrian; O – Ordovician; D – Devonian; Q – Quaternary.

identified Devonian fossils in 20 earlier obtained samples. Alla Shogenova (IGTUT) supplied results of wet silicate chemical analyses and X-ray fluorescence (XRF) spectrometry (both 122 samples), measurements of physical properties (94 samples; measurements made under the supervision of Lauri J. Pesonen and Fabio Donadini, University of Helsinki), and 46 thin sections of Ordovician and Devonian rocks. The thin sections were described by Anne Kleesment (IGTUT) and Anne Põldvere (GSE).

Photos of the core and selected intervals were taken by Gennadi Baranov (IGTUT) and Anne Põldvere (GSE). Elar Põldvere from the Institute of Ecology and Earth Sciences at the University of Tartu (IEESUT) provided technical assistance.

Useful comments by Jüri Plado, Juho Kirs, Oive Tinn (all from the IEESUT), Jaak Nõlvak, Asta Oraspõld, Dimitri Kaljo (all from the IGTUT) and Jaan Kivisilla (GSE) were of great help in finalizing the report.

CORE DESCRIPTION AND TERMINOLOGY

The description of the Tsiistre (327) core is presented in the form of a table (Appendix 1) containing the main lithological features of rock. The material studied comprises 95 mineralogical, 70 grain-size, 155 chemical and 86 XRD analyses, 94 analyses of physical properties and 46 thin sections. Acritarchs (11 samples) were used for age specification in the Cambrian part of the section. Fish, invertebrate and plant fossils (20 samples) were identified mainly in the Middle and Upper Devonian.

In addition to laboratory analyses, the degree of dolomitization of carbonate rocks was determined during field work using 3% hydrochloric acid, whereas the content of clay was estimated visually. The rocks are referred to as slightly argillaceous (insoluble residue 10–15%), medium argillaceous (15–20%) and highly argillaceous (20–25%) (Oraspõld 1975).

The **textures** of carbonate rocks are described following 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 content of carbonate clasts and skeletal fragments (described as grains) is given in most cases in per cent. Skeletal remains of organisms (bioclasts) are mainly < 1 mm in diameter. The size of chemogenic or biochemogenic ooliths is usually < 1 mm as well, while the size of carbonate intraclasts is > 1 mm. The micritic component consists of particles < 0.05 mm in diameter. As an exception in the chapter "Devonian" by A. Kleesment the textures of carbonate rocks are based on the classification of Folk (1980) and thus different nomenclature is used. A peculiar feature of sandstones of the Narva and Aruküla stages is the occurrence of strongly dolomite cemented sandstone globules (diameter 2–3 cm) in up to 30 cm thick irregularly cemented interbeds.

Depending upon the degree of recrystallization, several transitional textures can be observed (secondary textures occurring as patches or spots). In the description of a mixed texture the dominant component is given last, while less important components are placed before the basic word. The same principles were followed also in descriptive terms for other characteristics of the rock.

The textures recorded are illustrated by photographs of thin sections and selected intervals of the Tsiistre (327) core in Appendixes 2 and 3.

Several sedimentary **structures** are described in the style used in a previous issue of the bulletin (see Põldvere 2001). Variation of these structures is exemplified by photos of the core (Appendix 3). The relationships between different parts of rock are given in Appendix 1.

Fractions and terms for clay, silt and sand are given in Appendix 1. The term "terrigenous" is essentially synonymous with "noncarbonate" (e.g. terrigenous sand vs carbonate sand) and is applied to sediments originating from the land area and transported mechanically to the basin of deposition (Scholle 1978).

GENERAL GEOLOGICAL SETTING AND STRATIGRAPHY

The bedrock succession of the Tsiistre (327) core comprises Furongian (Upper Cambrian), Lower and Middle Ordovician, and Lower, Middle and Upper Devonian terrigenous and carbonate rocks (Fig. 2; Appendix 1), overlain by the Quaternary cover. The stratigraphy of the section is based on the correlation charts for the Cambrian (Mens & Pirrus 1997a, p. 39, table 6), Ordovician (Nõlvak 1997, p. 54, table 7) and Devonian (Kleesment & Mark-Kurik 1997, p. 108, table 10) of Estonia.

Furongian (Upper Cambrian) sandstones and silty claystones (interval 494.7–533.7 m; Appendix 1, sheets 18, 19; Appendixes 4, 5) in southeastern Estonia belong to the Petseri Formation (Mens & Pirrus 1997a). As this formation contains the oldest Furongian acritarch assemblage (see Paalits in this volume), it corres-

A

B Thickness of formations (m):

Formation	Ruhnu (500)	Tsiistre (327)	Mehikoorma (421)	Tartu (453)
Kriukai	7.4	7.9	10.28	9.6
Zebre	0.75	0.8	0.02	0.8
Leetse	0.15	–	–	0.4
Kallavere?	–	–	–	0.2
Petseri	–	39.0	8.0	5.6

C

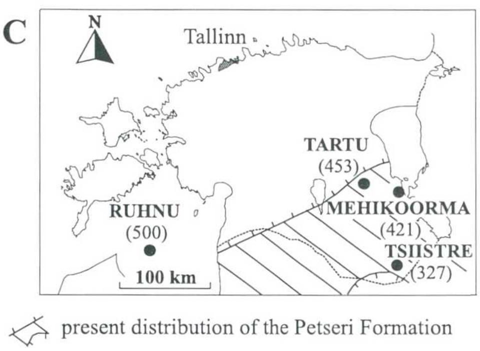


Fig. 3. (A) Schematic representation of erosional hiatuses (1–3) and lithology on the Cambrian–Ordovician boundary in selected core sections (see Põldvere & Paalits 1998 and Põldvere et al. 2003, 2005 for details), (B) thickness of formations and (C) location of drill holes. $Є_2$ – Middle Cambrian; $Є_3$ – Furongian (Upper Cambrian); O_1 – Lower Ordovician; O_2 – Middle Ordovician. Refer to Appendix 1 for lithology.

ponds to the global Paibian Stage that represents the lowermost Furongian in Estonia.

The Petseri Formation with a maximum thickness of 39 m is known only in a restricted area in southeastern Estonia, including the Tsiistre (327) core (Fig. 3; see Mens & Pirrus 1997a). In complete sections the formation can be subdivided into three parts: upper and lower sandstones and a silty claystone complex between them, in the middle of the formation. Sandstones contain skeletal fragments of inarticulate brachiopods and glauconite (Mens & Pirrus 1997a). Claystone yields shells and fragments of lingulates and acritarchs (see Paalits in this volume). The Petseri Formation, bounded by stratigraphic hiatuses, lies between Middle Cambrian and Lower Ordovician units. In the early Late Cambrian, sedimentation took place in southeastern Estonia between two rapidly subsiding areas in the east and west (Mens & Pirrus 1997b, fig. 135C).

In the Tsiistre (327) core, the upper and lower weakly cemented sandstones lie respectively at 494.7–509.7 and 511.7–533.7 m. On the basis of lithological similarities, the sandstone is assigned to the Petseri Formation. Palaeontological data from the core are not sufficient for making reliable biostratigraphic conclusions. Very fine and fine sand grains are mainly angular to subrounded. The upper sandstone complex has yielded shell fragments (e.g. *Ungula* sp.; Appendix 3, D-20), rare glauconite and feldspar grains (diameter < 0.1 mm). The silty claystone complex (509.7–511.7 m) contains patches of iron compounds, pyrite aggregates, mica flakes, shell fragments and very fine-grained sandstone interbeds (Appendix 1, sheet 19). The upper boundary of the formation is clear (Appendix 1, sheet 18), but the lower boundary was not reached at a depth of 533.7 m, because the drill hole does not extend deeper.

Iron-rich and mainly weakly cemented sandstones originate from the uplift of the territory, accompanied by erosion and subaerial weathering in the Late Cambrian.

The Furongian sediments are overlain by **Lower Ordovician** dolostones (interval 493.9–494.7 m; Appendix 1, sheet 18) corresponding to some parts of the Hunneberg and Billingen stages. White, yellow and violet mottled or brownish-red micro- to finely crystalline dolostones of the lower part of the Zebre Formation are glauconitic (Fig. 3; Appendix 2, T-46; Appendix 3, D-17…19). Smooth glauconite formations (20–60% of rock) are round and/or flat, but also sausage-shaped (Appendix 3, D-17a). Cracked flat forms have been subjected to external pressure. A surface covered with coarse dolomite crystals (size up to 3 mm, Appendix 3, D-19) occurs on the lower boundary of the Zebre Formation. Similar glauconite-rich dolostone and coarse dolomite crystals are found also in the lowermost Ordovician beds in the Ruhnu (500) core (Fig. 3; Põldvere *et al.* 2003, appendix 5, D-18).

The **Middle Ordovician** (interval 486.0–493.9 m; Appendix 1, sheet 18; Appendix 6) is represented by the Kriukai Formation corresponding to the Volkhov Stage. Very finely crystalline and finely crystalline dolostones are brownish-red with argillaceous and dolomitic marlstone interbeds (Appendix 2, T-45; Appendix 3, D-15). The rugged lower boundary of the Middle Ordovician is underlain by a 0.5 cm thick light grey dolostone bed. In the Ruhnu (500) section this boundary is limonitized (Põldvere *et al.* 2003, appendix 5, D-17).

The Ordovician dolostones in the Tsiistre area characterize the beginning of an Arenig transgression in the Baltic basin (Nestor & Einasto 1997). The sedimentation began in the epicontinental marine basin in deeper-water environments.

Well-preserved Lower and Middle Ordovician limestones are only 8.7 m thick in the Tsiistre (327) section and are covered by Devonian sediments, while in southeastern Estonia the Lower Devonian rocks commonly lie on the Llandovery (lower Silurian) or Upper Ordovician carbonate complexes (Fig. 4; Kleesment *et al.* 1980; Kleesment & Mark-Kurik 1997).

Complex geological-hydrogeological mapping at a scale of 1:200 000, which began in 1958 (Väärsi *et al.* 1964), enabled the study of deep drill hole sections in a wide area (Fig. 4). The positions of stratigraphic boundaries and the extent of Cambrian–Silurian rocks indicate that the crystalline basement was uplifted in the late Silurian and Early Devonian (Sildvee & Vaher 1995). In the Tsiistre area all younger Ordovician and Silurian sedimentary rocks related to the Late Silurian tectonic deformation were removed during the period of regional denudation.

Three basement uplifts around the Tsiistre area caused original disposition of the crystalline basement and sedimentary cover. The minor Haanja, Lokno and Mõniste uplifts are located, respectively, northeast-, east- and southwestward in the radius of 15–40 km (Puura & Vaher 1997, fig. 116). These are parts of the 20–30 km wide and 200 km long west–east trending Valmiera–Lokno Uplift in the Estonian–Latvian and Estonian–Russian border zones. Additionally, the Valmiera and Smiltene uplifts have been established southwestward from the Mõniste Anticline (up to 60 km), on the territory of Latvia. On the crest of

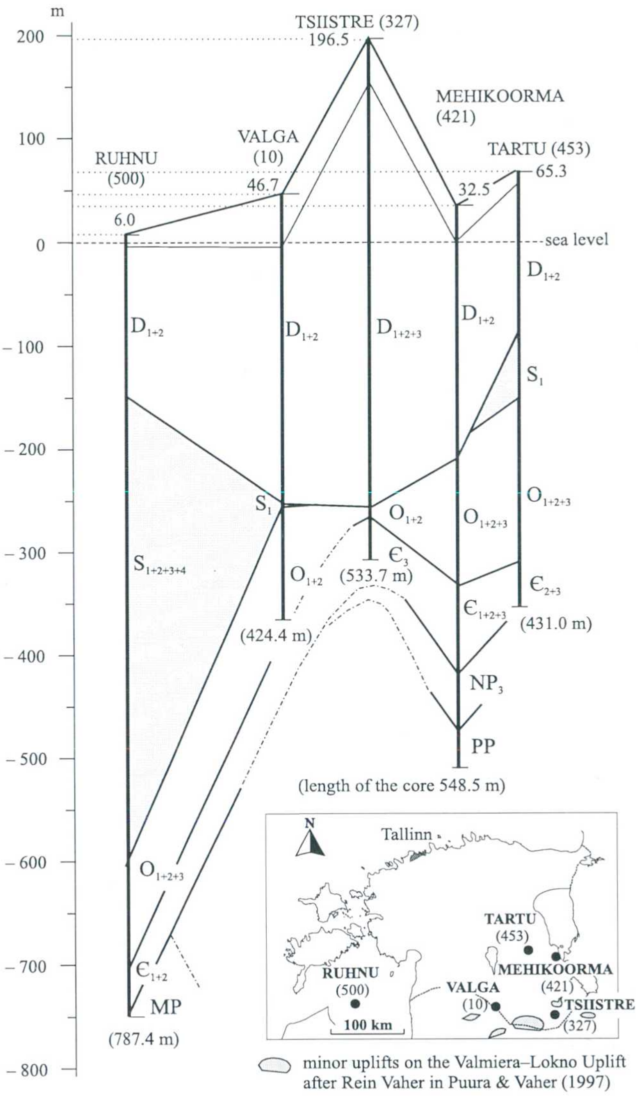


Fig. 4. Profile across the Ruhnu (500), Valga (10), Tsiistre (327), Mehikoorma (421) and Tartu (453) core sections (see Põldvere & Paalits 1998; Põldvere 2001; Põldvere et al. 2003, 2005 for details). PP – Palaeoproterozoic; MP – Mesoproterozoic; NP_3 *– Ediacaran (Upper Vendian);* Є$_{1+2+3}$ *– Lower + Middle Cambrian + Furongian (Upper Cambrian);* O_{1+2+3} *– Lower + Middle + Upper Ordovician;* $S_{1+2+3+4}$ *– Llandovery + Wenlock + Ludlow + Pridoli (Silurian Series);* D_{1+2+3} *– Lower + Middle + Upper Devonian; Q – Quaternary.*

the highest, Mõniste Anticline, the Palaeoproterozoic basement lies at the sea level of -230 m, descending northward to -500 m and southward to -1000 m (Vaher 1972; Puura & Vaher 1997).

The Mõniste Uplift has influenced the Devonian sedimentation (Paasikivi 1966). Signs of shallow sea recessions, redeposition and weathering often refer to tectonic development of southeastern Estonia. Lithological and mineralogical differences exist between different core sections in the rocks of the Aruküla, Burtnieki and Gauja stages (Middle Devonian). For example, about 30 km from the Tsiistre drill hole, in the Piusa quarry, dikes (up to 10 cm wide) filled with clasts of sedimentary rocks cut across the horizontal structure of the sandstones (Gauja Stage). The formation of dikes is probably related to the development of the Mõniste Uplift (Kleesment *et al.* 2003).

The **Lower Devonian** (interval 459.2–486.0 m; Appendix 1, sheet 17; Appendixes 4–8) is represented by sandstones and, in the upper quarter of the section, dolostones and dolomitic marlstones of the Mehikoorma Formation corresponding to the Rēzekne Stage. The lithology of the Devonian part of the section is described by A. Kleesment in a separate chapter of this volume.

The long non-deposition period was followed by Early Devonian rise of sea level when the sea flooded a great part of the East European Platform up to the Moscow Syneclise (Kuršs 1992; Plink-Björklund & Björklund 1999). At the beginning of the Rēzekne Age, poorly sorted and angular, mainly fine-grained sands deposited in the shallow marine basin in southeastern Estonia (Kleesment 1997); at the end of the age carbonate deposits with the admixture of terrigenous material accumulated.

The **Middle Devonian** (interval 67.1–459.2 m; Appendix 1, sheets 3–16; Appendixes 4–8) is represented mainly by sand- and siltstones, less by breccias, marl- and dolostones of the Pärnu, Vadja, Leivu, Kernavė, Aruküla, Burtnieki, Gauja and Amata formations corresponding to the Pärnu, Narva, Aruküla, Burtnieki, Gauja and Amata stages.

At the beginning of the Pärnu Age nearshore siliciclastic sediments deposited. Redeposition of sediments increased the roundness of grains (see Kleesment in this volume), which is characteristic of Estonian regions (Kleesment 1998). At the end of the Pärnu Age the transgression flooded the wide area of the East European Craton.

In Vadja time (Narva Age) shallow marine carbonate sediments accumulated. A peculiar landslide breccia, which is represented also in the Tsiistre section, developed in the eastern part of the Baltic Basin. The desiccation cracks and sandy to silty interlayers found in several places indicate that a subaerial environment existed for some time during the deposition or shallowing of the basin. At the end of Vadja time the basin turned shallower and the sea retreated southwards. A short sedimentation break was followed by a new flooding and the basin widened northwards, reaching the maximum extent at the end of Leivu time (Narva Age; Kleesment 1997). The main influx of terrigenous material from the Scandinavian massif was through the channel located in the area of present-day Lake Võrtsjärv. Kernavė time (end of the Narva Age) shows a regressive trend. The influx of terrigenous material and influence of freshwater streams reflect nearshore shallow sea conditions. Carbonate sedimentation was of only minor significance in southeastern Estonia.

In the Aruküla Age, in places distal and proximal delta fronts formed due to the accumulation of fluvial sediments, influenced by freshwater streams. The cyclic structure of shallow marine sediments shows frequent fluctuation of sea level and fluvial influence (Kleesment 1994).

Short-term breaks in sedimentation and temporal transgressions occurred in the Burtnieki Age. At the beginning of the age, subaquatic (possibly together with subaerial) delta plain formations accumulated periodically (Plink-Björklund & Björklund 1999).

In the Gauja Age the marine basin retreated repeatedly. The roundness of detrital particles increased considerably (see Kleesment in this volume). Redeposition of older sediments with constant influx of detrital material from the metamorphic massifs of the Scandinavian Caledonides coincided with probable humidification of climate (Kuršs 1992). The processes of weathering were intensive in the second half of the Gauja Age.

In the Amata Age the transgression began with the accumulation of nearshore sea sands and silts in a stable palaeogeographical situation. At the end of the age, the connection between sea and ocean in the southwest ceased to exist (Kleesment 1997).

The **Upper Devonian** (interval 45.0–67.1 m; Appendix 1, sheets 2, 3; Appendixes 6–8) is represented by dolostones of the Snetnaya Gora and Pskov formations corresponding to the Pļaviņas Stage.

In the Pļaviņas Age a new transgression started all over the East European Platform. Carbonate sediments accumulated in the southwestern part of Estonia. Salinity of the sea increased, but the Estonian territory was influenced by freshwater influx and had a rich assemblage of fauna (Sorokin 1978, 1981).

The **Quaternary** cover of the Tsiistre (327) core is 45.0 m thick (Appendix 1, sheets 1, 2). Sands and loamy sands of the last glaciation of Estonia (Raukas & Kajak 1997) formed in the Upper Pleistocene (Järva Formation, Võrtsjärve Subformation).

DISTRIBUTION OF FURONGIAN (UPPER CAMBRIAN) ORGANIC-WALLED MICROFOSSILS

Furongian (Upper Cambrian) sandstones and claystones in the Tsiistre (327) drill core are assigned to the Petseri Formation (interval 494.7–533.7 m; Appendix 1, sheets 18, 19). The formation is divided into three parts. Weakly and medium-cemented sandstones occur in the lower and upper parts (thickness respectively 22.0 and 15.0 m) of the section. In the lower part, fine to very fine (in places medium to fine) sand grains are subrounded to rounded and goethitized clayey iron compounds are found. In the upper part, very fine to fine sand grains are angular to subrounded, occurring together with rare glauconite (Appendix 3, D-21) and feldspar grains (both less than 0.1 mm in diameter), shell fragments and a conglomerate layer. In the medium-cemented conglomerate interlayer (Appendix 3, D-20), sand- and silt-sized grains are well rounded and brachiopod (*Ungula* sp.) shell fragments form up to 20% of rock.

The middle part (thickness 2.0 m) comprises claystone with pyrite aggregates, patches of iron compounds, mica flakes, shell fragments and very fine-grained sandstone interbeds.

In 2006, a total of 11 samples were collected from the Tsiistre (327) core (Table 1) to improve the stratigraphic subdivision of the Furongian part of the section. Sample depths were determined as intervals because of low core yield (35–80%). The core was in very bad condition for sampling, especially for micropalynological purposes. Recent weathering and high contamination with spores, pollen, fungi, roots, etc. was clearly visible. The size of the samples varied from 15 g for silty claystones and 40–50 g for silt- and sandstones. The samples were treated with a standard dissolving method using hydrofluoric acid. Na polytungstate heavy liquid was used for separation of fossils. Of the collected eleven samples only two yielded rare acritarchs (IP-7 and IP-8). The assemblage identified has low diversity and contains acritarchs well known from the Furongian Series. In general, the recorded palynomorphs are rather well preserved. The colour of acritarchs is pale or light yellow.

Table 1. List of Furongian (Upper Cambrian) acritarch samples from the Tsiistre (327) core

Sample	Sampled level (m)
IP-1	500.0–502.0
IP-2	503.0–505.0
IP-3	505.7–506.5
IP-4	508.0–508.7
IP-5	508.7–509.7
IP-6	509.7–510.8
IP-7	510.8–511.0
IP-8	511.0–511.7
IP-9	515.7–516.5
IP-10	516.7–517.7
IP-11	523.0–525.0

The following species were identified from the middle part of the Petseri Formation: *Cymatiogalea* aff. *cuvillieri* (Deunff) Deunff, *C. virgulta* Martin, *Leiofusa stoumonensis* Vanguestaine, *Leiosphaeridia* div. sp., *Micrhystridium* sp., *Stelliferidium cortinulum* (Deunff) Deunff, Gorka & Rauscher, *Stelliferidium* sp., *Timofeevia lancarae* (Cramer & Diez) Vanguestaine, *T. phosphoritica* Vanguestaine, *Veryhachium* sp. and *Vulcanisphaera turbata* Martin (see Appendix 9).

The assemblage of acritarchs documented in the Tsiistre (327) core is not as representative as the one formerly described from the Petseri Formation of the Hino (452), Põlva (423), Luutsniku (451) (Volkova *et al.* 1981; Volkova 1983, 1990), Tartu (453; Põldvere & Paalits 1998) and Mehikoorma (421; Paalits 2005) cores of southeastern Estonia. The stratigraphically important species *Cymatiogalea velifera* (Downie) Martin, *Pirea orbicularis* Volkova, *Poikilofusa* sp., *Veryhachium incus* Paalits and *V. setuensis* Paalits were not found at Tsiistre.

Samples IP-1…6 and IP-9…11 were barren or yielded only much organic material of modern origin. Thus we found no evidence to discuss about the age of the uppermost and lowermost parts of the Petseri Formation in the Tsiistre (327) section.

The palynological data available from the neighbouring regions allow us to suggest that the oldest early Furongian acritarchs and lithological analogues of the Lower Furongian are widely distributed over the East European Platform, including the areas of Russia, Ukraine and Poland. A similar "Petseri assemblage" of acritarchs has been documented from the Pskov district of Russia (Panikoviči core, Paalits 1992a; Petseri core (330), Volkova 1983) and the eastern part of the Leningrad district (Zarečie core, depth 162 m; Jankauskas 1980; Volkova 1990). The same complex of acritarchs has been recorded from the Rybinskaja-1, Tolbuhino-1 and Danilovskaja-11 cores. From the Tolbuhino Formation of the Moscow Syneclise acritarchs have been found, which Volkova (Volkova 1990; Volkova & Kirjanov 1995) assigned to the microflora BK1.

In northeastern Latvia, early Furongian acritarchs have been discovered from the *Obolus* Sandstone of the Strenči-8 core (approximately 90 km southwest of the Tsiistre (327) drill hole) (Fridrichsone & Zabelis 1993, 1994). According to Volkova *et al.* (1981; fig. 1), the Strenči-8 core is located in the westernmost part of the present distribution area of the Petseri Formation. Actually, as the lithological succession of rocks in the Strenči-8 core (Fridrichsone & Zabelis 1994) is similar to that of the Tsiistre (327) core, the acritarchs identified in the middle part of the unit contain several taxa known from Estonian younger strata. For instance, the genus *Impluviculus*, which first appears in the Ülgase Formation in North Estonia, and *Trunculumarium revinium* (Vanguestaine) Loeblich & Tappan have been recorded from the overlying Tsitre Formation (Paalits 1992b). Both taxa have never been found in the Petseri Formation (Volkova 1990; Paalits 1992a; Volkova & Kirjanov 1995). It is possible that the Furongian section is represented (at least partly) in northern and northeastern Latvia by younger strata than in East and South Estonian subsurface sections.

DEVONIAN

The Devonian sequence is completely represented only in southeastern Estonia. Four previous issues of the journal *Estonian Geological Sections* describe the Lower and Middle Devonian (Pärnu to Burtnieki stages, see Fig. 5; Kleesment & Valiukevičius 1998; Kleesment 2001, 2003, 2005). The Tsiistre (327) core comprises the entire Middle Devonian (additionally regional stages of the upper part: Gauja and Amata) and the lower part of the Upper Devonian (Pļaviņas Regional Stage).

The Tsiistre (327) core has been investigated repeatedly (Väärsi *et al.* 1964; Kleesment 1995; Kleesment & Mark-Kurik 1997; Kajak 1997) and correlated with the Devonian sequence of the Baltic region (Brangulis *et al.* 1982; Paškevičius 1997). All earlier collected samples were re-examined (Appendixes 4–7) and used in this work together with recently obtained data (Appendixes 2, 8). The chemical and mineralogical composition of rocks was determined according to the classification of Devonian rocks presented in Kleesment & Shogenova (2005), Shogenova & Kleesment (2006), Kleesment *et al.* (2007) and other widely used classifications (Miall 2000). In the description of the texture of carbonate rocks the terms of Folk (1980) were used. For the first time the microstructure of the Pļaviņas carbonate rocks of Estonia was studied with the scanning electron microscope (SEM) and the energy dispersive X-ray microanalyser (Link Analytical AN 10 000) at the Centre for Materials Research of Tallinn University of Technology.

Some new features were discovered in the Devonian sequence – calcite-filled vugs and fractures in dolostones of the Mehikoorma (Rēzekne Stage), Vadja and Leivu (both of the Narva Stage) formations (Appendix 2, T-24c, T-25, T-27a,b, T-39, T-43c).

The **Rēzekne Regional Stage** is represented in the Tsiistre (327) core by the ***Mehikoorma Formation*** (459.2–486.0 m, Appendix 1, sheet 17; core yield 60%). Most of the section (465.4–486.0 m) consists of violetish-grey and greyish-pink, weakly cemented, fine- and very fine-grained sandstone, containing at 469.5–474.3 m an interlayer of strongly dolomite-cemented fine- to medium-grained sandstone with siltstone interbeds (Appendix 5). The dolomite-cemented sandstone belongs to the group of mixed carbonate-siliciclastic rocks (for lithological types of rocks see Shogenova *et al.* in this volume; Appendix 2, T-44; Appendix 8) and has in some cases a globular structure (Appendix 3, D-14). The detrital material is mainly poorly to moderately sorted (Appendix 2, T-44). Roundness of particles increases in the middle part of the interval (Fig. 6). This regularity is observed in several cores of Estonia (Fig. 5).

The upper 6.2 m (459.2–465.4 m) of the formation is represented by slightly mottled (grey with violet patches and interbeds) dolostones and dolomitic marlstones, with interlayers and pockets containing silt- and sand-sized detrital grains (Appendix 2, T-43a,b; Appendix 3, D-12, D-13). In places the proportion of the detrital component is so high that the dolostone belongs to the group of mixed carbonate-siliciclastic rock (Appendix 8). Dolostone of the lower part is sometimes penetrated by pockets and fractures with complicated morphology and filled with transparent calcite crystals (Appendix 2, T-43c). In some places calcite pockets are violet-pigmented (Appendix 3, D-12). The complex is thin-bedded, often lenticular (Appendix 3, D-12).

According to mineralogical composition, the sandstones of the Mehikoorma Formation qualify as subarkoses (Folk 1980; McLane 1995), containing 75–91% quartz and 7–19% feldspars. The content of heavy minerals, mainly transparent allothigenic minerals and ilmenite, is relatively high in the lower part of the formation. Transparent heavy minerals are dominated by garnet, followed by a significant content of zircon, and of tourmaline in some levels (Appendix 4). The fraction < 0.005 mm is represented mainly by illite (Appendix 7). Mineralogical composition is typical of this stratigraphic level (see Kleesment & Mark-Kurik 1997).

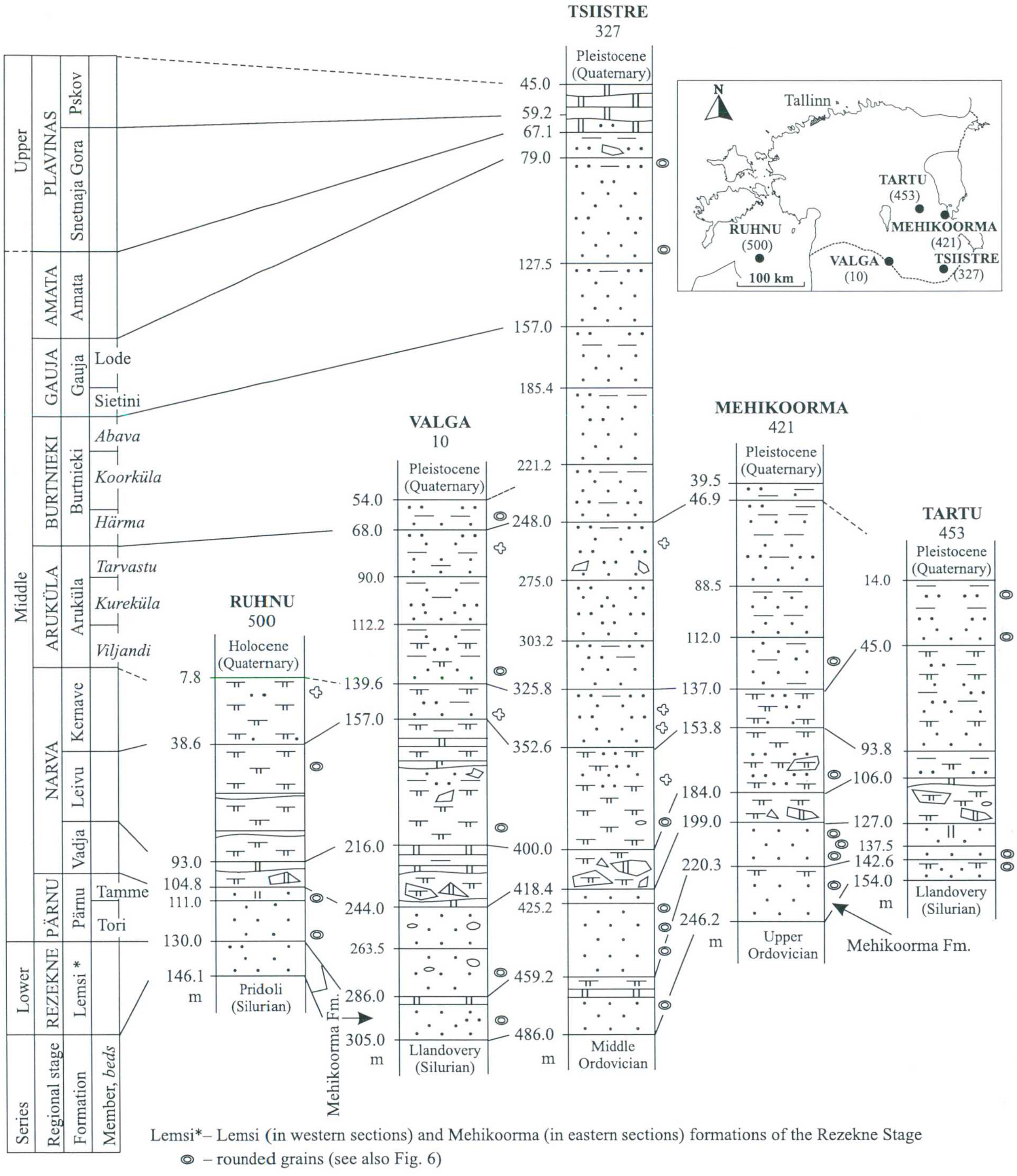


Fig. 5. *Correlation of Devonian sections (see Kleesment & Valiukevičius 1998 and Kleesment 2001, 2003, 2005 for details) and location of drill holes. For lithology refer to Appendix 1.*

The **Pärnu Regional Stage** (=Formation; 418.4–459.2 m, Appendix 1, sheets 15, 16; core yield 50%) is represented by the Tori and Tamme members.

The section of the ***Tori Member*** (425.2–459.2 m) is dominated by beige to grey and violetish-pink, weakly cemented, fine- to very fine-grained sandstone (Appendix 5). The ***Tamme Member*** (418.4–425.2 m) is represented by violetish- and greenish-grey, weakly cemented sandstone containing interbeds of strongly and medium-cemented thin-bedded siltstone and silty sandstone. In the upper part white ooliths are found.

According to mineralogical composition, sandstones are mainly subarkoses containing 75–92% quartz and 8–22% feldspars. Among heavy minerals (total 0.1–0.4%) usually transparent minerals predominate. Below 440.0 m Fe-hydroxides (7–54%) and in some cases mica minerals occur in considerable amounts. The transparent heavy mineral spectrum is dominated by

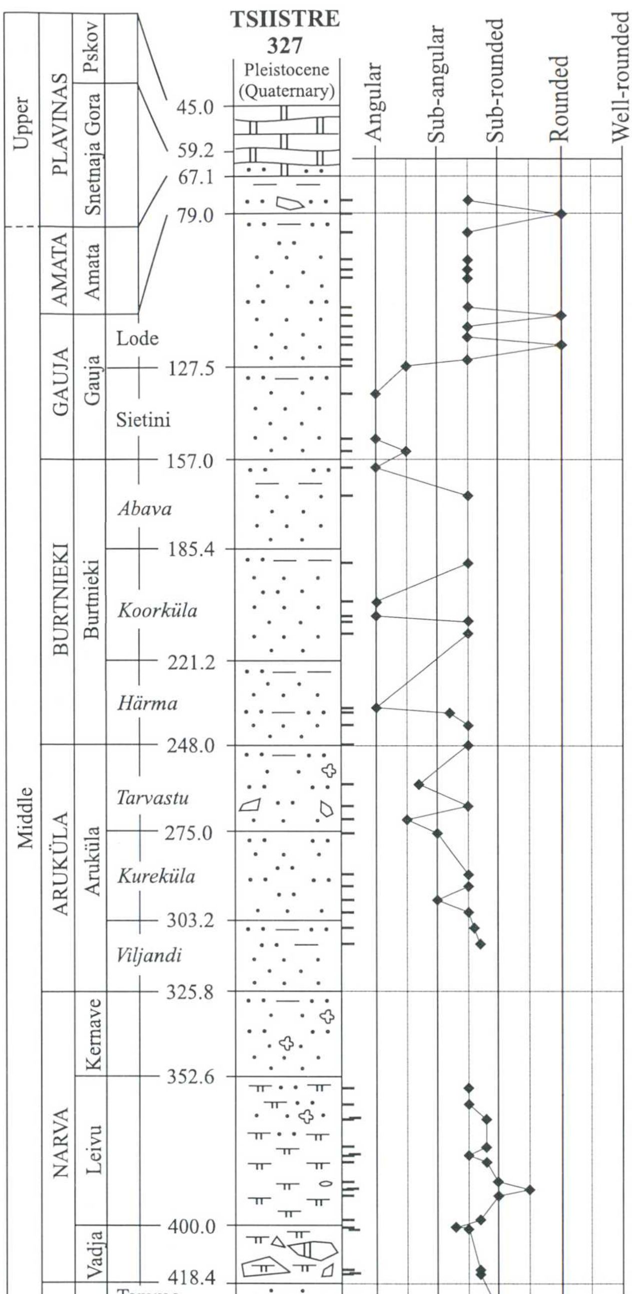


Fig. 6. Grain (size 0.005–2 mm) roundness (after Flügel 2004) of Devonian sediments of the Tsiistre (327) core. Sampling points are marked on the right side of the column. For lithology refer to Appendix 1.

garnet, accompanied by zircon and tourmaline, while apatite is abundant only in the lower part of the formation (Appendix 4). Such an association of transparent heavy minerals is characteristic of Southeast Estonia and East Latvia (Kleesment & Kuršs 1977). Detrital grains are rounded, in the upper part of the section subrounded and subangular (Fig. 6). Comparatively high roundness of grains in the Pärnu Stage deposits is observed in many sections of Estonia (Fig. 5). The fraction < 0.005 mm is dominated by illite (Appendix 7).

The **Narva Regional Stage** (325.8–418.4 m, Appendix 1, sheets 12–15; core yield 85%) is represented by the Vadja, Leivu and Kernavė (substages) formations, which can be traced over a large territory in the East Baltic and western Belarus. These units are distinguished on the basis of lithological as well as palaeontological data (Valiukevičius *et al.* 1986; Valiukevičius 2000).

The lower, ***Vadja Formation*** (400.0–418.4 m, Appendix 1, sheets 14, 15; core yield 80%) is characterized by alternating thin beds of grey dolomitic marlstone (predominating), light grey dolostone, grey to beige silt- and sandstone, and dark grey dolomitic claystone (Appendixes 6, 8).

Below 406.9 m there occur subangular and angular clasts of grey dolostone and reddish-brown dolomitic marlstone. Typical breccia is present in the intervals of 409.7–411.5 and 415.7–418.4 m. The carbonate component in dolomitic marlstone is aphano- to finely crystalline, many interbeds are rich in silt, sand, pigmented patches and lenticular interlayers (Appendix 2, T-36, T-37, T-38a). Detrital grains are mostly subrounded to subangular, in places rounded (Fig. 6; Appendix 2, T-37, T-38b). Often the content of detrital material is so high that dolomitic marlstone is assigned to the group of mixed carbonate-siliciclastic rock (Appendix 8).

Dolomite-cemented silt- and sandstone interbeds are found in the Tsiistre (327) section. The siltstone is often transitional to mixed carbonate-siliciclastic rock (Appendixes 6, 8). In fine-grained sandstones subrounded to subangular quartz grains prevail. Feldspar and muscovite, sometimes green biotite are present (Appendix 2, T-42). Siliciclastic interlayers occur mainly in the lower part of the section (Appendix 1, sheet 15). Sand- and siltstone interlayers are rare in the Vadja Formation of Estonian sections. In addition to the Tsiistre (327) core, they are found only in the Värska (6) section in southeastern Estonia (Kleesment & Shogenova 2005).

At 401.4 m dolomitic claystone contains a thin silty interlayer penetrated by silt- and clay-filled pockets marking a possible level of desiccation cracks (Appendix 2, T-38b). The intervals of 401.4–401.6 and 403.6–403.8 m contain aphano- (Appendix 2, T-39, T-41) to finely crystalline (Appendix 2, T-40) dolostone, which is in places breccia-like and fractured. Fractures and pockets are filled with transparent finely to coarsely crystalline (0.03–0.5 mm) calcite (Appendix 2, T-39, T-41). In places rock is stained with Fe-hydroxides (Appendix 2, T-39b, T-41).

According to mineralogical composition, the sandstones are subarkoses. Transparent minerals and ilmenite are the main constituents of the heavy fraction. Garnet with zircon admixture predominates among transparent heavy minerals (Appendix 4). In the < 0.005 mm fraction illite is prevalent, together with chlorite (Appendix 7).

The middle, ***Leivu Formation*** (352.6–400.0 m, Appendix 1, sheets 13, 14; core yield 98%) is represented by dolomitic marlstone (about 80% of the section) containing numerous interbeds of dolo- and siltstone and rare interbeds of sand- and claystone. Grey and violetish-grey mottled dolomitic marlstone with the very finely to finely crystalline carbonate component is silty, often patchy (Appendix 2, T-22b, T-30a), or net-shaped-pigmented (Appendix 2, T-31b, T-34). Mottled rock occurs in the upper part of the formation (Appendix 3, D-9, D-10; Kleesment & Mark-Kurik 1997; Kleesment & Shogenova 2005). The lower 20 m is highly silty dolomitic marlstone often belonging to the group of mixed carbonate-siliciclastic rocks and showing varieties transitional to silt- and sandstone (Appendix 2, T-32, T-33; Appendixes 6, 8). Similar layers occur also higher (Appendix 2, T-29). The enrichment with detrital partings is frequently observed in pockets and interlayers (Appendix 2, T-32). The lower bed of the Leivu Formation contains poorly sorted detrital grains and carbonate clasts (Appendix 2, T-35a).

The middle part of the formation (366.7–379.6 m) contains many interbeds (thickness 0.1–0.5 m) of light grey and violetish-grey, in places argillaceous, aphano- to finely crystalline dolostone. Dolostone is often penetrated by fractures and pockets, which are filled with transparent, mainly finely crystalline calcite and in some cases occur inside rusty Fe-pigmentation (Appendix 2, T-24c, T-25, T-27a,b). Fractures up to 1 mm in diameter are filled with very clear coarsely crystalline (size 0.3–0.9 mm) calcite (Appendix 2, T-27a,b; Fig. 7). Rare silt-sized particles (mainly 0.02–0.03 mm; ca 1%) are found. In places subangular and subrounded grains are concentrated in lenses and pockets containing up to 50% sand- and silt-sized partings and also rounded fine clasts of carbonate rock (Appendix 2, T-23). Dolostone forms about 10% of this interval.

Interlayers of greenish-grey, in places mottled siltstone and fine- to very fine-grained sandstone with varieties transitional to mixed carbonate-siliciclastic rocks form 10% of the formation (Appendixes 5, 8). Dolomite-cemented varieties predominate. Clay-cemented varieties may contain calcite-cemented globules (Appendix 2, T-26). Detrital material is moderately to poorly sorted; particles are mainly subrounded and subangular (Appendix 2, T-33). Rounded particles are found on one level in the lower part of the Leivu Formation (Fig. 6). Mica flakes are often oriented subparallel to bedding, in some cases covering bedding surfaces. Dark grey silty claystone forms about 1% of the formation.

According to mineralogical composition, the sandstones of the Leivu Formation qualify as arkoses. In the lower part quartz grains are mainly subrounded, in the upper part subangular. Mica-rich layers are rare. Ilmenite and iron hydroxides constitute the main part of the heavy fraction. Garnet prevails in the transparent heavy mineral spectrum, supplemented by large amounts of zircon (Appendix 4). In the < 0.005 mm fraction illite predominates. The lower part of the formation contains also chlorite, the upper part, besides chlorite, in some cases minor admixture of kaolinite (Appendix 7).

In places abundant phosphate fossil fragments are found (Appendix 2, T-24a,b, T-29, T-32, T-33). Flower -like peculiar carbon?-containing microplankton fossils (Appendix 2, T-30) occur in mottled dolomitic marlstone at 380.0 m.

The thickness of the Leivu Formation in Estonian sequences is variable, increasing significantly from north to south. As in the Tsiistre (327) core, the formation is thick in the entire South Estonian–Latvian area (Fig. 5; Valiukevičius *et al.* 1986; Kleesment & Mark-Kurik 1997). The Leivu Formation of the Mehikoorma (421) and Tsiistre (327) sections shows a high content of siliciclastic component (Kleesment 2005).

The upper, ***Kernavė Formation*** (325.8–352.6 m, Appendix 1, sheets 12, 13; core yield 65%; earlier the Gorodenka Formation, see Kleesment 2005) is represented by intercalation of reddish- to violetish-brown sand- and siltstone, in places with bluish- and greenish-grey interbeds and patches. Sandstone forms 65% of the formation and is indistinctly thin-bedded and very fine-grained (Appendix 5). Weakly to medium clay-cemented sandstone is predominating. In the lower part of the formation sandstone is occasionally strongly dolomite-cemented and may have globular structure (Fig. 5). Dolomite-cemented globules are found in the Kernavė Formation of many sections, but in the Tsiistre (327) core globules are calcite-cemented (Appendix 3, D-8; Appendix 8, sample depth 349.0 m).

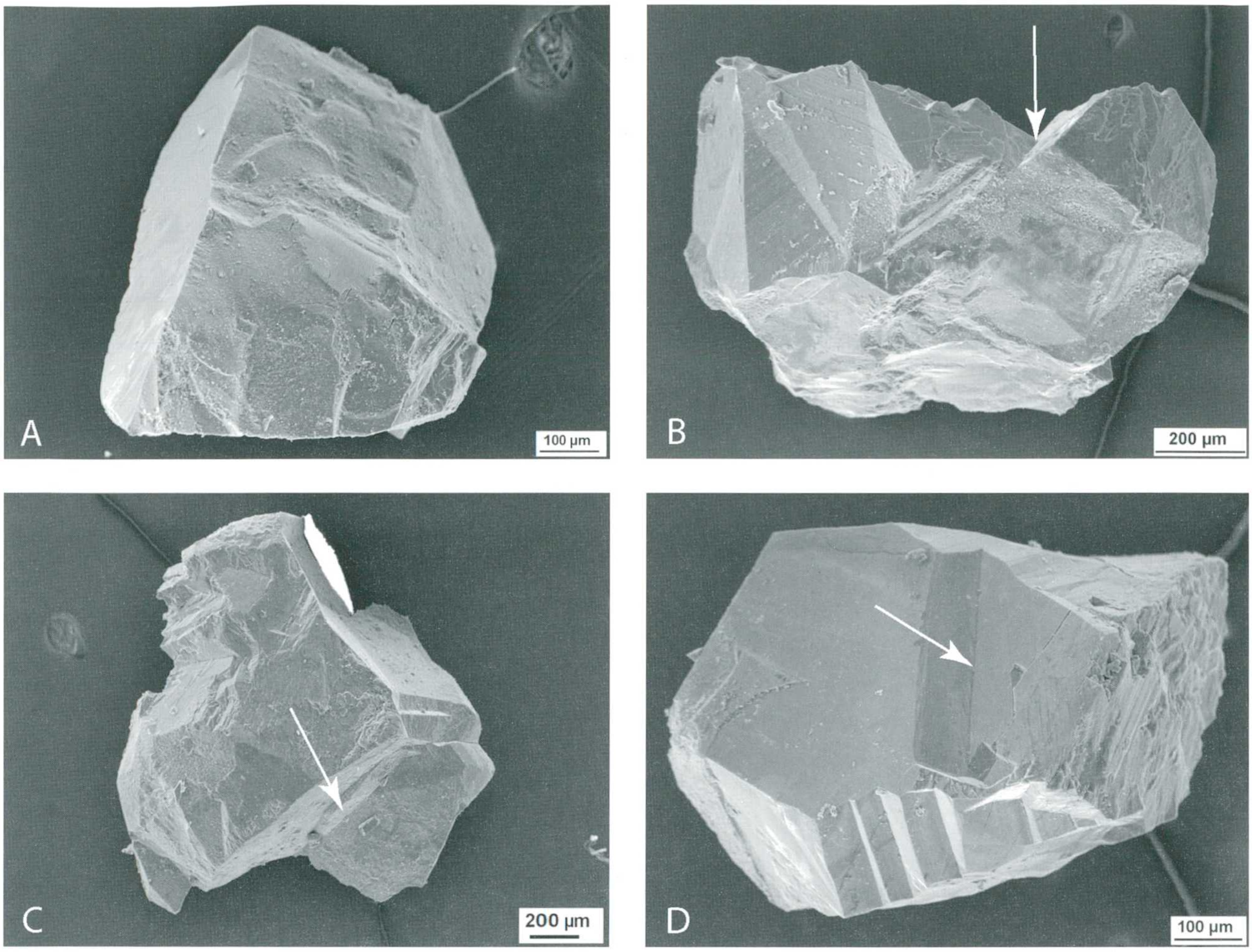


Fig. 7. Anhedral (A) and subhedral (B–D) calcite crystals from vugs embedded in dolostone. Elements of saddle structure are observable (arrows in B–D). Tsiistre (327) core, depth 374.9 m; Middle Devonian, Eifelian, Narva Stage, Leivu Formation; SEM images.

Siltstone makes up 30% of the formation. Siltstone is mainly medium-cemented, with sandy and clayey interbeds. Light greenish-grey, reddish-brown and violetish-grey interlayers, mottled with greenish-grey spots, are predominating, but also reddish-brown beds occur (Appendix 3, D-7).

According to mineralogical composition, the sandstones qualify as arkoses and subarkoses. The composition of heavy minerals varies largely. Iron hydroxides, micas, transparent allothigenic minerals and ilmenite–magnetite are the most significant components. In some cases, the content of dallite is considerable, possibly showing the presence of phosphate fossil fragments. The transparent heavy mineral spectrum is represented by the zircon–tourmaline–apatite assemblage, while the content of garnet is small (Appendix 4). Usually the garnet content is higher in the Kernavė Formation, especially in South Estonia (Valiukevičius *et al.* 1986; Kleesment & Mark-Kurik 1997). The composition of clay fraction in the formation is also different from that of other sections. Besides predominating illite–kaolinite (5–10%), in places minor chlorite is found (Appendix 7; Kleesment 2005). In southeastern Estonia kaolinite occurs as an exception also in the Aruküla Formation, while in most cases it appears first in rocks of the Burtnieki Formation (Kleesment 1994, 1995).

In comparison with the other sections of Estonia, the Kernavė Formation in the Tsiistre (327) core, as in the Mehikoorma (421) and Värska (6) cores of southeastern Estonia (Kleesment 2005; Kleesment & Shogenova 2005), shows a high proportion of sandstones and low content of dolomite. Unfortunately, the quality of the Tsiistre (327) core, which was extracted in 1963, was not sufficient for making thin sections.

The **Aruküla Regional Stage** (=Formation; 248.0–325.8 m, Appendix 1, sheets 9–12; core yield 85%) is divided into three cyclic units: Viljandi, Kureküla and Tarvastu beds. These beds are observable in all sections of the Devonian Baltic Basin, corresponding to definite evolutionary stages (Kleesment 1994).

The lower, ***Viljandi Beds*** (303.2–325.8 m, Appendix 1, sheets 11, 12; core yield 55%) are characterized by thin-bedded intercalation (Appendix 2, T-21; Appendix 3, D-6) of sand- and siltstones. The complex is reddish-brown with light greenish-grey interbeds. Very fine-grained, in places fine-grained sandstone forms 50% of the unit (Appendix 5). Highly clayey to sandy siltstones and silty sandstone varieties are common.

Rocks are mainly weakly to medium-cemented by clay, which is usually pigmented by Fe-hydroxides. Rare strongly dolomite-cemented varieties (of the mixed carbonate-siliciclastic group; Appendix 8) contain in places dolomite-cemented globules. Detrital particles are poorly to moderately sorted, quartz grains are subangular to subrounded (Fig. 6). Mica flakes are generally oriented along bedding planes (Appendix 2, T-20, T-21).

According to mineralogical composition, sandstones are arkoses and subarkoses, with some mica-rich levels. The heavy fraction consists of mica, Fe-hydroxides, ilmenite and transparent allothigenic minerals. Among transparent heavy minerals zircon, tourmaline and apatite are the main constituents (Appendix 4). The clay fraction (< 0.005 mm) contains 85–90% illite, 10–15% kaolinite and minor admixture of chlorite (Appendix 7).

The middle, ***Kureküla Beds*** (275.0–303.2 m, Appendix 1, sheets 10, 11; core yield 90%) are represented by a horizontal thin-bedded complex of reddish- to violetish-brown and grey siltstone (65%), and reddish- to yellowish-brown sandstone (35%). Sandstone is fine-grained and in places silty (Appendix 5), siltstone is clayey to sandy and often contains thin interlayers of very fine-grained sandstone. Mainly clay-cemented rocks have small dolomite admixture (Appendix 2, T-16, T-17, T-18b, T-19; Appendix 8) and are often enriched in Fe-hydroxides (Appendix 2, T-15, T-18a). In places pigmentation forms net-shaped patches (Appendix 2, T-17). The upper part of the unit includes some interlayers of silty dolomitic marlstone and dolomite-cemented siltstone of the mixed carbonate-siliciclastic rock group (Appendix 2, T-16, T-17; Appendix 8). Detrital material is moderately to poorly sorted, quartz grains are mainly subangular to subrounded (Appendix 2, T-16b, T-18, T-19), rarely rounded (Appendix 2, T-15). The roundness of grains decreases upwards (Fig. 6).

Mineralogically the sandstone of the Kureküla Beds is mostly subarkose, containing 75–95% quartz, 5–20% feldspars and mica-rich thin interbeds. In the heavy fraction ilmenite and transparent allothigenic minerals predominate. In some places the content of mica, Fe-hydroxides and leucoxene is high. Transparent heavy minerals are dominated by zircon and tourmaline, in places accompanied by apatite (Appendix 4). The clay fraction (< 0.005 mm) contains 75–90% illite, 10–20% kaolinite and small amounts of chlorite (Appendix 7).

The upper, ***Tarvastu Beds*** (248.0–275.0 m, Appendix 1, sheets 9, 10; core yield 90%) are represented by alternating grey and violetish- to brownish-grey mottled siltstone (55%), and reddish- to violetish-brown sandstone (45%). Intercalation of indistinct thin layers and patches of clayey to sandy siltstone varieties is common. Sandstone is mainly very fine-grained, with the admixture of fine-grained particles (Appendix 5), and weakly to medium-cemented by clay, containing interbeds and patches enriched in Fe-hydroxides (Appendix 2, T-12a,c, T-13, T-14). In places pigmentation forms net-shaped patches (Appendix 2, T-12b).

Rare strongly dolomite-cemented sandstone interbeds (partly consisting of mixed carbonate-siliciclastic rocks) occur in the upper part of the Tarvastu Beds (Appendix 8). Dolomite concentrates usually in patches (Kleesment 1994), inducing in places globular structure (Fig. 5; Appendix 2, T-12a, T-14b; Appendix 1, sheet 10). In some places single dolomite rhombs are present in the matrix (Appendix 2, T-13). Detrital material is moderately to poorly sorted; roundness of quartz grains is variable, whereas subangular and subrounded grains predominate (Fig. 6; Appendix 2, T-12b,c, T-13, T-14a).

According to mineralogical composition, the sandstones are arkoses and subarkoses, containing 71–78% quartz and 17–20% feldspars and in places notable amounts of mica. The heavy fraction consists of mica, ilmenite and transparent allothigenic minerals, supplemented in some levels with Fe-hydroxides and leucoxene. Among transparent heavy minerals zircon and tourmaline are prevailing, in places accompanied by apatite (Appendix 4). The clay fraction (< 0.005 mm) contains 65–80% illite, 20–35% kaolinite and minor admixture of chlorite (Appendix 7).

In southeastern Estonia the content of carbonate-cemented siliciclastic rocks is low and grain-size is smaller than average values (Kleesment & Shogenova 2005). Transparent heavy minerals of the Tsiistre (327) core show low contents of garnet and apatite and an increased content of zircon. The content of tourmaline is comparatively high in some interbeds (Appendix 4). Somewhat unexpected is the upwards decreasing roundness of grains, because earlier an opposite tendency has been established for the Aruküla Formation (Kleesment 1994). The relatively high kaolinite content of the rocks of the Aruküla Formation in southeastern Estonia has been mentioned up to now only in the uppermost Tarvastu Beds (Kleesment 1994). In the Tsiistre (327) core kaolinite is found in the entire Aruküla Formation section, while in the Tarvastu Beds its content is 20–35% (Appendix 7).

The **Burtnieki Regional Stage** (= Formation; 157.0–248.0 m, Appendix 1, sheets 6–9; core yield 80%) is divided into three cyclic units: the Härma, Koorküla and Abava beds (Kleesment 1995).

The lower, ***Härma Beds*** (221.2–248.0 m, Appendix 1, sheets 8, 9; core yield 75%) are represented by light violetish- and pinkish-grey, occasionally white, weakly cemented sandstone (85%) containing interlayers of bluish-, yellowish-, greenish- and violetish-grey mottled siltstone (10%), and violetish- and bluish-grey claystone (5%). Sandstone is mostly fine-grained (Appendix 5). Siliciclastic rocks have a clay matrix (Appendix 8).

Mineralogically the sandstones are subarkoses, with the quartz content of 90–97%. Ilmenite predominates (47–69%) among heavy minerals. The content of heavy allothigenic transparent minerals is comparatively high, especially in the 0.01–0.1 mm fraction (Appendix 4). Zircon (80–83%) predominates, while in the 0.05–0.1 mm fraction also tourmaline (12–43%) and staurolite (14–37%) are significant (Appendix 4). Clay minerals are represented by approximately equal amounts of illite and kaolinite, but in some cases kaolinite prevails (Appendix 7).

The middle, ***Koorküla Beds*** (185.4–221.2 m, Appendix 1, sheets 7, 8; core yield 80%) are represented by reddish-brown, light pinkish- and brownish-grey, weakly cemented sandstone (90% of the section) containing rare violetish- and bluish-grey siltstone interlayers. Sandstone is fine- and medium-grained, including also some coarse-grained interbeds (Appendix 5). Rare elongated quartz grains (5–10 mm across) are found.

Mineralogically the sandstones qualify as subarkoses, with the quartz content of 82–94%. Ilmenite is clearly predominating (43–71%) among heavy minerals. The content of heavy allothigenic transparent minerals is 18–45%. In places leucoxene and Fe-hydroxides occur in notable amounts (Appendix 4). Transparent heavy minerals in the 0.01–0.1 mm fraction are dominated by zircon (43–87%), followed by garnet and rutile. In the 0.05–0.1 mm fraction, the zircon–tourmaline association predominates in the lower part, whereas garnet and staurolite are leading minerals in the upper part of the Koorküla Beds (Appendix 4). Illite (50–75%) is the chief mineral among clay minerals, the content of kaolinite is 25–50% (Appendix 7).

The upper, ***Abava Beds*** (157.0–185.4 m, Appendix 1, sheets 6, 7; core yield 85%) are represented in the lower part by reddish-brown, fine-grained sandstone (85% of the section), while reddish-, violetish-, yellowish- and bluish-grey mottled sandy siltstone predominates in the upper part (Appendix 5). Sandstones qualify as subarkoses and quartzarenites (Appendix 4) with rounded grains (Fig. 6). Siltstone is very rich in mica. Ilmenite prevails (55–80%) among heavy minerals. Transparent heavy minerals make up 14–30%; in the 0.01–0.1 mm fraction zircon is most abundant (80–84%), followed by rutile (7–11%) and staurolite (3–10%). The 0.05–0.1 mm fraction is represented by the zircon–tourmaline–staurolite association (Appendix 4). Among clay minerals illite and kaolinite occur in almost equal amounts, but in some cases kaolinite prevails (Appendix 7).

Clay minerals of the Burtnieki Formation are represented by almost equal amounts of illite and kaolinite (Appendix 7), whereas in South Estonian sections usually illite predominates (Kleesment 1995).

The **Gauja Regional Stage** (= Formation; 79.0–157.0 m, Appendix 1, sheets 3–6; core yield 85%) is represented by the Sietini and Lode members. The heavy mineral content of members is similar: 85–90% quartz and more than 60% ilmenite, but the assemblage of transparent heavy minerals differs notably. In the Sietini Member, zircon always predominates in this group. In the Lode Member, however, tourmaline sometimes dominates over zircon (Appendix 4; Kleesment 1995). Usually the Lode Member is the most kaolinite-rich level in the Devonian of Estonia. In the Tsiistre (327) core the illite and kaolinite contents are almost equal. Illite prevails only in the topmost part of the section, and kaolinite content equals that of the Abava Beds of the Burtnieki Formation (Appendix 7).

The ***Sietini Member*** (127.5–157.0 m, sheets 5, 6; core yield 90%) is represented mainly by pinkish-grey and light red, weakly cemented, fine- to medium-grained (Appendix 5) sandstone, which forms 85% of the member. In places sandstone contains rare quartz grains (up to 2 cm in diameter). Sand and silt grains are mostly angular (Fig. 6). The upper part is dominated by violetish-, yellowish- and light grey (with blue shade) mottled, weakly to medium-cemented siltstone with considerable amounts of Fe-hydroxides in the matrix (Appendix 8).

According to mineralogical composition, the sandstones qualify as subarkoses and quartzarenites, containing 87–98% quartz. In the heavy fraction ilmenite predominates (50–73%). Transparent heavy minerals account for 23–38%. In the 0.01–0.1 mm fraction zircon (59–80%) and staurolite (8–25%) prevail. The 0.05–0.1 mm fraction is represented by the zircon–tourmaline–staurolite association (Appendix 4).

Among clay minerals the contents of illite and kaolinite are almost equal (Appendix 7).

The ***Lode Member*** (79.0–127.5 m, Appendix 1, sheets 3–5; core yield 80%) is represented by a weakly cemented complex of yellowish- and light grey sandstone (content 68%) and light- and violetish-grey, in places reddish-brown siltstone (31%; Appendix 2, T-11), containing thin interbeds of grey and brown claystone. Sandy and clayey siltstone varieties are concentrated in the upper part of the member. Silt- and claystones are wavy thin-bedded.

Sandstone is fine-grained and very fine-grained (Appendix 5). Cement is usually iron-pigmented clay (Appendix 8). Pigmentation is irregular, often occurring along bedding surfaces (Appendix 2, T-11).

The mineralogical composition of the member was investigated mainly in the 0.01–0.1 mm fraction (Appendix 4). Sandstones are mostly subarkoses and quartzarenites, containing 89–99% quartz. In the heavy fraction ilmenite predominates (54–74%). Transparent allothigenic minerals make up 14–29%; siltstones show sporadically high contents of mica (up to 45%). In places, especially in the upper part of the member, leucoxene occurs in notable amounts (10–28%). The heavy transparent minerals are represented by the tourmaline–zircon assemblage accompanied by staurolite and rutile. In the upper part, as typical of this level, tourmaline predominates (Appendix 4; Kleesment 1995). Quartz grains in the lower part of the member are rounded, in the upper part subangular and subrounded particles prevail (Fig. 6). Clay minerals are represented by the illite–kaolinite assemblage. Kaolinite is prevalent in the lower part, illite in the upper part of the member (Appendix 7).

The **Amata Regional Stage** (=Formation; 67.1–79.0 m, Appendix 1, sheet 3; core yield 60%) is represented by mottled (greenish-grey, with violetish-, brownish- and pinkish-grey patches and reddish-brown interbeds), sandy and clayey siltstones (content 80%). The lower part of the stage is grey sandstone (10%) with clay- and siltstone clasts (5–8 cm across) derived from the lower beds. Interlayers of mottled claystone (10%) occur everywhere (Appendix 5).

The mineralogical composition of the 0.1–0.01 mm fraction has been determined only in two samples (Appendix 4). The lower sample is rich in quartz (98%). Among heavy minerals transparent allothigenic minerals, especially tourmaline and zircon are significant. Siltstones in the upper sample contain mica and feldspars, and transparent heavy minerals are dominated by tourmaline. Quartz grains in the basal part are subangular to subrounded (Fig. 6). Illite predominates in the clay fraction, while kaolinite occurs only in the basal part of the formation (Appendix 7).

The Amata Formation has been investigated only in a few cores of Estonia. The Tsiistre (327) core is one of the best examined sections (Kleesment 1995; Kleesment & Mark-Kurik 1997).

The **Pļaviņas Regional Stage** (45.0–67.1 m, Appendix 1, sheets 2, 3; core yield 70%) is represented by dolostones of the Snetnaya Gora and Pskov formations. The formations are distributed in a restricted area in southeastern Estonia and have been studied only in a few drill cores (Kajak 1997).

The ***Snetnaya Gora Formation*** (59.2–67.1 m, Appendix 1, sheet 3; core yield 60%) is represented by horizontally thin-bedded, in places platy, yellowish- and greenish-grey (with violetish-grey interbeds and reddish-brown patches), very finely to finely crystalline dolostones. Dolomite crystals are often zoned, having cloudy cores and transparent rims (Appendix 2, T-10). Vugs (0.1–1 cm, in the basal part < 3 cm across; Appendix 1, sheet 3), fish remains and moulds of shelly fossils are found. Carbonate fossils have dissolved during diagenesis, only phosphate ones are preserved. In places argillaceous, silty and sandy dolostone (Appendixes 6, 8) contains some marl-, clay- and siltstone interbeds (thickness 1–3 mm). Illite predominates in the clay fraction (Appendix 7).

The ***Pskov Formation*** (45.0–59.2 m, Appendix 1, sheets 2, 3; core yield 70%) is represented by horizontally thin-bedded (with rusty planes and laminae; Appendix 2, T-4, T-8; Appendix 3, D-2, D-4, D-5), light yellowish-grey, in places pinkish- and greenish-grey dolostones (insoluble residue < 10%). In the interval of 51.0–59.2 m some detrital-rich fine interbeds (Appendix 2, T-8; Appendix 3, D-5; Appendixes 6, 8) contain > 25% insoluble residue (Appendix 8). Rare phosphate fossil remains are found (Appendix 2, T-9). In the lower part of the formation dolostone is finely crystalline (Appendix 2, T-5…7), in the upper part coarsely to medium-crystalline (Appendix 2, T-1…3). Euhedral dolomite crystals are zoned and carry signs of recrystallization (Fig. 8E,F; Appendix 2, T-2…4). Altered rock is vuggy (Appendix 2, T-2, T-3, T-5; Appendix 3, D-3) and contains often moulds of shelly fossils (Appendix 3, D-1). In places Fe-hydroxide rims surround vugs (Appendix 2, T-6) and rust occurs between dolomite crystals (Appendix 2, T-1, T-4, T-8). Generally dolostones of the Pskov Formation are poor in iron (Appendix 8). The occurrence of Fe-hydroxides on some levels may refer to iron-removing processes during diagenesis.

Peculiarities of dolomitization and dedolomitization

Lower and Middle Devonian carbonate sediments (the greater part of dolostones belong to the Narva

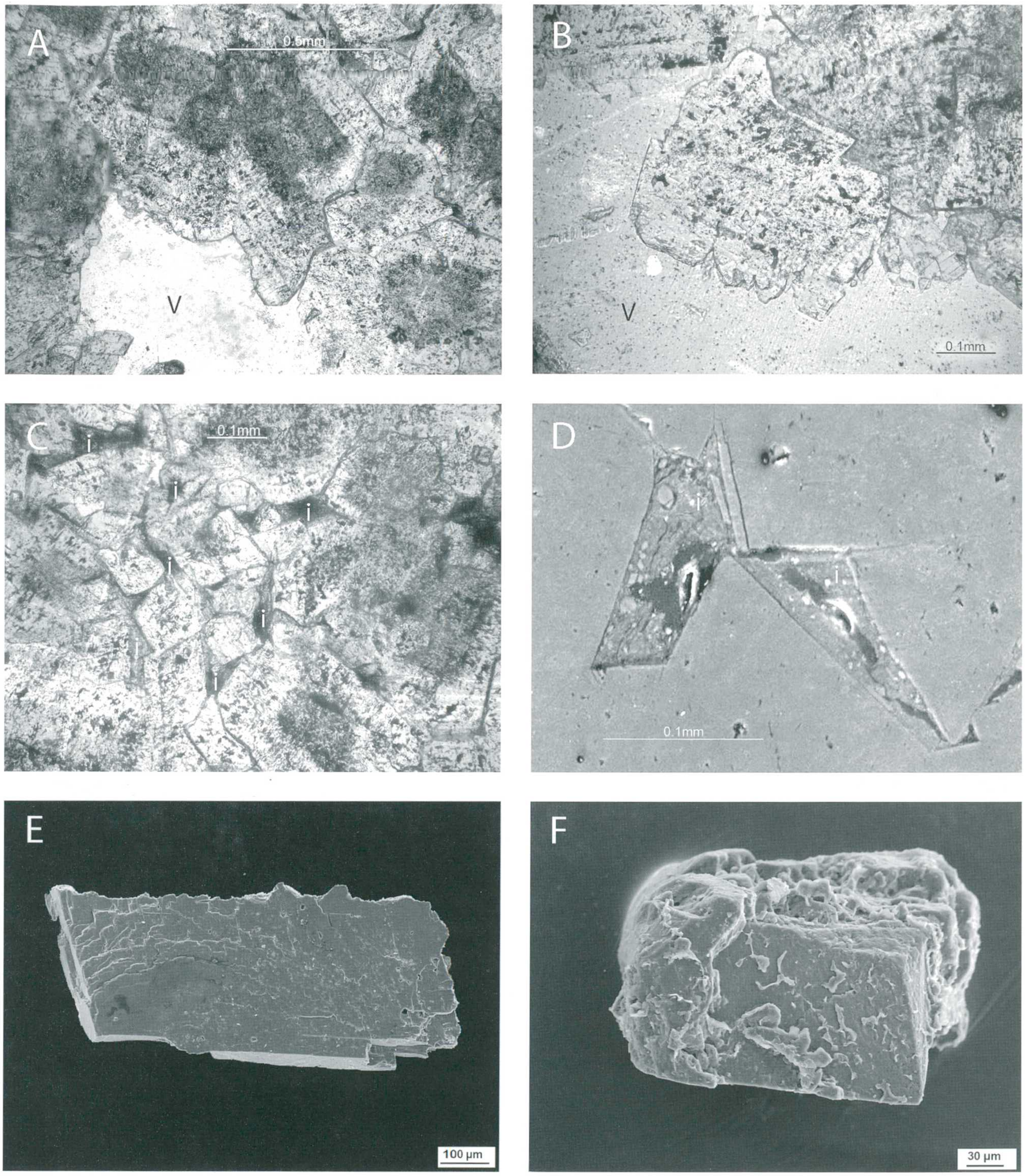


Fig. 8. (A), (B) Zoned coarse dolomite crystals from vugs (marked with V). (C) Illite (i) between different-sized zoned dolomite crystals. (D) SEM image of illite. (E), (F) Euhedral dolomite crystals from vugs (SEM images). Tsiistre (327) core, depth 47.2 m; Upper Devonian, Frasnian, Pļaviņas Stage, Pskov Formation.

Stage) accumulated in tidal-flat environment poor in organic matter under semiarid climate conditions and changed during early diagenesis (Tänavsuu 2004; Kleesment & Shogenova 2005). Upper Devonian dolostones (Pļaviņas Stage) are notably different. They contain less Fe, Mn and insoluble residue (see Shogenova *et al.* in this volume; Appendix 8), and are conspicuous for high porosity (Appendix 2, T-2, T-3, T-5; Appendix 3, D-3) and microstructure. While Lower and Middle Devonian dolostones are very finely to aphanocrystalline (Appendix 2, T-23, T-25, T-27, T-39...41, T-43), Upper Devonian dolostones are coarsely to finely crystalline, often with clear euhedral dolomite crystals, vugs and moulds of dissolved shells

(Appendix 3, D-1). Dolomite crystals are concentrated around vugs (Fig. 8A–C; Appendix 2, T-1…8, T-10) and precipitated in vugs (Fig. 8E,F). Transparent authigenic euhedral dolomite crystals (size < 0.8 mm; Appendix 3, D-1), partly filling vugs (Fig. 8E,F), and zoned crystals occur in the matrix (Fig. 8C; Appendix 2, T-3). The cloudy cores of dolomite crystals and transparent external layers show no differences in the Ca to Mg ratio. By EDS yellowish-brown formations were detected between zoned crystals containing Al, Si, K and Fe (Fig. 8C,D), which probably represent authigenic partings of illite. Despite low iron content the dolostones of the Pskov Formation (Pļaviņas Stage, Appendix 8) contain in places rusty Fe-hydroxides marking bedding planes and thin interlayers (Appendix 2, T-4, T-8; Appendix 3, D-2, D-4, D-5). One calcite-filled vug displayed unusual corrosion of a phosphate fragment (Appendix 2, T-39c).

Organic-rich lime muds accumulated in the sea basin in the Pļaviņas Age and dolomitized after lithification, probably in the middle phase of diagenesis. Late burial dolomitization is evidenced by moulds of strongly recrystallized shells, zoned coarsely crystalline dolomite and high secondary porosity. These characteristics resemble those of shallow burial dolostone described in Zenger (1983), Purser *et al.* (1994), Suchy *et al.* (1996), Green (2005), Lavoie *et al.* (2005), Fu *et al.* (2006), and pore-filling illite between zoned crystals of dolostone is similar to that described in Tekn & Sari (2002).

Middle and late diagenetic dolomitization is usually connected with iron-enrichment (Bhattacharyya & Seely 1994). The small content of Fe and Mn in the dolostones of the Pļaviņas Stage refers to low redox potential during recrystallization of dolomite (Brandt 1994). Iron output by recrystallization is obvious. During recrystallization the iron incorporated in dolomite can be precipitated as Fe-hydroxide (Flügel 2004). In the Tsiistre (327) dolostones iron-rich fluids have migrated along bedding planes and detrital-rich interlayers, which are pigmented by Fe-hydroxides (Appendix 3, D-2, D-4, D-5). Iron hydroxides are precipitated also in the matrix (Appendix 2, T-1, T-4, T-7, T-8). In many cases iron pigmentation is connected with authigenic calcite (Appendix 2, T-24c, T-25). Possibly the scurce material was derived from the high salinity marine basin of the Dubniki Age (Upper Devonian, following the Pļaviņas Age; Sorokin 1978, 1981).

Vugs and fractures filled with transparent authigenic dolomite crystals are common in the Vadja and Leivu formations (Kleesment & Shogenova 2005; Shogenova & Kleesment 2006). During the study of the Tsiistre (327) section calcite-filled vugs, fractures and pockets in dolostones of the Mehikoorma (Rēzekne Stage), Vadja and Leivu (both Narva Stage) formations (interval 356.4–465.4 m; Appendix 2, T-24c, T-25, T-27a,b, T-39, T-43c) were examined in detail. Some vugs contain clear anhedral and subhedral coarsely crystalline calcite (Fig. 7; Appendix 2, T-27a,b). Some relicts of dolomite crystals are found (Appendix 2, T-39b). Dolomite-filled fractures and pockets are rare in the Tsiistre (327) section.

Possibly dedolomitization of the region is connected with gypsum-bearing fluids. X-ray microanalyses by Link Analytical AN 10 000 revealed calcite poor in Mg and Fe. Crystals are anhedral and subhedral with elements of saddle structure (Fig. 7B–D). Saddle dolomite is characteristic of the late diagenetic phase (Flügel 2004); saddle calcite is rare (Kostecka 1993). In the Tsiistre (327) section late diagenetic dolomite crystals have probably been replaced by calcite.

Dedolomitization that proceeded from calcium-rich sulphatic waters, formed due to dissolution of gypsum, has been described in many publications (Folkman 1969; Bischoff *et al.* 1994; Vierek 2005). Interlayers of depositional gypsum lie on the dolostones of the Pļaviņas Stage, in the Upper Devonian section of Estonia, Latvia and NW Russia (Sorokin 1978, 1981; Kajak 1997). In Estonian sections authigenic gypsum is found also in the lower part of the Middle Devonian (Vadja and Leivu formations of the Narva Stage; Kleesment 2001, see appendix 1, sheet 8; Kleesment & Shogenova 2005).

The study of the Devonian section was supported by research projects SF0332524s03 and SF0320080s07, and grant 5726 of the Estonian Science Foundation.

DISTRIBUTION OF DEVONIAN FOSSILS

In the Tsiistre (327) core Devonian fossils (Appendix 1, sheets 2–17) are comparatively numerous in the Upper Devonian Snetnaya Gora Formation and especially in the Middle Devonian Leivu Formation (Table 2). The greater abundance of fossils in these units is probably due to the lithological composition of rocks (mainly dolostones and dolomitic marlstones) and a higher core yield. Fish remains and lingulate brachiopods predominate in samples. The fossils are largely fragmental. Complete shells of lingulates are seldom found (Appendix 3, D-11). Conchostracans and gyro-

Table 2. Fishes, invertebrates and plants in the Tsiistre (327) core (identified by E. Mark-Kurik)

Series	Stage	Regional stage	Depth (m)	Fishes, invertebrates (lingulate and articulate brachiopods, conchostracans) and plants
Upper Devonian	Frasnian	Pļaviņas	Pskov Formation	
			46.8	Articulate brachiopods
			Snetnaya Gora Formation	
			62.0	Fishes: Sarcopterygii; conchostracans: *Asmussia vulgaris* Lutkevitch
			62.7–62.8	Fish fragments
			64.25	Fishes: *Bothriolepis cellulosa* Pander, *Glyptolepis* sp., *Onychodus* sp., Osteolepididae gen. indet., *Moythomasia perforata* (Gross)
			65.0–67.1	Fish? fragments
Middle Devonian	Givetian	B*	Burtnieki Formation, Koorküla Beds	
			221.4	Fishes: *Psammosteus* sp. indet.
		Aruküla	Aruküla Formation, Kureküla Beds	
			299.0	Lingulates
			Aruküla Formation, Viljandi Beds	
			309.2	Fishes: Osteolepididae gen. indet.
	Eifelian	Narva	Kernavė Formation	
			338.45–338.50	Lingulates
			352.2–352.6	Fishes: *Devononchus*?, Osteolepididae gen. indet., *Glyptolepis* sp. indet.; charophytes (trochiliscs)
			Leivu Formation	
			360.45	Lingulates: *Bicarinatina bicarinata* (Kutorga)
			360.8–363.6	Lingulates
			362.0	Lingulates: *Bicarinatina bicarinata* (Kutorga)
			371.1–371.2	Fishes: *Asterolepis*?
			375.3	Fishes: Psammosteidae gen. indet., *Asterolepis estonica*? Gross, Osteolepididae gen. indet., *Glyptolepis* sp. indet., *Onychodus*?; lingulates
			386.3	Lingulates
			386.6–386.7	Fishes: Sarcopterygii; lingulates
			386.8–388.0	Lingulates
			Vadja Formation	
			402.8	Fishes: Osteolepididae gen. indet.; lingulates
		P*	Pärnu Formation, Tamme Member	
			425.0	Plant fossils

Remarks: P* – Pärnu Regional Stage; B* – Burtnieki Regional Stage.

gonites of charophyte algae (= trochiliscs), as well as unidentified plant remains are rare. In the Devonian of Estonia the charophytes are particularly frequent in the Kernavė and Viljandi formations, but they range from the Tamme Formation, Pärnu Regional Stage, and further up to the Aruküla Regional Stage inclusive (Kõrts & Mark-Kurik 1997, table 29).

The richest and most diverse Eifelian and Givetian fish faunas (Mark-Kurik 1997) are poorly represented in the Tsiistre core. More frequent forms in these faunas are psammosteid heterostracans (*Tartuosteus, Pycnosteus, Psammolepis*; in some units also *Psammosteus*), placoderms: arthrodires and antiarchs (*Asterolepis, Bothriolepis*), acanthodians, sarcopterygians: porolepiforms (*Glyptolepis*), osteolepiforms, struniforms (*Onychodus*), dipnoans and actinopterygians (*Cheirolepis, Moythomasia*). Acanthodians and actinopterygians had a squamation consisting of small scales, which favoured their preservation. Scales and teeth of sarcopterygians are also well preserved. Acanthodian scales were not identified in the Tsiistre samples, but a fin spine of *Devononchus*? shows that this group was present in these sediments.

The Middle Devonian fish faunas became gradually richer during the Eifelian and Givetian (Mark-Kurik 2000). Alterations in their composition were too small to reflect substantial changes in environmental conditions. However, the fauna became somewhat poorer closer to the end of the Burtnieki Age (in Abava time) when huge arthrodires *Homostius* and *Heterostius*, and gigantic psammosteids *Tartuosteus* and *Pycnosteus* disappeared, and *Psammolepis* and *Psammosteus*, and large forms of *Asterolepis* of the *ornata-radiata* group started to predominate (Mark-Kurik & Nemliher 2003).

An important event in the evolution of vertebrates took place in the Gauja Age: a possible ancestor or a close relative of tetrapods, the prototetrapod *Livoniana multidentata* appeared (Ahlberg *et al.* 2000). In Estonia its locality is in Jõksi hamlet on the Piusa River. The Gauja and Amata fish faunas are comparatively close, although the dominant Late Devonian placoderms of the genus *Bothriolepis* occur already in the Amata Age. The Middle Devonian age dating of the Gauja Stage by Mark-Kurik *et al.* (1999, fig. 2) is based on contemporaneous occurrences of miospore assemblages in other parts of the East European Platform, Belarus and the Moscow Basin, and on some fish finds.

The Snetnaya Gora Formation contains typical Late Devonian forms, such as *Bothriolepis* (*B. cellulosa* Pander) and *Moythomasia*. In the Meeksi Brook outcrop near Vastseliina, NE of Tsiistre, there occur the ptyctodont *Ctenurella* and probably the dipnoan *Rhinodipterus*. *Moythomasia, Ctenurella* and *Rhinodipterus* are known in the Snetnaya Gora fish localities in Latvia and Pskov Region, and in the Bergish Gladbach quarry, Late Devonian of Rhineland (Ivanov 1990).

CHEMICAL COMPOSITION AND PHYSICAL PROPERTIES OF THE ROCK

The investigated Ordovician (Lower, Middle) and Devonian (Lower, Middle, Upper) section of the Tsiistre (327) core (Appendix 1) is represented by pure and variously argillaceous carbonate rocks (dolostones, dolomitic marlstones), mixed carbonate-siliciclastic rocks (silty and sandy dolomitic marlstones, dolomite-cemented sand- and siltstones) and siliciclastic rocks (sand- and siltstones). A total of 122 rock samples were studied by geochemical methods (Appendix 8). Of those, 94 samples were additionally studied by petrophysical methods (Appendix 10). Thin sections were made in the Institute of Geology at Tallinn University of Technology (IGTUT) from 46 samples to determine relationships between minerals, skeletal and nonskeletal rock-forming grains, cements, fabric, porosity and diagenetic alteration of rocks (Appendix 2).

Methods

The bulk chemical composition of the rocks was determined in pressed powders (made in the Geological Survey of Estonia) by XRF spectrometry in the IGTUT. The insoluble residue (IR), MgO and CaO contents were additionally measured by wet chemical analysis.

Physical properties of the rock were analysed on cylinders, 25.4 mm in diameter and 27–28 mm high, at room temperature and pressure in the Solid Earth Geophysics Laboratory of the University of Helsinki. The methods applied in the study of density, P-wave velocity and magnetic susceptibility are described in detail in Shogenova *et al.* (2006). The control measurements of density and porosity were made in the IGTUT using water saturation during one week at room temperature and normal pressure. The control measurements showed that several samples were undersaturated by water in vacuum. The density and porosity of the most porous Upper Devonian dolostones could not be measured by the water saturation method, as these rocks contained large open vugs 1–12 mm in diameter (see Appendix 3, D-3). The porosity of the measured samples with open vugs was underestimated (Appendix 2, T-3, T-4, T-10), being roughly as high as 20–25%.

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 using standard statistical criteria such as F-test.

Composition of rock samples

The IR, MgO and CaO contents found by wet chemical analysis, and other chemical parameters measured by XRF analysis were used to determine the rock lithology (Fig. 9, Appendix 8; Vingisaar *et al.* 1965). Rock types were distinguished according to the classification of Devonian rocks presented in Kleesment & Shogenova (2005) and other widely employed classifications (Mount 1985; Jackson 1997; Miall 2000; Selley 2000). Because of nearly complete dolomitization of carbonate rocks in the studied drill core, we could discriminate four lithological rock types on the basis of one chemical parameter, IR (Fig. 9, Appendix 8): (1) pure and variously argillaceous dolostone (IR < 25%; 42 samples), (2) dolomitic marlstone (IR 25–50%; 11 samples), (3) mixed carbonate-siliciclastic rock (IR 50–70%; 20 samples), (4) siliciclastic rock (IR > 70%; 49 samples).

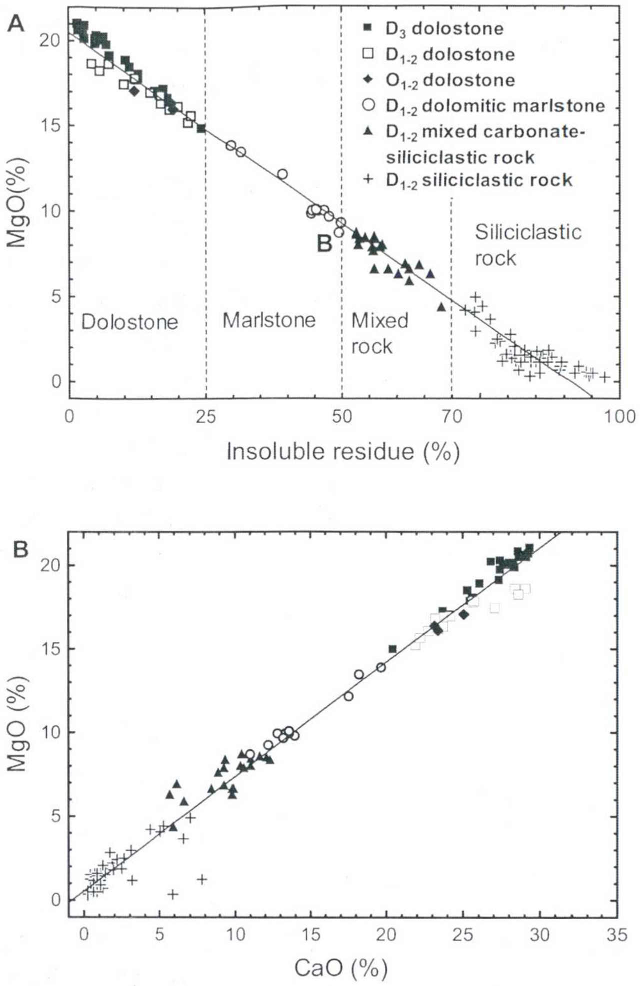


Fig. 9. (A) MgO content versus insoluble residue content, both measured by wet chemical analysis. Correlation coefficient R = -0.99 for all samples. O_{1-2} – Lower and Middle Ordovician; D_{1-2} – Lower and Middle Devonian; D_3 – Upper Devonian.
(B) MgO content versus CaO content, both measured by wet chemical analysis, R = 0.99 for all samples.

The MgO content in Upper Devonian dolostones (average 19.2%) is higher than in Lower and Middle Devonian and Ordovician dolostones (Table 3, Figs 9, 10; Appendix 8). The MgO and CaO contents in the Lower and Middle Devonian dolostones of the earlier studied sections (Shogenova & Kleesment 2006) are close to those of the Tsiistre (327) drill core, but vary in marlstones, mixed carbonate-siliciclastic and siliciclastic rocks. The MgO content is lower in these rocks in the Tsiistre (327) drill core, making up on average 10.6% in marlstones, 7.4% in mixed carbonate-siliciclastic and 1.6% in siliciclastic rocks, while the respective values in eight earlier studied drill cores in southern Estonia are 13.3, 8.4 and 3.1% (Shogenova & Kleesment 2006). The average CaO contents are 14.5, 9.4 and 1.8% in the marlstones, mixed carbonate-siliciclastic and siliciclastic rocks of the Tsiistre section (Table 3), but respectively 18.2, 10.5 and 3.9% in earlier studied rocks (Shogenova & Kleesment 2006).

The IR content of Upper Devonian dolostones (average 8.3%) is lower than that of the older rocks (Table 3).

The total iron (Fe_2O_3total) content of most of the studied rocks, measured by XRF, correlates with Al_2O_3 (indicator of clay content) with the common correlation coefficient 0.91 (Figs 10, 11; Appendix 8). The Fe_2O_3total/Al_2O_3 ratio is in the range 0.09–1.18. For most of the studied rocks this ratio is lower than 1. In general it is higher in carbonate rocks and lower in siliciclastic rocks. The total iron content of Upper Devonian dolostones has high positive correlation with Al_2O_3 and IR (correlation coefficients R = 0.95 and 0.93, respectively) and negative correlation with MgO (R = -0.94).

The total iron content is lowest in dolostones, decreasing upsection (average 0.87, 1.56 and 2.8% respectively in the Upper Devonian, Lower and Middle Devonian, and Lower and Middle Ordovician), higher in marlstones (average 3.83%) and highest in mixed carbonate-siliciclastic rocks (average 4.73%). It varies widely in siliciclastic rocks (Table 3).

The MnO content of Lower and Middle Devonian siliciclastic and mixed rocks has positive correlation with MgO content (correlation coefficient R = 0.86; Fig. 12A) and negative correlation with IR content (-0.87; Figs 10, 12B). In contrast, the MnO content of Upper Devonian dolostones correlates positively with IR content (R = 0.83; Fig. 12B) and total iron content (R = 0.73; Fig. 12C) and negatively with MgO content (R = -0.80; Fig. 12A). The MnO content of Lower and Middle Devonian dolostones does not show significant correlations with MgO and IR contents, and any other chemical parameters. The MnO content of Upper Devonian dolostones is lower than that of Lower and Middle Devonian dolostones, and between these values in Ordovician dolostones. The MnO contents of marlstones, mixed carbonate-siliciclastic rocks and siliciclastic rocks (Table 3) are in the ranges close to those in the earlier studied six drill cores (Kleesment & Shogenova 2005; Shogenova *et al.* 2005). The highest MnO content was determined in one marlstone and in the dolostones of the Leivu Formation (Figs 10, 12; Appendix 8).

The mineralogical variations observed in thin-sections (Appendix 2) of the Tsiistre (327) drill core are supported by the chemical composition of rock (Table 3, Figs 9–12; Appendix 8).

Porosity and density

The porosity–wet density plot may be used for lithological discrimination of different rock types (Shogenova & Puura 1998; Shogenova *et al.* 2003, 2005). In general, the measured wet density of carbonate rocks in the

Table 3. Statistical parameters of the composition and properties of rocks in the Tsiistre (327) drill core

Method	Studied parameter	Dolostone			Dolomitic marlstone	Mixed carbonate-siliciclastic rock	Siliciclastic rock
		Upper Devonian	Lower and Middle Devonian	Lower and Middle Ordovician	Lower and Middle Devonian		
		Minimum–Maximum / **Average** / Standard deviation (number of measured samples)					
Wet chemical analysis	Insoluble residue (%)	1.7–24.3/**8.3**/6.4(25)	4.3–22.4/**14.3**/5.9(14)	12.0–19.2/**16.7**/4.1(3)	29.7–49.8/**43.2**/6.8(11)	52.6–68.0/**58.1**/4.6(20)	72.4–97.4/**84.1**/6.0(49)
	MgO (%)	14.9–21.0/**19.2**/1.6(25)	15.3–18.4/**17.6**/1.1(14)	16.0–17.1/**16.5**/0.5(3)	8.7–13.8/**10.6**/1.7(11)	4.4–8.8/**7.4**/1.1(20)	0.2–4.9/**1.6**/1.1(49)
	CaO (%)	20.4–29.4/**26.8**/2.3(25)	21.9–29.0/**25.0**/2.4(14)	23.2–25.1/**23.9**/1.0(3)	11.0–19.7/**14.5**/2.8(11)	5.7–12.3/**9.4**/2.0(20)	0.3–7.8/**1.8**/1.9(49)
	FeO (%)	0.01–0.31/**0.10**/0.08(25)	0.01–0.31/**0.14**/0.08(14)	0.10–0.21/**0.16**/0.06(3)	0.09–0.40/**0.22**/0.09(11)	0.01–0.53/**0.22**/0.16(20)	0.02–0.38/**0.12**/0.09(49)
	Fe_2O_3 (%)	0.26–1.48/**0.66**/0.32(23)	0.72–1.84/**1.21**/0.57(3)	–	2.42–3.11/**2.77**/0.49(2)	1.86–4.63/**1.09**/2.99(9)	0.33–7.36/**3.44**/1.97(43)
	Fe_2O_3total (%)	0.36–1.64/**0.77**/0.32(23)	0.88–2.08/**1.39**/0.62(3)	–	2.52–3.40/**2.96**/0.62(2)	2.00–5.12/**3.23**/1.19(9)	0.40–7.48/**3.57**/1.99(43)
XRF	SiO_2 (%)	1.2–19.9/**6.5**/5.1(25)	3.2–17.1/**10.7**/4.4(14)	9.0–13.5/**11.7**/2.4(3)	23.0–38.4/**33.3**/5.2(11)	38.5–61.0/**47.1**/6.6(20)	55.5–94.6/**70.1**/9.9(49)
	Al_2O_3 (%)	0.4–6.2/**1.8**/1.4(25)	0.9–4.9/**2.7**/1.2(14)	2.6–4.0/**3.5**/0.8(3)	4.0–12.2/**1.8**/2.5(11)	2.9–14.2/**9.6**/3.4(20)	2.5–17.5/**11.2**/4.7(49)
	TiO_2 (%)	0.02–0.32/**0.20**/0.08(25)	0.04–0.22/**0.13**/0.06(14)	0.16–0.23/**0.21**/0.04(3)	0.20–0.58/**0.43**/0.11(11)	0.09–0.70/**0.48**/0.17(20)	0.16–1.05/**0.65**/0.25(49)
	Fe_2O_3total (%)	0.28–2.54/**0.87**/0.53(25)	0.73–2.82/**1.56**/0.63(14)	2.66–3.04/**2.80**/0.21(3)	1.55–5.69/**3.83**/1.33(11)	1.93–9.36/**4.73**/2.06(20)	0.29–8.51/**4.61**/2.61(49)
	MnO (%)	0.035–0.103/**0.062**/0.020(25)	0.098–0.267/**0.183**/0.051(14)	0.112–0.153/**0.127**/0.023(3)	0.108–0.284/**0.148**/0.049(11)	0.067–0.210/**0.114**/0.036(20)	0.008–0.138/**0.038**/0.023(49)
	K_2O (%)	0.1–2.2/**0.8**/0.6(25)	0.4–2.3/**1.3**/0.6(14)	1.2–2.0/**1.8**/0.5(3)	2.4–5.0/**3.6**/1.0(11)	1.3–6.0/**4.0**/1.4(20)	1.0–6.4/**4.2**/1.3(49)
	P_2O_5 (%)	0.01–0.06/**0.03**/0.01(25)	0.05–0.66/**0.12**/0.17(14)	0.05–0.11/**0.07**/0.04(3)	0.04–0.28/**0.13**/0.07 (11)	0.03–0.63/**0.18**/0.13(20)	0.03–0.34/**0.11**/0.08(49)
	S (%)	0.017–0.074/**0.029**/0.015(25)	0.026–0.094/**0.052**/0.020(14)	0.013–0.018/**0.016**/0.003(3)	0.009–0.035/**0.020**/0.007(11)	0.005–0.029/**0.015**/0.006(20)	0.005–0.113/**0.011**/0.017(49)
Water saturation	Dry density (kg/m^3)	2130–2700/**2440**/160(21)	2320–2650/**2476**/112(14)	2560–2590/**2580**/180(3)	1586–2578/**2249**/256(10)	2103–2500/**2330**/130(13)	1764–2324/**2073**/106(28)
	Wet density (kg/m^3)	2410–2720/**2550**/100(20)	2475–2699/**2578**/73(14)	2640–2660/**2650**/12(3)	2431–2616/**2506**/79(4)	2420–2540/**2500**/59(6)	2036–2433/**2262**/152(5)
	Grain density (kg/m^3)	2650–2760/**2710**/30(20)	2716–2786/**2757**/22(14)	2770–2810/**2780**/25(3)	2681–2708/**2691**/130(4)	2600–2680/**2620**/33(6)	2509–2617/**2569**/48(4)
	Porosity (%)	2.3–17.0/**9.5**/5.0(20)	4.3–16.6/**10.2**/4.0(14)	6.3–8.5/**7.5**/1.1(3)	3.9–14.9/**10.9**/5.0(4)	4.2–13.8/**8.1**/3.9(6)	10.5–27.2/**18.3**/6.5(5)
Acoustic	P-wave velocity (m/s)	2008–5793/**3933**/1040(24)	2796–5777/**4347**/893(14)	4086–4246/**4186**/87(3)	1624–4576/**2922**/1237(4)	2480–4523/**3519**/799(6)	978–2546/**1660**/653(5)
Volume normalized	Magnetic susceptibility (10^{-5} SI)	0.3–8.4/**2.6**/1.8(25)	2.6–8.1/**5.2**/1.7(14)	5.3–11.4/**7.9**/3.2(3)	4.2–23.4/**11.5**/5.0(10)	3.3–20.0/**9.6**/4.9(13)	1.6–20.2/**11.9**/4.9(28)

– parameter not measured.

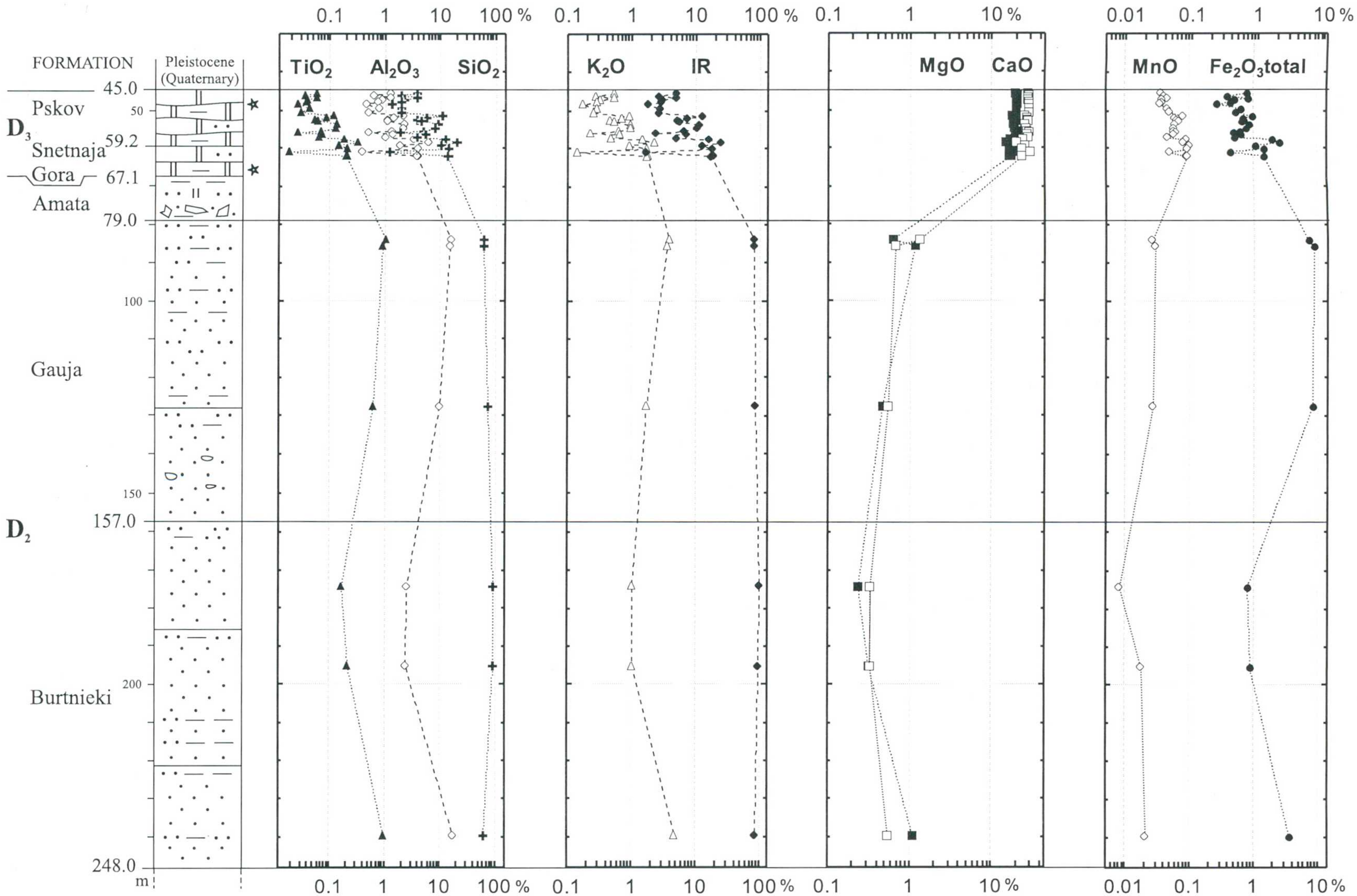
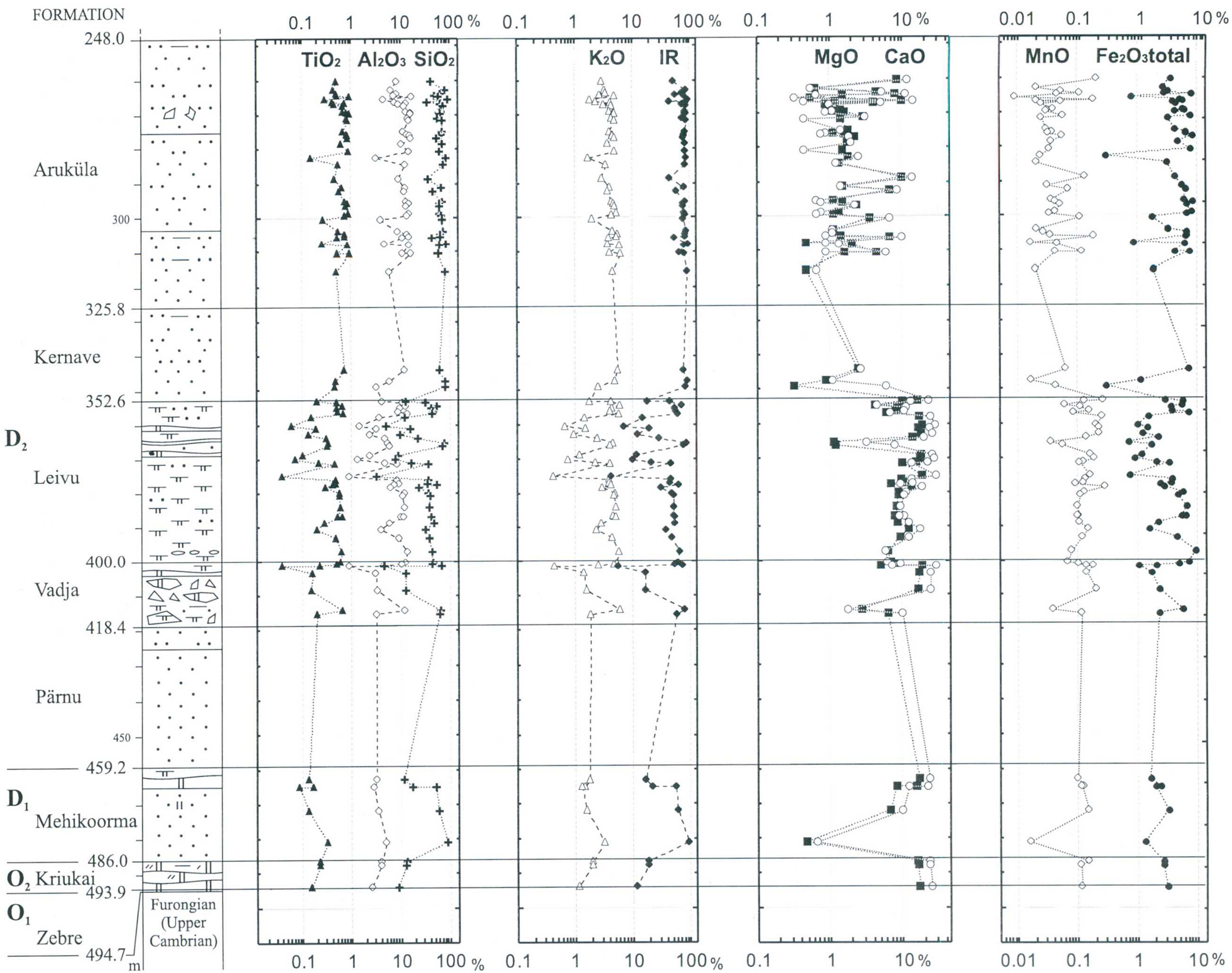


Fig. 10. Chemical composition of the Tsiistre (327) core (on two pages). CaO, MgO and insoluble residue (IR) measured by wet chemical analysis, other oxides measured by XRF analysis. O_1 – Lower Ordovician; O_2 – Middle Ordovician; D_1 – Lower Devonian; D_2 – Middle Devonian; D_3 – Upper Devonian. Refer to Appendix 1 for lithology and distribution of regional stages.



TSIISTRE (327) DRILL CORE

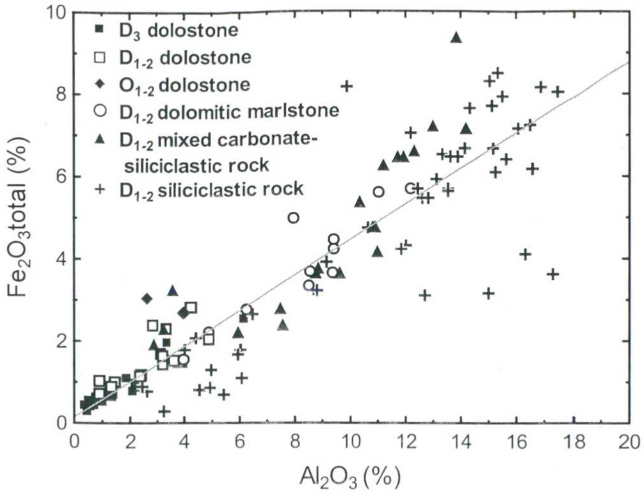


Fig. 11. Total iron content versus Al_2O_3 content, both measured by XRF analysis. Correlation coefficient R = 0.91 for all rocks (122 samples), R = 0.83 for all dolostones (42 samples), R = 0.95 for Upper Devonian dolostones (25 samples), R = 0.95 for Lower and Middle Devonian dolostones and marlstones (25 samples), R = 0.86 for siliciclastic rocks (49 samples) and R = 0.88 for mixed carbonate-siliciclastic rocks (20 samples). O_{1-2} – Lower and Middle Ordovician; D_{1-2} – Lower and Middle Devonian; D_3 – Upper Devonian.

Tsiistre (327) drill core is higher than that of mixed carbonate-siliciclastic and siliciclastic rocks (Table 3, Figs 13A, 14; Appendix 10). Dolostones have the highest density for the given porosity, while mixed carbonate-siliciclastic and siliciclastic rocks have the lowest density. Upper Devonian dolostones can be discriminated from Lower and Middle Devonian dolostones on the porosity–density plot. The latter have a higher density for the given porosity than Upper Devonian rocks. Mixed carbonate-siliciclastic and siliciclastic rocks have a lower density for the same porosity. The mean wet and grain densities of Upper Devonian rocks were lower than those of Lower and Middle Devonian dolostones (Table 3).

All carbonate and siliciclastic rock samples of the Tsiistre (327) core show relatively low (indicated by much scatter on the graphs) but significant positive correlation between porosity and Al_2O_3 content ($R = 0.43$), an indicator of the presence of clay (Fig. 13B). The samples with positive porosity–Al_2O_3 correlation are characterized by primary porosity associated with sedimentation processes. The porosity, which does not correlate with clay content, could be called secondary and is associated with diagenetic processes. The porosity–Al_2O_3 correlation is 0.71 for Upper Devonian rocks but lower for Lower and Middle Devonian rocks. This correlation is highest for the 6 mixed carbonate-siliciclastic samples. Relatively low porosity–Al_2O_3 correlations in the studied drill core could be an evidence of the great role of secondary porosity and other diagenetic processes in the rocks.

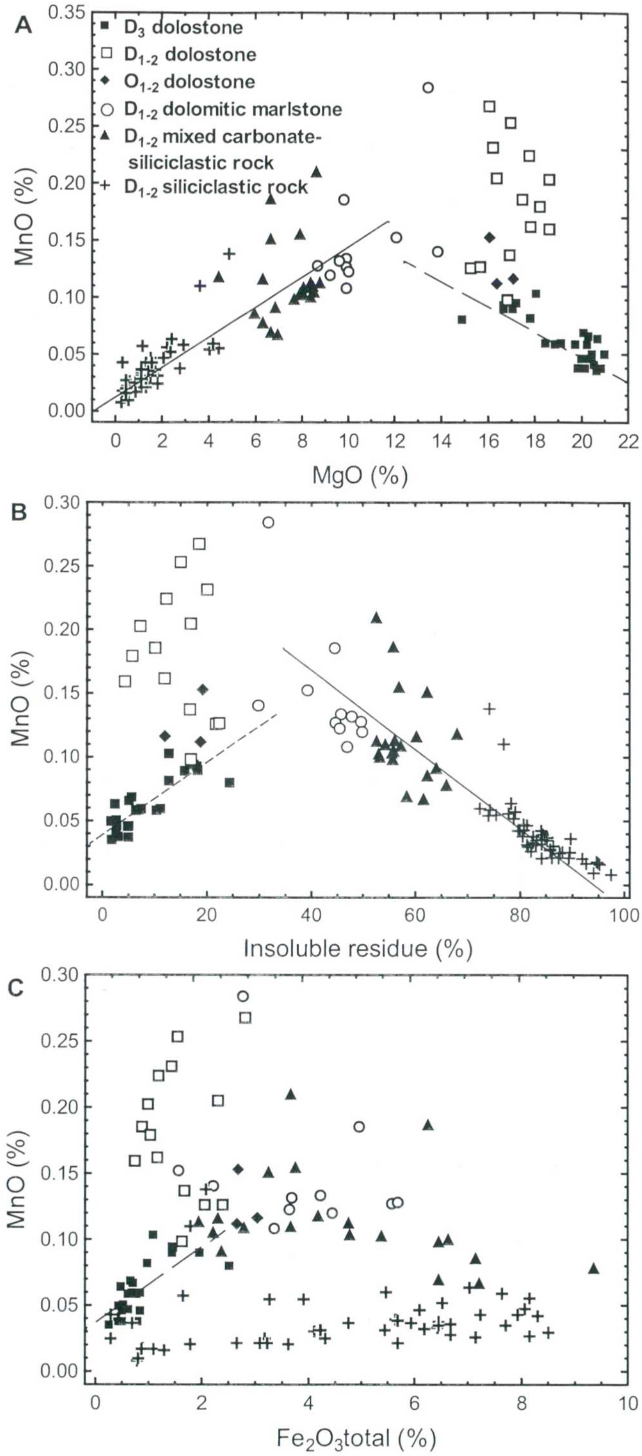


Fig. 12. (A) MnO content measured by XRF analysis versus MgO content measured by wet chemical analysis. Correlation coefficient R = –0.80 for Upper Devonian dolostones (25 samples; dashed regression line), R = 0.86 for siliciclastic and mixed carbonate-siliciclastic rocks together (69 samples; solid regression line). O_{1-2} – Lower and Middle Ordovician; D_{1-2} – Lower and Middle Devonian; D_3 – Upper Devonian.

(B) MnO content versus insoluble residue content, both measured by XRF analysis. Correlation coefficient R = 0.83 for Upper Devonian dolostones (25 samples; dashed regression line), R = –0.87 for siliciclastic and mixed carbonate-siliciclastic rocks together (69 samples; solid regression line).

(C) MnO content versus total iron content, both measured by XRF analysis. Correlation coefficient R= 0.73 for Upper Devonian dolostones (25 samples; dashed regression line).

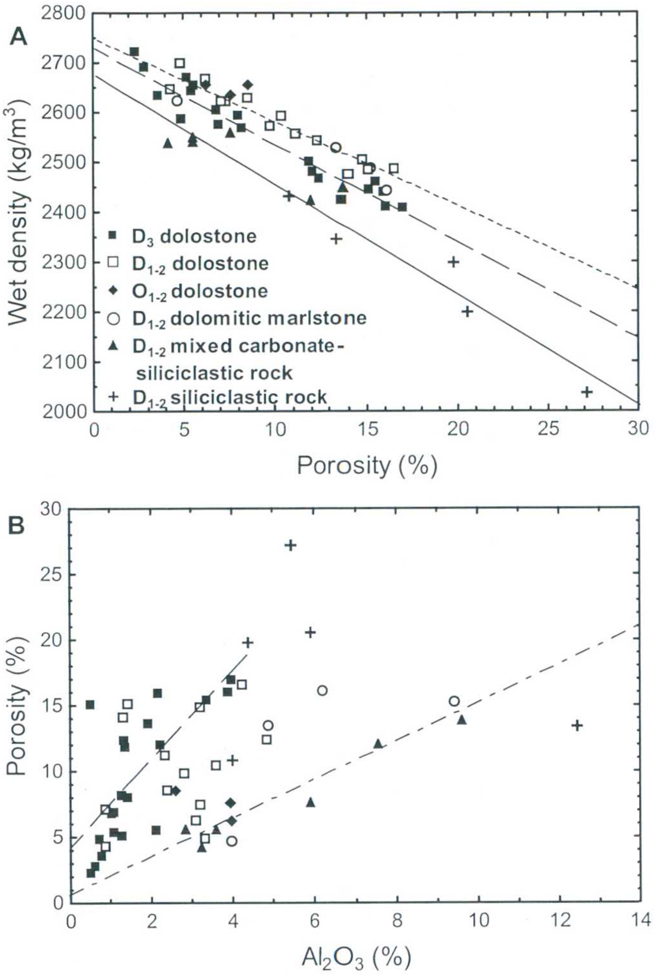


Fig. 13. (A) Wet density versus porosity. Correlation coefficient R = -0.90 for all rocks (52 samples), R = –0.93 for all dolostones (37 samples), R= -0.97 for Upper Devonian dolostones (20 samples; dashed regression line), R = -0.96 for Lower and Middle Devonian dolostones and marlstones (18 samples; dotted regression line), R = -0.97 for siliciclastic and mixed carbonate-siliciclastic rocks together (11 samples; solid regression line). O_{1-2} – Lower and Middle Ordovician; D_{1-2} – Lower and Middle Devonian; D_3 – Upper Devonian.
(B) Porosity versus Al_2O_3 content measured by XRF analysis. Correlation coefficient R = 0.43 for all rocks (52 samples), R = 0.42 for all dolostones (37 samples), R = 0.71 for Upper Devonian dolostones (20 samples; dashed regression line) and R= –0.97 for mixed carbonate-siliciclastic rocks (6 samples; dashed–dotted regression line).

P-wave velocity

The relationship between P-wave velocity and porosity is different for various lithological types. The highest velocity was measured in 41 samples of dolostones, the lowest in siliciclastic rocks (Table 3; Figs 14, 15; Appendix 10). The P-wave velocity of Upper Devonian dolostones (Appendix 2, T-1...8, T-10) for the given porosity is lower than the velocity of Lower and Middle Devonian rocks (Table 3; Appendix 2, T-23...25, T-27, T-39...41). The P-wave velocity of marlstones (Appendix 2, T-28, T-34) is lower than that of dolostones and mixed carbonate-siliciclastic rocks (Table 3; Appendix 2, T-29, T-32, T-42). A P-wave velocity higher than 5000 m/s was determined in several dolostones of the Leivu and Vadja formations (Appendix 2, T-39 and T-41) and in the Upper Devonian (Appendix 2, T-4 and T-10). These Upper Devonian rocks have lower porosity and lower clay content than dolostones with lower P-wave velocity. The P-wave velocity of all measured samples has negative correlation with porosity, -0.84 (Fig. 15). The P-wave velocity–porosity correlation is higher in Upper Devonian dolostones (-0.94) and in Lower and Middle Devonian siliciclastic and mixed carbonate-siliciclastic rocks (-0.88). This negative correlation is lower but significant in Lower and Middle Devonian dolostones and marlstones (-0.80).

Magnetic susceptibility

Low-field magnetic susceptibility in the studied rock sequence correlates with total iron content (Figs 14, 16; Appendix 10) and increases from diamagnetic and paramagnetic to ferromagnetic minerals as in all Estonian sedimentary rocks (Shogenova 1999; Shogenova *et al.* 2003, 2005). The correlation coefficient of magnetic susceptibility with total iron content is 0.86 for all rock samples from the Tsiistre (327) core. The correlation was highest in Upper Devonian dolostones (0.98) and lowest in siliciclastic and mixed carbonate-siliciclastic rocks (0.70). The highest magnetic susceptibility was measured in the Middle Devonian rocks, including one dolomitic marlstone from the Leivu Formation (sample depth 380.0 m, 23.3×10^{-5} SI, total iron content 5.69%; Appendix 2, T-30; Appendixes 8, 10), one silty and sandy dolomitic marlstone from the Vadja Formation (sample depth 400.9 m, 20.0×10^{-5} SI, total iron content 4.77%; Appendix 2, T-37; Appendixes 8, 10) both pigmented by Fe-hydroxide, and in siltstone (sample depth 344.2 m, 20.2×10^{-5} SI, total iron content 7.03%; Appendixes 8, 10). The lowest magnetic susceptibility was determined in Upper Devonian dolostones (average 2.6×10^{-5} SI) with the lowest total iron content (average 0.87%; Table 3; Appendix 2, T-1...8, T-10; Appendix 10), except for one dolostone with magnetic susceptibility of 8.4×10^{-5} SI with the total iron content of 2.53% (Appendixes 8, 10). Magnetic susceptibility and total iron content are higher in Lower and Middle Devonian dolostones (Table 3, Appendix 2, T-23...25, T-27, T-39...41, T-43; Appendixes 8, 10). The average magnetic susceptibility of the three Ordovician samples (7.9×10^{-5} SI), with the average total iron content of 2.80%, is the highest among dolostones (Table 3, Appendixes 8, 10). Glauconite-bearing dolostone of the Zebre Formation had the highest magnetic susceptibility among these rocks (Appendix 2, T-46). The magnetic susceptibility

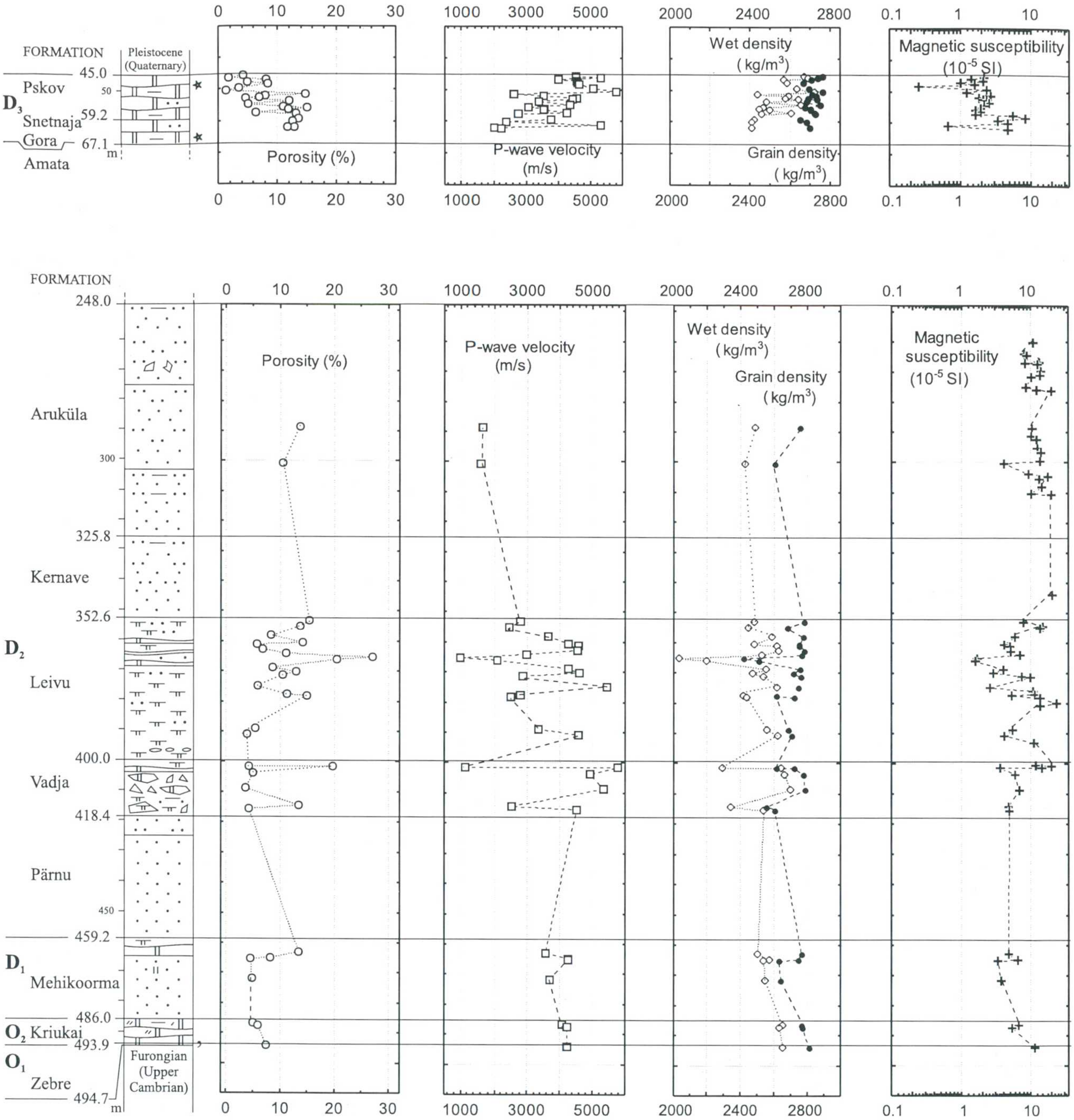


Fig. 14. Physical properties of the Tsiistre (327) core. O_1 – Lower Ordovician; O_2 – Middle Ordovician; D_1 – Lower Devonian; D_2 – Middle Devonian; D_3 – Upper Devonian. Refer to Appendix 1 for lithology and distribution of regional stages.

of dolomitic marlstones is higher than that of dolostones and varies in a wide range (Table 3), reaching the highest values in the studied core. The magnetic susceptibility of siliciclastic rocks and mixed carbonate-siliciclastic rocks varies widely, with correspondingly wide ranges of total iron content (Table 3). Sandstones (Appendix 2, T-19, T-26, T-44; Appendixes 8, 10) show the lowest and reddish-brown iron-hydroxide-pigmented siltstones (Appendix 2, T-21) the highest values among siliciclastic rocks.

In general, magnetic susceptibility correlates with iron minerals occurring in the clay fraction of the rock (Fig. 16B, Appendixes 8, 10). Rock samples with higher magnetic susceptibility for the given total iron and clay content (Fig. 16) contain abundant mica flakes and are pigmented by iron hydroxides (Appendix 2, T-30, T-37, T-38). The samples with lower magnetic susceptibility for the given total iron and clay content may include calcite crystals (Appendix 2, T-26).

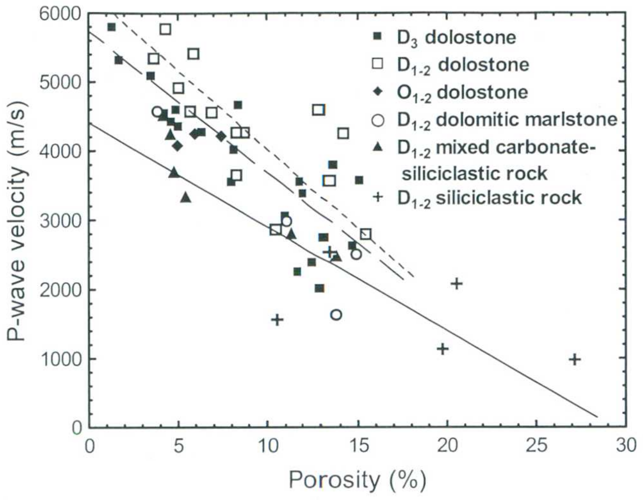


Fig. 15. P-wave velocity versus porosity. Correlation coefficient R = –0.84 for all rocks (52 samples), R = –0.83 for all dolostones (37 samples), R = -0.94 for Upper Devonian dolostones (20 samples; dashed regression line), R = –0.80 for Lower and Middle Devonian dolostones and marlstones (18 samples; dotted regression line), R = -0.88 for siliciclastic and mixed carbonate-siliciclastic rocks together (11 samples; solid regression line). O_{1-2} – Lower and Middle Ordovician; D_{1-2} – Lower and Middle Devonian; D_3 – Upper Devonian.

Conclusions

The examined samples of the Tsiistre (327) drill core are represented mainly by Devonian carbonate, mixed carbonate-siliciclastic and siliciclastic rock. The Upper Devonian dolostones that were studied for the first time showed significant differences in the composition and properties in comparison with Middle and Lower Devonian dolomitized rocks (Figs 9, 11–13, 15, 16). Significant and very strong correlations were revealed in all studied parameters of Upper Devonian dolostones. Iron minerals and MnO content have high positive correlation with the argillaceous part of the rock. The MgO/CaO ratio is higher and the Fe_2O_3total/Al_2O_3 ratio is lower than in older dolostones. The highest MgO content, and the lowest clay, total iron and manganese contents should have caused a higher density and lower porosity of Upper Devonian rocks, but they have not. The influence of secondary porosity and diagenetic mineralization has changed the properties of the rock in the opposite direction. The contents of primary iron and manganese were not changed during diagenesis, but their mineral forms could be.

The specific features of Upper Devonian dolostones are high secondary porosity, caused by leaching of dolostones during dolomitization, and lower grain and bulk density, lower P-wave velocity and magnetic susceptibility compared to older dolostones resulting from other diagenetic processes. Particularly significant are relatively high positive correlation of magnetic susceptibility with porosity ($R = 0.68$), and negative correlation with density ($R = -0.63$) and P-wave velocity ($R = -0.71$). Correspondingly P-wave velocity has negative correlation with total iron content (-0.70), manganese (-0.70) and other chemical compounds entering the clay part of the rocks, and positive correlation with CaO and MgO (0.82 and 0.79).

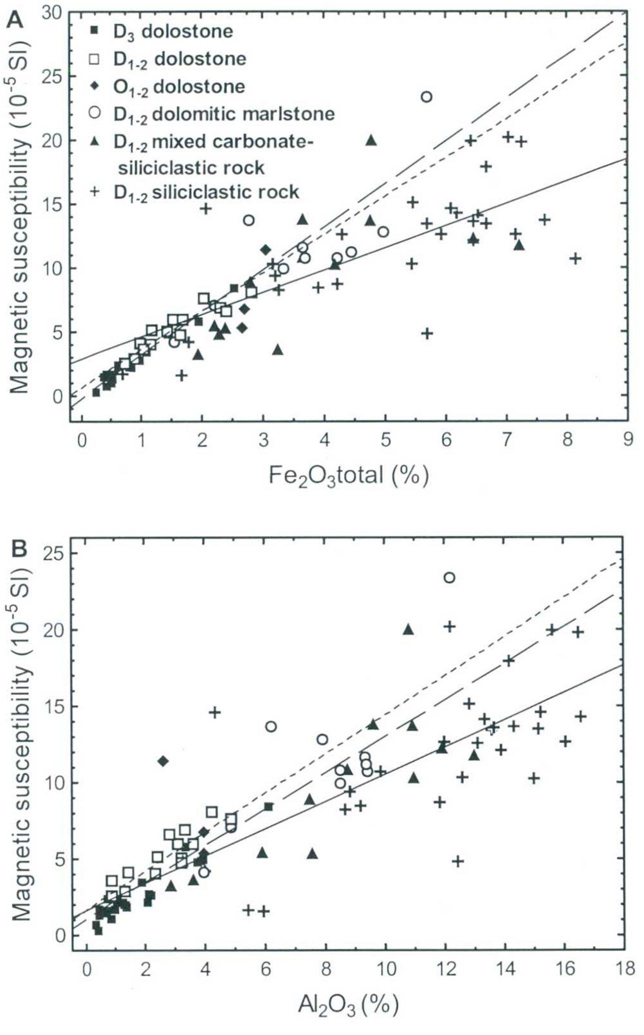


Fig. 16. (A) Magnetic susceptibility versus total iron content. Correlation coefficient R = 0.86 for all rocks (93 samples), R = 0.94 for all dolostones (42 samples), R = 0.98 for Upper Devonian dolostones (25 samples; dashed regression line), R = 0.91 for Lower and Middle Devonian dolostones and marlstones (24 samples; dotted regression line), R = 0.70 for siliciclastic and mixed carbonate-siliciclastic rocks together (41 samples; solid regression line). O_{1-2} – Lower and Middle Ordovician; D_{1-2} – Lower and Middle Devonian; D_3 – Upper Devonian.
(B) Magnetic susceptibility versus Al_2O_3 content. Correlation coefficient R = 0.85 for all rocks (93 samples), R = 0.82 for all dolostones (42 samples), R = 0.96 for Upper Devonian dolostones (25 samples; dashed regression line), R = 0.89 for Lower and Middle Devonian dolostones and marlstones (24 samples; dotted regression line), R = 0.71 for siliciclastic and mixed carbonate-siliciclastic rocks taken together (41 samples; solid regression line), R = 0.81 for mixed carbonate-siliciclastic rocks (13 samples).

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APPENDIX 1

DESCRIPTION OF THE TSIISTRE (327) 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, formations and members.

CORE BOX NO./FIGURES — Numbers of boxes, location of the intervals of core illustrated on CD-ROM (photos of thin sections marked as T-1…46 and detailed core photos as D-1…21 in Appendixes 2 and 3).

DEPTH/SAMPLES — Depth of the boundaries and sample levels: A, acritarchs; F, X-ray fluorescence samples; Fr, fossil remains; G, granulometric samples; K, chemical samples; M, mineralogical samples; Ph, physical properties; 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: 50.

SEDIMENTARY STRUCTURES — According to the 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. Distinct nodular structures are missing, in places indistinctly nodular structure is observed.

MARLSTONE BEDS — The most frequent thicknesses of the marlstone beds. Contacts between marlstone and other types of rock may be distinct (D) or indistinct (IND). The colour of rocks was 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, Devonian part of core is performed after preliminary description compiled by K. Kajak (Väärsi *et al.* 1964); the dominant size of limestone crystals (in italics) was estimated visually: cryptocrystalline (< 0.005 mm), microcrystalline (0.005–0.01 mm), very finely crystalline (0.01–0.05 mm), finely crystalline (0.05–0.1 mm), medium-crystalline (0.1–1.0 mm) and coarsely crystalline. 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), pebbles (10–100 mm) and cobbles (> 100 mm).

Appendix 1 continued.

LEGEND

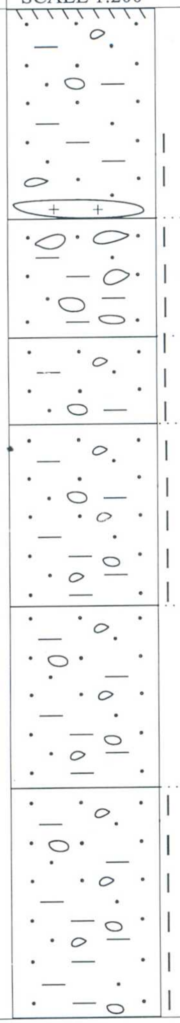
- cultivated soil
- loamy sand
- sandstone
- sandstone, dolomite-cemented
- clayey sandstone or clayey sand (Pleistocene)
- siltstone
- clayey siltstone
- a, b — siltstone (a), sandstone (b), dolomite-cemented
- claystone
- silty claystone
- a, b — dolostone: very finely to coarsely crystalline (a), crypto- and micro-crystalline (b)
- a, b — skeletal dolostones: grains 10–25% (a) and grains 25–50% (b)
- a, b — argillaceous (a) and silty (b) dolostone

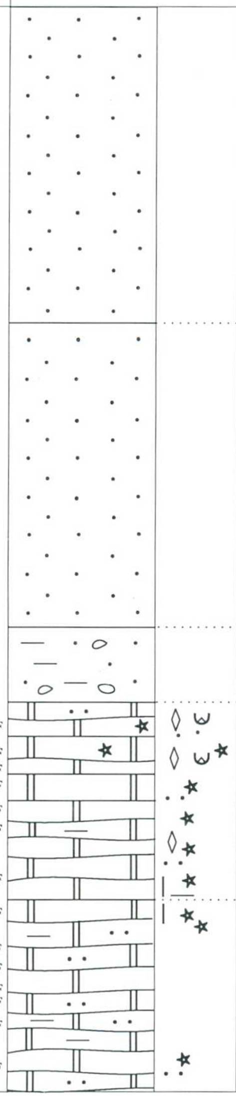
- dolomitic marlstone
- breccia
- conglomerate
- a, b — fine (a; 0.05–1.0 mm) and coarse (b; > 1 mm) bioclasts
- a, b, c — horizontal bedding: thin (a), medium (b) and thick bedding (c)
- wavy bedding
- nodular
- thin intercalation
- nodules
- a, b, c, d — horizontal, thin bedding (a), wavy bedding (b), lenses (c), cross-bedding (d) in sand-, silt-, clay- and marlstones
- discontinuity surface
- mud-cracks
- slickenside
- veins
- burrows

- caverns (vugs)
- mottled, red-coloured and yellow streaks
- ooliths
- clastic material
- granite cobble
- sandstone globules
- a, b, c — silt- (a) and sand-sized (b) grains, and clay admixture (c)
- glauconite grains
- Q, F — quartz (Q) and fedspar (F) grains
- dolomite
- calcite
- micas (in general)
- pyrite
- brachiopods
- trilobites
- cephalopods

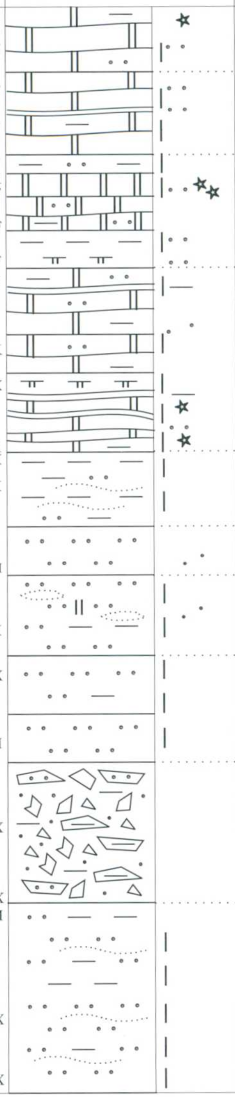
DESCRIPTION OF THE TSIISTRE (327) CORE

Location: 57° 40' 23" N, 27° 11' 31" E. Length of the core 533.7 m. Elevation of the top 196.5 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
Upper Pleistocene, Quaternary		Core is lost		0.0–5.5			(Core yield 85%)			Loamy sand cover (thickness 0.2 m) underlain by brown weathered **loamy sand** with gravel and rare pebbles. Clasts derived mainly of carbonate rock. The lowermost 0.5 m includes cobble of pink coarse-grained granite
				5.5–8.7			(Core yield 65%)			Brownish-grey **loamy sand** with pebbles (diameter 5–10 cm). Carbonate clasts make up 75% of pebbles, 90% of rocks are Ordovician and Silurian, the rest of Devonian age
				8.7–11.0			(Core yield 55%)			Brownish-grey (the lowermost part yellowish-grey) **loamy sand** with gravel and pebbles (diameter 1–4, rarely up to 10 cm; carbonate pebbles make up 75%, the rest are igneous)
				11.0–15.8			(Core yield 70%; poor quality)			Dark brown **loamy sand** with gravel (mainly clasts of igneous rock) and pebbles (diameter 5–10 cm; mainly carbonate clasts)
				15.8–20.6			(Core yield 80%; poor quality)			Probably **loamy sand** with gravel and pebbles
				20.6–26.6			(Core yield 70%)			Brownish-grey (in the upper part brown) **loamy sand** with gravel (predominantly clasts of igneous) and pebbles (diameter 1–8 cm; mainly carbonate clasts)

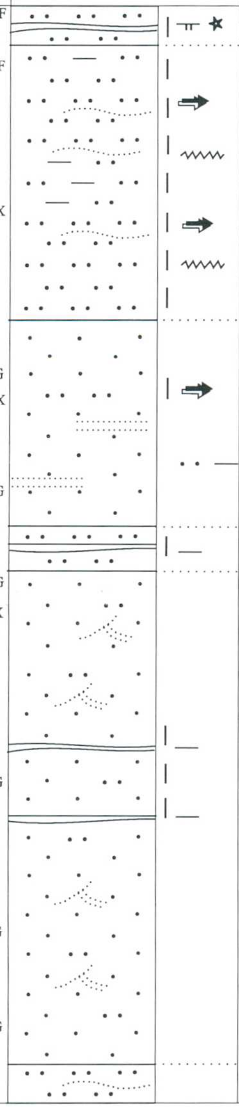
STANDARD UNITS	LOCAL STRATIGRAPHIC UNITS	CORE BOX NO.	FIGURES	DEPTH (m)	SAMPLES	LITHOLOGY	SEDIMENTARY STRUCTURES	MARLSTONE BEDS	MARLSTONE PERCENTAGE	SHORT DESCRIPTION
Upper Pleistocene, Quaternary		Core is lost		26.6			(Core yield 70%, poor quality)			Grey, *fine-grained* **sand**
				35.0			(Core yield 70%)			Light yellow, *fine-grained* **sand**, grain size varies in the lowermost 1.0 m
				43.0			(Core yield 50%)			Greenish-grey **loamy sand** with gravel and pebbles (diameter 1–2 cm, mainly carbonate clasts)
Upper Devonian Frasnian	Plavinas Stage Pskov Formation	9	T-1, D-1, T-2, D-2, T-3, D-3, T-4	45.0	K PhTF, Ph F, Fr K PhTF, K PhTF, Ph F, Ph F, PhTF		Horizontal, thick- to thin-bedded, in places massive (Core yield 60%)			Light yellowish-grey, in places greenish-grey, the lowermost 0.2 m grey, violet and green mottled, vuggy, *medium-crystalline* (in places *finely* to *coarsely crystalline*), in the lower half *coarsely crystalline* **dolostone**. In vugs (size 0.5–5, rarely up to 30 mm) and brachiopod moulds are found dolomite crystals (size up to 2 mm). The rock has signs of recrystallization. A brownish-red iron-pigmented surface occurs at 49.9 m
		10	T-5, T-6	50.2	Ph F, Ph F, K PhTF, Ph F, PhTF, Ph F, Ph F		Horizontal, thin-bedded; lower 0.7 m in places wavy, thin- to thick-bedded (Core yield 80%)			Light yellowish-grey, in places pinkish- and greenish-grey, *finely crystalline*, in places *medium-crystalline* **dolostone** with rare argillaceous and silty interbeds (thickness 0.5–2 mm). The uppermost 1 m is rich in vugs (size 0.5–2 cm), some vugs are found in the lower part. The lowermost part includes iron-pigmented surfaces

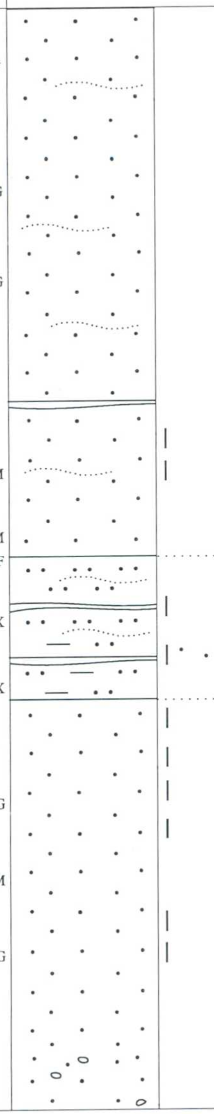
LITHOLOGY

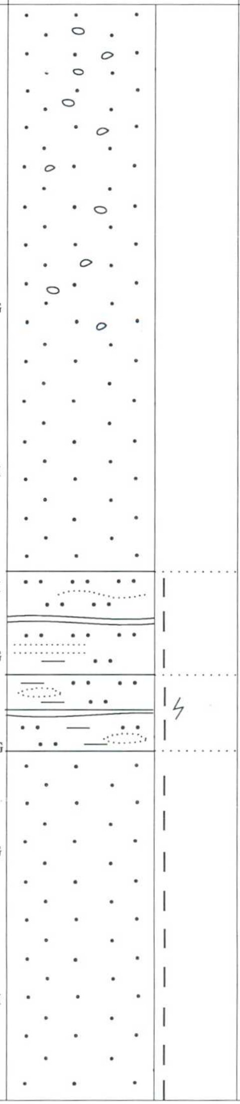


STANDARD UNITS	LOCAL STRATIGRAPHIC UNITS	CORE BOX NO.	FIGURES	DEPTH (m)	SAMPLES	SEDIMENTARY STRUCTURES	MARLSTONE BEDS	MARLSTONE PERCENTAGE	SHORT DESCRIPTION
Upper Devonian Frasnian	Plavinas Stage, Pskov Fm.	10	T-7, D-4, D-5		PhT F, PhF, KPh F				☞ follow up
Upper Devonian Frasnian	Plavinas Stage, Pskov Fm.	10 / 11	T-8	57.1	Ph Ph F T F, Fr K Ph T F	Horizontal, thin-bedded, platy (Core yield 65%)	1–5 cm; IND grey		Yellowish-grey, *finely crystalline* to *very finely crystalline* **dolostone** with reddish-brown silty dolostone and dolomitic marlstone lenses and interbeds (thickness 0.1–5 cm)
Upper Devonian Frasnian	Plavinas Stage, Snetnaya Gora Formation	11	T-9, T-10	59.2	X Ph F, K Ph F, Ph T F, X, Fr F Ph F	Claystone thin-bedded; dolostone massive, in places lens-shaped, in the lower part medium-bedded	0.2–2 cm; IND greenish-grey	10	Yellowish- and greenish-grey, with violet patches, *microcrystalline* to *finely crystalline* **dolostone** with silty and argillaceous interbeds (thickness 0.1–1 cm). The uppermost 0.5 m and lowermost 0.4 m greenish-grey silty dolomitic claystones with brownish-red interbeds (thickness 0.05–0.3 cm)
Upper Devonian Frasnian	Plavinas Stage, Snetnaya Gora Formation	core is lost		62.2	Fr X, Fr K, X, Fr, K	Horizontal, thin-bedded, in places lens-shaped (Core yield 55%)	0.2–2 cm; IND yellowish- and violetish-grey	< 10	Light grey (with yellowish-, violetish- or greenish-grey interbeds and reddish-brown patches), argillaceous, in places sandy and silty, *finely crystalline* **dolostone** with siltstone interbeds (thickness 1–3 mm). A siltstone interbed occurs at 62.7–62.8 m. The interval of 65.0–65.4 m is dolomitic marlstone with clay- and siltstone interbeds. In places vugs (diameter 0.1–3 cm) are filled with clay
Middle Devonian Givetian	Amata Stage, Amata Formation	13		67.1	G X, G X	Wavy, indistinctly bedded, in places rubbly			Intercalation of violetish-grey and grey mottled silty **claystone** and brownish-grey clayey **siltstone**
Middle Devonian Givetian	Amata Stage, Amata Formation	13		69.1	X, G M	Indistinctly bedded			Greenish-grey, weakly to medium-cemented **siltstone**, with clayey and sandy interbeds. Clay content decreases downwards
Middle Devonian Givetian	Amata Stage, Amata Formation	13		70.4	X X	Indistinctly bedded, in places lens-shaped			Greenish-grey (with violetish-, brownish- and pinkish-grey patches), weakly to strongly cemented **siltstone** with dolomitic, sandy and brown clayey interbeds (thickness < 2 cm). The uppermost 0.2 m is medium-cemented
Middle Devonian Givetian	Amata Stage, Amata Formation	14		72.5	X, M	Wavy, indistinctly bedded (Core yield 65%)			**Siltstone**, medium-cemented. The clayey upper part is yellowish- and violetish-grey with reddish-brown interbeds, the sandy lower part light greenish-grey with violetish-grey patches
Middle Devonian Givetian	Amata Stage, Amata Formation	14		75.3	X, X	Breccia-like (Core yield 20%)			Grey **sandstone**, sandy and clayey **siltstone**, and light bluish-grey **claystone** with light greenish- and yellowish-grey clay- and siltstone fragments (diameter 5–8 cm) derived from the lower beds
Middle Devonian Givetian	Gauja Stage, Gauja Formation, Lode Member	15		79.0–84.0	M, X, X	Wavy, indistinctly bedded, in places rubbly; clayey siltstone thin-bedded, in places wavy (Core yield 50%)			Light grey and violetish-grey (with yellowish- and brownish-grey, rarely with brownish-red interbeds, the lowermost 0. 6 m is violetish-brown) **siltstone** with clayey interbeds. Clay content changes vertically. Yellow iron hydroxide patches are found at 79.7–80.3 m. Light grey silty claystone occurs at 79.0–79.1 and 79.4–79.5 m

STANDARD UNITS	LOCAL STRATIGRAPHIC UNITS	CORE BOX NO.	FIGURES	DEPTH (m)	SAMPLES	LITHOLOGY	SEDIMENTARY STRUCTURES	MARLSTONE BEDS	MARLSTONE PERCENTAGE	SHORT DESCRIPTION
Middle Devonian Givetian	Gauja Stage Gauja Formation Lode Member	T-11		84.0 85.0	M PhT F F		Wavy, indistinctly bedded (Core yield 40%)			Light bluish-grey, in places reddish-brown, weakly to medium-cemented (in places by dolomite), **siltstone** with sandy and clayey interbeds
		15		92.3	X		Wavy, indistinctly bedded (Core yield 65%)			Violetish- and reddish-brown, in places with yellowish-grey spots or patches, at 87.7–88.2 and 90.0–91.0 m light yellowish- and violetish-grey, the lowermost 1.3 m is dark violetish- and brownish-grey, weakly to medium-cemented (by clay rich in iron compounds) **siltstone** with greenish-grey sandy interbeds (thickness 1–10 cm). The layers at 85.0–85.2 and 88.0–89.4 m are highly clayey. Slickensides are covered with clay and inclined
		16		97.7	M G X M G		Indistinctly bedded, in places thin-bedded (Core yield 85%)			Light grey to white, in places with green, blue and yellow shade, weakly cemented, *very fine-grained* **sandstone**. At 93.8–94.8 m occurs **siltstone** (clay content increases downwards), in the upper part yellow and brown mottled, in the lower part violetish-grey, with green and brown spots. Brownish-grey weakly cemented sandy siltstone (interval 96.0–96.2 m) lies on the 3 cm thick silty claystone bed (light greenish- and yellowish-grey). Slickenside angle is 45°
				98.9			Indistinctly bedded			Light bluish- to greenish-grey, with yellow and brown spots (in the lowermost 0.15 m white), weakly cemented **siltstone** with violetish-grey silty claystone interbeds (thickness 1–25 cm)
		17 18 19		112.0	M G X M G M G G M G		Indistinctly thin-bedded and cross-bedded			Yellowish-grey and light grey, weakly cemented, in places silty, in the upper part *fine-grained*, in the lower part *very fine-grained* **sandstone**. Mottled clayey interlayers 0.1–1.0 cm thick lie at 103.0–106.0 m
				113.0			Indistinctly bebbed (Core yield 60%)			White, with blue shade, medium- to weakly cemented **siltstone** with violetish-brown clayey interbeds (thickness 0.5–2 cm)



STANDARD UNITS	LOCAL STRATIGRAPHIC UNITS		CORE BOX NO.	FIGURES	DEPTH (m)	SAMPLES	LITHOLOGY	SEDIMENTARY STRUCTURES	MARLSTONE BEDS	MARLSTONE PERCENTAGE	SHORT DESCRIPTION
Middle Devonian Givetian	Gauja Stage Gauja Formation	Lode Member	20, 21		113.0	M G, M G, M M G G, M, M		Wavy, indistinctly bedded; silt- and claystone thin-bedded (Core yield 85%)			Light grey, the uppermost 5.5 m with green and yellow shade, weakly cemented, *very fine-grained*, in the lowermost 2.2 m *fine-grained*, **sandstone** (quartz grains rounded in places). Greenish- and yellowish-grey silt- and claystone interlayers lie at 123.2–123.8 m. Bedding surfaces are impregnated by iron compounds, rust-brown at 124.0–125.6 m
			22		127.5	Ph F, X, X		Wavy, indistinctly bedded, in places thin-bedded and rubbly			Violetish, yellowish and light grey (with blue shade) mottled, weakly to medium-cemented, in places clayey, **siltstone**. In places, particularly at 128.8–128.9, 130.1–130.4 and 131.0–131.1 m occur light grey (with violet, yellow and blue shade) silty claystone interlayers. A mottled silty **sandstone** bed occurs at 130.0–130.1 m
		Sietini Member	23, 24		131.3	M G, M, MG		Not observable (Core yield 90%)			Weakly cemented **sandstone**: at 131.3–140.6 m pinkish-grey and light red (with light yellowish-grey interbeds, at 135.4–136.5 m light greenish-grey), *fine-grained*; at 140.6–150.8 m light grey, *fine-* and *medium-grained* (rare quartz grains are up to 2 cm in diameter); below 150.8 m light grey to white, *very fine-grained*. Sand and silt grains mainly angular. A white bed (thickness 3 cm) lies on the lower boundary

STANDARD UNITS	LOCAL STRATIGRAPHIC UNITS	CORE BOX NO.	FIGURES	DEPTH (m)	SAMPLES	LITHOLOGY	SEDIMENTARY STRUCTURES	MARLSTONE BEDS	MARLSTONE PERCENTAGE	SHORT DESCRIPTION
Middle Devonian Givetian	Gauja Stage Gauja Formation Sietini Member	25, 26, 27			MMGG, M					☞ follow up
	Burtnieki Stage Burtnieki Formation Abava Beds	27, 28		157.0	X X, M G		Wavy, indistinctly bedded; the lowermost 0.3 m horizontal, thin-bedded, in places rubbly			Violetish-, yellowish- and bluish-grey mottled (at 158.2–158.4 m light bluish-grey), weakly cemented, in places clayey and sandy **siltstone** with silty claystone interbeds (thickness 0.5–2.0 cm). Violetish-grey silty claystone (with rare sandy and clayey siltstone interlayers) beds lie at 159.0–159.4 m. A 0.3 m thick light bluish-grey, medium-cemented clayey siltstone bed occurs on the lower boundary
		28		159.7	G, G		Wavy, indistinctly bedded, lens-shaped (Core yield 60%)			Reddish-brown, yellow, violet and grey mottled, clayey **siltstone**, at 160.4–160.6 m with violet spots and fractures (surfaces covered with bluish-grey clay). The lowermost 0.2 m is dark violetish-grey, weakly cemented siltstone
		28, 29, 30		161.7	X M G, M		Not observable (Core yield 85%)			Reddish-brown, in the lower part with violet shade, weakly cemented, *fine-grained* (in the lowermost 0.4 m *fine-* to *medium-grained*) **sandstone**. Quartz grains mainly rounded

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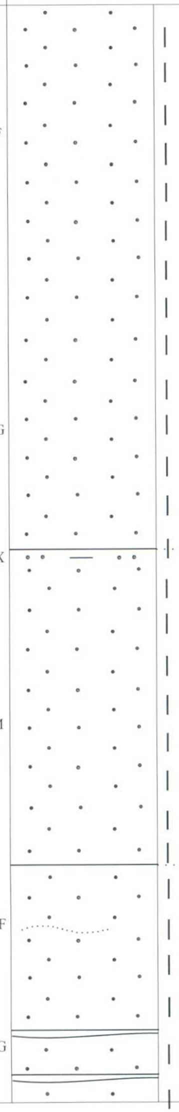
Middle Devonian Givetian	Burtnieki Stage Burtnieki Formation Abava Beds	30 31 32			MGF MMGG					☞ follow up
	Koorkila Beds	core is lost		185.4	GX M		Not observable; the uppermost 0.2 m thin-bedded (Core yield 75%)			Light pinkish- and brownish-grey, weakly cemented, *fine-* and *medium-grained* **sandstone**. Rare elongated quartz grains 5–10 mm in diameter are found. The uppermost 0.2 m is violetish- and yellowish-grey mottled clayey siltstone
		34 35		193.8	MG F G		Not observable (Core yield 70%)			Reddish-brown (with violet shade), weakly cemented, *fine-* to *medium-grained* **sandstone**. Light grey, mainly *coarse-* and *medium-grained* sandstone interlayers lie at 198.0–201.0 m

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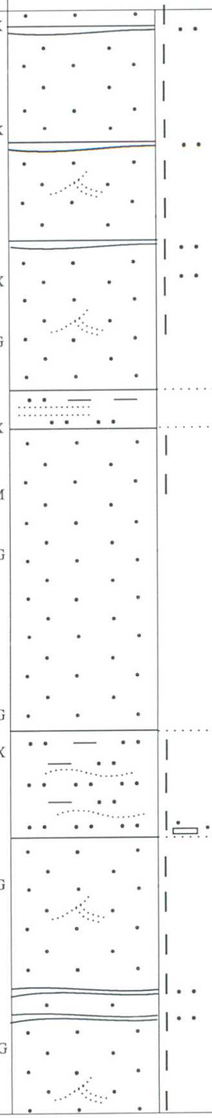
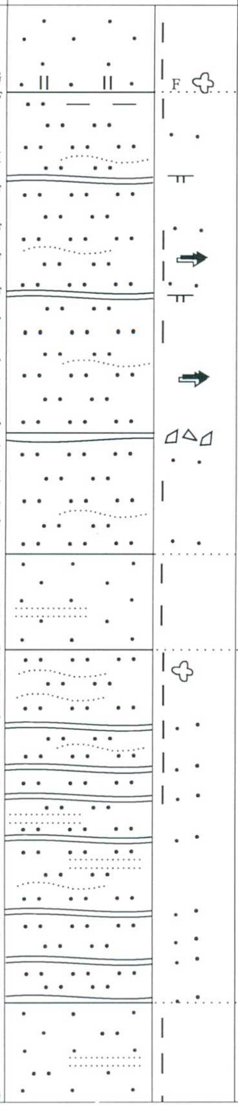
Middle Devonian Givetian	Burtnieki Stage Burtnieki Formation Koorküla Beds	35		205.0	MMG					☞ follow up
		36 37 38		221.2	M M MMG X X MG		Not observable (Core yield 80%)			Reddish-brown (at 211.0–213.5 m with violet shade, at 208.7–211.0 m yellowish-grey), weakly cemented, *fine-grained* **sandstone**. Violetish- and bluish-grey or reddish-brown clayey siltstone and silty claystone interbeds lie at 208.6–208.7, 209.8–209.9, 213.7–214.1 and 216.3–216.4 m. The uppermost 0.5 m is grey (with brown spots) sandy siltstone
				222.6	Fr X		Thin-bedded			Light grey, and yellowish- and greenish-grey (at 221.65–221.68 m violetish-grey), clayey **siltstone** with light bluish-grey silty claystone and sandy siltstone interbeds (thickness 0.1–4.0 cm). Silt content increases downwards
	Härma Beds	39			MG		Indistinctly thin-bedded and cross-bedded (Core yield 75%)			Light pinkish- and violetish-grey, weakly cemented, *fine-grained* **sandstone**. In places, particularly at 229.3–229.4, 232.4–232.6 and 235.0–235.2 m, light bluish-grey clayey siltstone and violetish-grey silty claystone interlayers (thickness 0.3–2.0 cm) are found. The lower- and uppermost metres of the complex are almost white and grain-size of sandstone is less than 0.1 mm

STANDARD UNITS	LOCAL STRATIGRAPHIC UNITS	CORE BOX NO.	FIGURES	DEPTH (m)	SAMPLES	LITHOLOGY	SEDIMENTARY STRUCTURES	MARLSTONE BEDS	MARLSTONE PERCENTAGE	SHORT DESCRIPTION
Middle Devonian Givetian	Burtnieki Stage Burtnieki Formation Härma Beds	40 41			X X M X M M G					☞ follow up
				239.0			Thin-bedded; siltstone in places platy (Core yield 80%)			Intercalation of bluish-grey, weakly cemented clayey **siltstone** and violetish-grey silty **claystone** layers (thickness 1–20 cm). In the middle part of the complex siltstone interbeds dominate; clay content is highest in the lower and upper parts
		42		240.0	F X M M G M M G		Not observable (Core yield 80%)			Light violetish- and pinkish-grey, below 242.2 m white, weakly cemented, *fine-* and *very fine-grained* (material changes vertically) **sandstone**
	Aruküla Stage Aruküla Formation Tarvastu Beds	43		248.0	X		Wavy, indistinctly bedded			Light grey, with mottled (dark grey, violetish- and brownish-grey) and greenish-grey interbeds, at 248.2–250.0 m with violet and yellow spots, weakly and medium-cemented, in places clayey and sandy **siltstone**, at 250.5–250.75 m rich in mica flakes
		44		250.8	M G M G		Indistinctly thin-bedded and cross-bedded (Core yield 85%)			Reddish-brown (lowermost 0.8 m light grey to white, at 256.9–257.0 m yellowish-grey), weakly cemented, *very fine-grained* **sandstone**. At 254.8–255.8 m greyish- and greenish-white siltstone interlayers (thickness 0.5–1 cm) are found. A strongly cemented *fine-grained* sandstone bed (thickness 0.3 m), with strongly dolomite-cemented globules (0.1–0.4 cm across), occurs on the lower boundary

STANDARD UNITS	LOCAL STRATIGRAPHIC UNITS	CORE BOX NO. / FIGURES	DEPTH (m) / SAMPLES	LITHOLOGY	SEDIMENTARY STRUCTURES	MARLSTONE BEDS	MARLSTONE PERCENTAGE	SHORT DESCRIPTION
Middle Devonian, Givetian	Aruküla Stage, Aruküla Formation, Tarvastu Beds	T-12	M G; Ph T F					☞ follow up
		45; 46; T-13; T-14; 47	260.3 – 272.5; X; F; X Ph F; Ph F F; F; Ph F; Ph F; Ph T F; Ph F; X; X_X F; Ph F F; X X; Fr Ph T F; Ph F		Wavy, indistinctly bedded, in the lower part in places horizontal and platy (Core yield 90%)	< 2 cm; IND dark grey	< 1	Medium-cemented **siltstone**: (1) 260.5–261.2, 264.0–265.6, 266.4–267.1 and 270.7–272.0 m violetish- and yellowish-grey mottled, mainly clayey; (2) 261.2–264.0, 265.6–266.4, 268.5–268.7, 269.8–270.0 and 272.0–272.3 m light grey and mainly sandy; (3) 267.1–267.5, 268.4–269.8, 270.0–270.7 and 272.3–272.5 m violetish- and reddish-brown, with clayey and sandy interbeds. Siltstone varieties change vertically in thin layers and patches, cement is mainly clay with admixture of dolomite. Interbeds of silty dolomitic marlstone and dolomite-cemented siltstone occur in the upper part. The uppermost 0.2 m is grey (with violet spots), silty claystone. At 269.3–269.5 m breccia-like clasts (< 10 cm across) of claystone cemented with siltstone are found. Slickensides (angle 45°) are covered with clay
			272.5 – 275.0; M G X		Thin-bedded (Core yield 60%)			Violetish- and reddish-brown, in the uppermost 0.2 m white, weakly cemented, *very fine-grained* **sandstone**
	Kureküla Beds	T-15; 48; 49	275.0 – 284.4; Ph F; Ph T F; Ph F X; F; X F; F; M G; F; X		Wavy, indistinctly bedded, in places horizontal and thin-bedded			Reddish-brown (with violet shade), below 279.0 m with light greenish-grey and greyish-brown spots and interbeds, strongly (uppermost 2 m) to medium-cemented **siltstone**. At 277.0–277.2, 278.1–278.3, 278.7–279.2, 279.9–280.5, 281.8–282.1, 283.2–283.5 and 284.0–284.4 m patches and interbeds of light greenish-grey, weakly to medium-cemented sandy siltstone, at 280.1–280.2 and 282.1–282.3 m interlayers of white, weakly to medium-cemented *very fine-grained* sandstone are present
		50	284.4 –; F; M G		Indistinctly thin-bedded (Core yield 75%)			Reddish-brown (uppermost 0.3 m brownish-grey), weakly cemented, *fine-* and *very fine-grained* (changes vertically) **sandstone**. The middle part contains medium-cemented sandstone with silty interbeds



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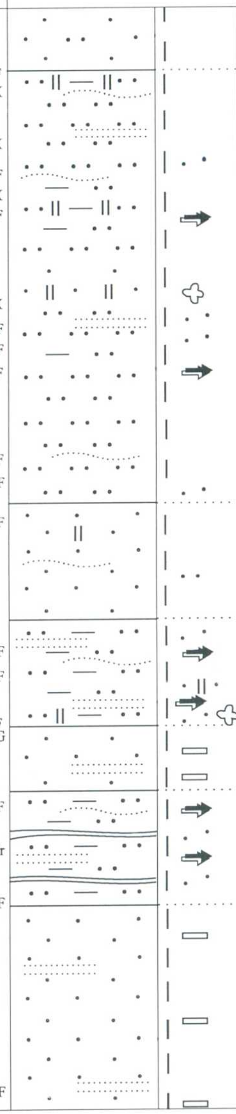
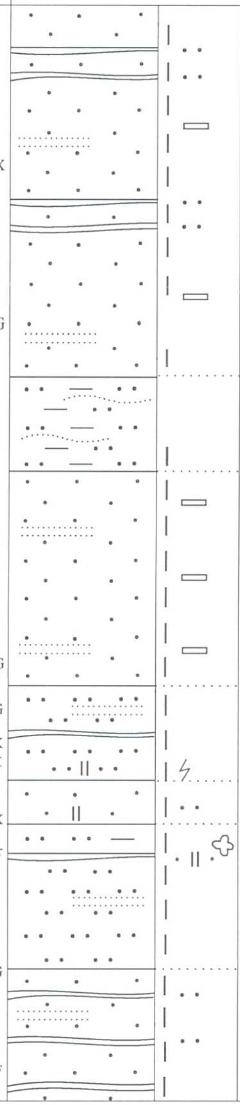
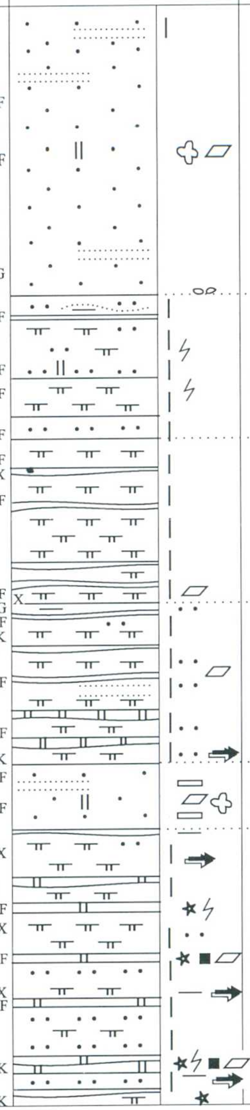
Middle Devonian, Givetian	Aruküla Stage, Aruküla Formation, Kureküla Beds	T-16						☞ follow up
		50; T-17; 51; T-18; 52	288.7 PhTF, X, X, Ph F, X, PhTF, X, Ph F, F, X PhTF, Fr F, Ph F		Wavy, indistinctly bedded (Core yield 85%)			Violetish- and reddish-brown (at 288.7–289.7, 292.2–293.0 and 295.2–295.7 m with grey spots), medium-cemented (in places strongly cemented) clayey **siltstone**. At 291.0–292.3, 295.0–295.2, 295.7–296.8 and 299.9–300.1 m light bluish- and greenish-grey sandy siltstone interlayers are found. At 293.6–294.4 m occurs *very fine-* to *fine-grained* sandstone, in the upper part reddish-brown, in the lower part grey and with strongly cemented globules (0.1–0.3 cm across). At 299.5–299.9 m sandstone is also *very fine-* to *fine-grained*. At 288.7–288.8 and 292.3–292.5 m interbeds of dolomite-cemented siltstone are present. Rocks of the complex are mainly cemented by clay. Slickensides (angle 45°; surfaces covered with clay) intersect one another at an angle of 90°
		T-19	300.1 X MG, PhTF		Indistinctly bedded (Core yield 90%)			Reddish-brown, weakly to medium-cemented, *very fine-grained* **sandstone**, at 300.6–301.1 m strongly dolomite-cemented. At 302.2–302.3 m violetish-brown siltstone, at 302.3–302.8 m silty sandstone interbed occur
	Aruküla Stage, Aruküla Formation, Viljandi Beds	53; T-20	303.2 Ph F, X Ph F, X PhTF, F		Wavy, indistinctly bedded			Reddish-brown (with violet shade), medium-cemented clayey **siltstone** with grey sandy siltstone patches and interbeds. Below 305.8 m dolomite-cemented sandstone occurs, covered by a 2 cm thick grey interbed with strongly cemented globules (0.1–0.3 cm across)
			306.0 MG		Thin-bedded (Core yield 65%)			Dark reddish-brown, weakly cemented, *very fine-* and *fine-grained* **sandstone** with mica flakes
		D-6	307.7 F, Ph F, Fr, X Ph F Ph TF		Wavy, indistinctly bedded, in the lower part thin-bedded (Core yield 90%)			Reddish-brown (in places with violet shade), medium-cemented, clayey **siltstone** with light bluish- and greenish-grey sandy interbeds (thickness 0.1–10 cm; in places dolomite-cemented) and horizontal slickensides
		T-21; 54; 55	310.7, MG F		Thin-bedded (Core yield 65%)			Reddish-brown (with violet shade, at 324.3–324.5 m white), weakly cemented, *very fine-grained* **sandstone** with mica flakes on some levels. In places, particularly at 310.0–318.0 and 321.0–322.0 m, reddish-brown (with violet shade) and light greenish-grey interlayers of clayey siltstone occur

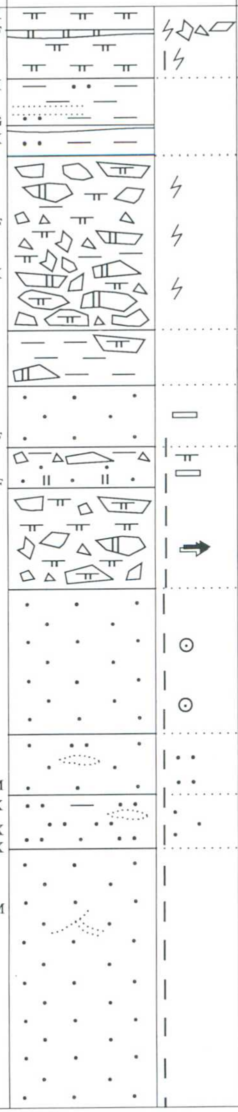


STANDARD UNITS	LOCAL STRATIGRAPHIC UNITS	CORE BOX NO.	FIGURES	DEPTH (m)	SAMPLES	LITHOLOGY	SEDIMENTARY STRUCTURES	MARLSTONE BEDS	MARLSTONE PERCENTAGE	SHORT DESCRIPTION
Middle Devonian: Givetian	Aruküla Stage, Aruküla Formation, Viljandi Beds	55			X, MG					follow up
Middle Devonian: Eifelian	Narva Stage, Kernave Formation	56		325.8			Wavy, indistinctly bedded and rubbly (Core yield 55%)			Reddish-brown (with violet shade) and light grey (in the upper part only), weakly to medium-cemented clayey **siltstone**
		57		328.3	MG		Thin-bedded (Core yield 60%)			Reddish-brown (with violet shade), weakly to medium-cemented, *very fine-grained* **sandstone**, in places with mica flakes
				334.0	G, X, X		Thin-bedded (Core yield 55%)			Violetish-brown (at 335.9–336.0 m light bluish- and greenish-grey), medium-cemented **siltstone** with sandy and clayey interbeds (thickness 0.5–2.0 cm). The lowermost 0.5 m is dolomite-cemented, with grey thin spots and vertical fractures
				336.5	X		Thin-bedded (Core yield 60%)			Reddish-brown, with violet shade, weakly to medium-cemented (in places by dolomite), silty *very fine-grained* **sandstone**
		58		337.7	Fr, MG		Indistinctly bedded, in the upper part thin-bedded (Core yield 70%)			Reddish-brown (with violet shade), in the lower part light violetish-brown with bluish- and greenish-grey interbeds and patches, weakly to medium-cemented **siltstone**. At 338.45–338.50 m light grey, strongly cemented sandstone with dolomite-cemented globules (1–2 cm across) is found
			D-7	341.5	Ph F					follow down



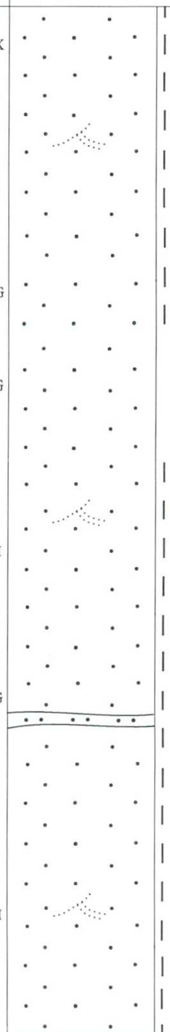
STANDARD UNITS	LOCAL STRATIGRAPHIC UNITS	CORE BOX NO.	FIGURES	DEPTH (m)	SAMPLES	LITHOLOGY	SEDIMENTARY STRUCTURES	MARLSTONE BEDS	MARLSTONE PERCENTAGE	SHORT DESCRIPTION
Middle Devonian, Eifelian, Narva Stage	Kernave Formation	59	D-8	– 352.6	M G F; X F; Fr M G		Horizontal, indistinctly bedded (Core yield 75%)			In the upper part violetish-grey and light reddish-brown (at 344.8–345.0 and 345.1–345.2 m greyish-white), in the lower part bluish- and greenish-white, weakly to medium-cemented, *very fine-grained* **sandstone**. At 341.5–344.0 m bluish- and violetish-grey siltstone interlayers occur. At 348.8–349.0 m calcite-cemented globules (0.1–0.4 cm across) are found. The lowermost 0.2 m is strongly cemented and contains siltstone pebbles
	Leivu Formation	60	D-9; T-22	352.6–356.4	F Ph F; Ph F; Ph F; Ph T F		Wavy and horizontal, indistinctly thin- to thick-bedded	Up to 10 cm; IND violetish-grey (greenish-grey mottled) and grey (violet mottled)	50	Intercalation of **siltstone** and **dolomitic marlstone**. Siltstone is light greenish-grey and reddish-brown (violet and greenish-grey mottled), in places clayey, medium-cemented (by dolomite), in the lower part strongly cemented. Dolomitic marlstone is violetish-grey and grey, in places silty and with vertical fractures. A thin argillaceous dolostone bed occurs at 353.1 m, violetish-grey dolomitic silty claystone at 354.2–354.4 m
		61	T-23; D-10	356.4–360.8	F X; X K Ph F; Fr X Ph T F		Indistinctly bedded	Up to 20 cm; IND reddish-brown (with violet shade and grey patches), in the lower part greenish-grey (with violetish-brown patches)	90	Reddish-brown, in the lower part greenish-grey **dolomitic marlstone**, in the uppermost part silty. At 357.7–357.75, 358.0–358.15, 359.7–359.8, 360.2–360.3 and 360.4–360.5 m grey dolostone interlayers occur, the lowermost one containing fractures and vugs (up to 2 mm across), filled with calcite and surrounded by iron compounds
		62	T-24; D-11; T-25	360.8–365.0	G; X Fr Ph T F K; Fr; K Ph T F; K Ph F; K		Indistinctly thin-bedded, the lowermost 1.4 m horizontal	0.2–30 cm; IND and D light grey (with blue and green shade), in places reddish-brown and grey mottled	65	Light grey (in places reddish-brown and silty), **dolomitic marlstone** with interbeds of greyish-violet and reddish-brown medium-cemented (by dolomite) siltstone, and light grey dolostone (in places with violet shade, silty, argillaceous) containing fractures and calcite-filled (often iron-pigmented) pockets. The uppermost part is clayey
			T-26	365.0–366.7	Ph F; M Ph T F		Horizontal, thin-bedded			Light greenish-grey, medium- to strongly cemented, *very fine-grained* **sandstone**, in places with calcite-cemented globules (0.1–0.3 cm across). Bedding surfaces are covered with mica flakes
		63; 64		366.7–	X; K; K Ph F; X; K Ph F; Fr Ph Ph F X F; K; K K		Dolomitic marlstone massive, in places rubbly; dolostone horizontal, medium- to thin-bedded; siltstone horizontal, thin-bedded	Up to 50 cm; IND and D light to dark grey (in places with violet shade or brown mottled) and violetish-brown	70	**Dolomitic marlstone** with dolostone, siltstone and claystone interbeds. **Dolomitic marlstone** is grey (uppermost 1.3 m reddish-brown), in places silty (silt content changes vertically) and with vertical fractures (surfaces covered with clay). The lower part contains rare sand-sized quartz grains and cube-shaped vugs. Dolostone interlayers (thickness 0.1–0.5 m) are light grey and grey (with violet shade), in places argillaceous, *crypto-* to *very finely crystalline*, with pyrite crystals, vugs and calcite-filled fractures. Dolostone occurs at 368.0–368.1, 368.5–369.0, ☞

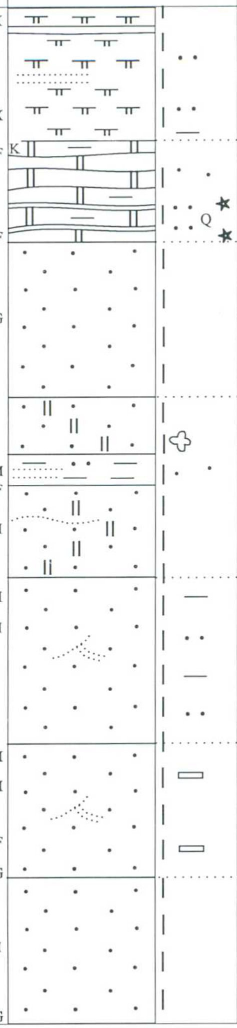
STANDARD UNITS	LOCAL STRATIGRAPHIC UNITS	CORE BOX NO. / FIGURES	DEPTH (m) / SAMPLES	LITHOLOGY	SEDIMENTARY STRUCTURES	MARLSTONE BEDS	MARLSTONE PERCENTAGE	SHORT DESCRIPTION
Middle Devonian Eifelian	Narva Stage Leivu Formation	64 T-27 T-28 T-29 65	X Ph T F Fr K Ph F Ph T F M Fr Ph T F K Ph F 379.6				70	☞ 370.1–370.2, 371.3–371.5, 372.7–373.2, 373.6–373.8, 374.8–375.0, 375.5–375.6, 377.5–377.6 and 377.7–378.1 m. Siltstone interbeds (thickness 0.2–0.3 m) are greenish-grey (in places light brown and violetish-grey), medium- to strongly cemented (by dolomite), in places sandy and clayey. Siltstone occurs at 370.3–370.6, 373.4–373.6 and 377.2–377.5 m. Dolomitic claystone interbeds at 373.2–373.4 and 375.6–375.7 m (thickness 0.1–0.2 m) are dark grey and greenish-grey
		T-30 T-31 66	X M Fr Ph T F Ph T F X X X F K K X 386.5 Fr		Horizontal and wavy; dolomitic marlstone visually massive, in the lower part indistinctly bedded and thin-bedded; dolostone thin-bedded	Up to 20 cm; IND grey, reddish- and violetish-brown (in places light brown and grey with greenish- and violetish-grey patches)	90	Grey, at 379.6–381.6 and 385.0–386.5 m reddish- and violetish-brown mottled silty **dolomitic marlstone** with rare dolostone and dolomitic claystone interbeds, and slickensides (angle 45°). At 381.6–383.0 m grey (with brown patches) dolomitic **claystone** occurs, in places silty. At 381.1–381.2 and 383.0–383.1 m brownish-grey, fractured, *very finely crystalline* dolostone is found
		T-32 67 T-33 T-34 68	F M Fr F Fr K X M Fr Ph T F K Fr Ph T F X K X Ph T F F M K X		Horizontal and wavy; dolomitic marlstone visually massive, in the lower part indistinctly bedded and thin-bedded; dolostone and siltstone thin-bedded	Up to 20 cm; IND reddish- and violetish-brown (in places light brown and grey with brownish-violet, greenish- and violetish-grey patches)	85	Reddish- and violetish-brown mottled (with grey patches), at 394.9–397.0 m grey, silty **dolomitic marlstone** with some dark grey (with brown patches) siltstone interbeds (in places rich in rounded sandy grains). At 386.5–386.8 and 388.6–388.9 m occurs brownish-grey to light brown (with greenish-grey patches), medium-cemented (by dolomite) clayey siltstone. The interval of 390.5–390.8 m is grey and light brown, argillaceous and silty, *finely crystalline* dolostone. At 396.7–397.0 and 399.6–400.0 m dark grey **conglomerate** interbeds are present: dolostone and dolomitic marlstone fragments (up to 1.5 cm across, subangular and subrounded) cemented with dolomitic marlstone. In places phosphate fossil fragments are found. Slickensides (angle 45°) are encountered
	Vadja Fm.	69 T-35 T-36 T-37 T-38 70 T-39	400.0 Ph T F Ph T F Ph T F Fr Ph T F Fr		Horizontal, visually massive, in the upper part thin- to medium-bedded; dolostone thin-bedded and breccia-like (Core yield 90%)	Up to 10 cm; IND and D grey (with violetish-brown patches)	70	Intercalation of grey, fractured silty **dolomitic marlstone**, grey, fractured *crypto-* to *very finely crystalline* **dolostone** (beds up to 4, rarely 10–20 cm thick) and **siltstone** (containing thin layers of dark grey claystone) interbeds. At 401.4–401.6 and 403.6–403.8 m fractured, argillaceous, *microcrystalline* dolostone occurs, the lower bed is crushed (breccia-like) and contains calcite-filled fractures (width up to 0.15 cm)



STANDARD UNITS	LOCAL STRATIGRAPHIC UNITS	CORE BOX NO. / FIGURES	DEPTH (m) / SAMPLES	LITHOLOGY	SEDIMENTARY STRUCTURES	MARLSTONE BEDS	MARLSTONE PERCENTAGE	SHORT DESCRIPTION
Middle Devonian, Eifelian	Narva Stage, Vadja Formation	T-40; 70	K; Ph T F					☞ follow up
			404.9; X; G; X		Horizontal, thin-bedded	Up to 2 cm; IND grey	< 10	Dark grey, silty and dolomitic **claystone**, with rare grey dolomitic marlstone and *cryptocrystalline* dolostone interbeds
		71; T-41	406.9; Ph T F; X		Breccial, highly crushed (Core yield 85%)	Up to 10 cm; D and IND grey	< 50	Grey **breccia**: fragments (1–10 cm across) of *cryptocrystalline* to *very finely crystalline* dolostone (in places argillaceous or silty) and dolomitic marlstone cemented with grey dolomitic marlstone and claystone. Below 409.7 m percentage of clasts increases notably
		core is lost	411.5		Breccial	D and IND grey	?	Greenish-grey dolomitic **claystone** with rare clasts of grey dolostone and dolomitic marlstone, in the lowermost part is developed kaolinization
			413.0; M; Ph F		Indistinctly bedded (Core yield 65%)			Beige (the lowermost 0.2 m reddish-brown, strongly cemented), medium-cemented, *very fine-grained* **sandstone** with mica-containing interbeds
		T-42	414.6; M; X; Ph T F		Indistinctly bedded and breccial (Core yield 65%)	D and IND grey, violetish- and reddish-brown mottled	70	Successive layers from above: (1) grey dolomitic **claystone** (thickness 0.1 m); (2) grey dolostone and reddish-brown dolomitic marlstone clasts cemented with violetish-brown **dolomitic marlstone** (thickness 0.3 m); (3) grey, medium-cemented, *very fine-grained* **sandstone** with mica flakes and siltstone interbeds, the lowermost 0.2 m violetish-grey and strongly cemented (by dolomite). At 415.7–418.4 m **breccia** occurs: grey dolomitic marlstone and dolostone fragments cemented with violetish-grey and reddish-brown mottled dolomitic marlstone
	Pärnu Stage, Pärnu Formation, Tamme Member	72	418.4		Not observable (Core yield 5%)			Violetish-grey, strongly to weakly cemented, *fine-grained* **sandstone** with white ooliths
			422.2; M; M		Indistinctly bedded (Core yield 75%)			Light greenish-grey (with yellow and violet shade), strongly to weakly cemented, silty, *very fine-grained* **sandstone**
			423.8; X; X		Horizontal, thin-bedded (Core yield 80%)			Grey and violetish-grey, weakly to medium-cemented, sandy **siltstone**, with light greenish-grey sandstone interbeds (thickness 0.1–2.0 cm)
	Tori Member	core is lost	425.2; Fr; X; M		Thin-bedded and cross-bedded (Core yield 55%)			In the upper part beige to orange, at 440.3–444.1 m grey (below light violetish-pink), weakly cemented (at 430.6–430.7 m strongly cemented), *fine-* to *very fine-grained* **sandstone**. A violetish-grey, medium-cemented siltstone interbed lies at 450.7–451.0 m

TSIISTRE (327) DRILL CORE

STANDARD UNITS	LOCAL STRATIGRAPHIC UNITS	CORE BOX NO. / FIGURES	DEPTH (m) / SAMPLES	LITHOLOGY	SEDIMENTARY STRUCTURES	MARLSTONE BEDS	MARLSTONE PERCENTAGE	SHORT DESCRIPTION
Middle Devonian Eifelian	Pärnu Stage Pärnu Formation Tori Member	core is lost ↓ 73 74	MGX MG MG M MG M 459.2					☞ follow up

STANDARD UNITS	LOCAL STRATIGRAPHIC UNITS	CORE BOX NO.	FIGURES	DEPTH (m)	SAMPLES	LITHOLOGY	SEDIMENTARY STRUCTURES	MARLSTONE BEDS	MARLSTONE PERCENTAGE	SHORT DESCRIPTION
Lower Devonian Emsian	Rezekne Stage Mehikoorma Formation	74		459.2	MK X, X		Horizontal, thin-bedded (Core yield 50%)	Up to 2 cm; IND greenish-grey, with violet patches and interbeds	< 90	Greenish-grey (with violet patches and interbeds), **dolomitic marlstone**. Clay, silt and dolomite content changes vertically. At 462.4–462.55 m a silty claystone interbed, in the lower part thin dolostone interbeds are present
			T-43, D-12, D-13	462.7	PhT F, K, Ph F, Ph F		Indistinctly thin-bedded (Core yield 70%)			Light greenish-grey (with violet patches and interbeds), in places sandy and argillaceous (in the lower part sandy and silty), *finely* to *crypto-crystalline* **dolostone**. Below 463.5 m occur subrounded to rounded quartz- (grain diameter 0.3–1.0 mm) and calcite-filled vugs (diameter 0.5–1.0 cm). At 464.4–464.45 and 465.05–465.1 m violetish- and greenish-grey, weakly cemented thin interbeds of sandy siltstone are found
				465.4	MG		Indistinctly bedded (Core yield 85%)			Light violetish- and pinkish-grey, weakly cemented *fine-grained* **sandstone**
		75	D-14, T-44	469.5	G M M, X PhT F, M		Indistinctly bedded; claystone and siltstone thin-bedded (Core yield 25%)			Greyish-pink and greyish-violet, strongly cemented (by dolomite), *fine-* to *medium-grained*, in the lower part *fine-grained*, **sandstone**. Dolomite-cemented globules (0.1–0.3 cm across) at 470.5–470.9 m occur. At 471.0–471.8 m brownish- and greyish-violet silty claystone and sandy or clayey siltstone, in the middle part a greenish- and violetish-grey, medium-cemented *fine-grained* sandstone interbed are found
		↑ core is lost ↓		474.3	M, GM		Indistinctly bedded (cross-bedded) (Core yield 45%)			Greyish-pink (the uppermost part pinkish-violet), weakly cemented, *very fine-* to *fine-grained* **sandstone** (grains rounded, cement includes iron compounds), with greyish-brown silty interbeds (thickness up to 10 cm)
				478.7	M, M, F		Thin-bedded and cross-bedded (Core yield 90%)			Greyish-pink and greyish-violet (at 478.7–478.2 and 480.7–481.0 m dark violet), weakly cemented, *very fine-* to *fine-grained* **sandstone** (quartz grains mainly rounded). Cement includes iron compounds. Bedding surfaces are covered with mica flakes
		76		482.2 – 486.0	MG, M, X MG		Not observable (Core yield 60%)			Violetish- and pinkish-grey, weakly cemented, *fine-grained* **sandstone** (grains angular) with rare coarser sand grains

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Middle Ordovician (Arenig)	Volkhov Stage; Kriukai Formation	76; core is lost; 77	T-45; D-15	486.0–493.9	PhF; PhTF; K	SCALE 1:200	Wavy, medium-bedded and indistinctly nodular (Core yield 100%)	0.05–0.5 cm; D dark brownish-red	< 5	Brownish-red, in places argillaceous, *very finely crystalline* to *finely crystalline* **dolostone** (grains > 10%, in places 25%; fine and coarse bioclasts) with dolomitic marlstone and argillaceous dolostone patches (1.0 cm across) or interbeds. A 0.5 cm thick light grey bed lies on the rugged lower boundary
Lower Ordovician (Arenig)	Hun–Bil* stages; Zebre Formation	77	D-16; T-46; D-17	493.9–494.3	PhTF	SCALE 1:50	Wavy, indistinctly bedded	0.05–0.5 cm; D dark brownish-red	< 5	Brownish-red, *very finely crystalline* **dolostone** (same as previous). Light greenish-grey, argillaceous beds (thickness 0.3–2.0 cm) lie at 493.9, 494.1, 494.2 and 492.24 m. The discontinuity surfaces are limonitized
			D-17; D-18	494.3–494.5			Indistinctly nodular			Yellow, violet and brown mottled, *microcrystalline* glauconitic **dolostone**. Glauconite grains (diameter 0.02–0.2 cm, 20–60% of rock) are accumulated into distinct patches (2.0–4.0 cm across; about 30% of rock). Rare quartz grains are less than 0.05 mm in diameter. A weathered argillaceous interbed occurs at 494.35–494.4 m
			D-18; D-19	494.5–494.7			Not observable			White, yellow, violet and brown mottled, *finely crystalline* glauconitic **dolostone**, impregnated by iron oxides and weathered. Glauconite grains (diameter 0.02–0.1 cm) are well-rounded and make up 30% of rock. The lower boundary is covered by coarse dolomite crystals and single glauconite grains
Furongian (Upper Cambrian); Paibian Stage	Petseri Formation	77	D-20	494.7	MG; A; MG; A; MG	SCALE 1:200	Indistinctly thin-bedded (Core yield 35%)			Light yellowish-grey, weakly to medium-cemented, *very fine-* to *fine-grained* **sandstone** (grains angular to sub-rounded) with rare glauconite (particularly at 505.7–507.5 m) and feldspar grains (both less than 0.1 mm in diameter), and shell fragments. The upper part contains a piece of conglomerate interlayer: medium-cemented sand- and siltstone (grains well-rounded), with brachiopod shell fragments (20% of rock)

Hun–Bil*– Hunneberg–Billingen stages

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Furongian (Upper Cambrian) Paibian Stage	Petseri Formation	D-21 77	A A A M G					☞ follow up
			509.7 A G A A 511.7		Thin-bedded, in places lens-like (Core yield 80%)			Grey, silty **claystone**, with *very fine-grained* sandstone interbeds. Pyrite aggregates, patches of iron compounds (diameter 2–3 mm), mica flakes (0.05–0.1 mm across) and shell fragments (< 0.2 mm across) are found
			M G A					
		78 ↑ core is lost ↓	A M G A M G G 533.7		Not observable (Core yield 60%)			Yellowish-grey, with clayey patches of iron compounds (goethitized; diameter up to 2 mm), weakly cemented, *fine-grained* to *very fine-grained* (in places *medium-* to *fine-grained*) **sandstone** (grains sub-rounded to rounded)

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)

Forthcoming issue:
Männamaa (F–367) drill core