ISOS-14 Field Guide
The Ordovician of Estonia

Edited by Olle Hints and Ursula Toom

14th International Symposium on the Ordovician System, Estonia, July 19-21, 2023
Pre-conference Field Excursion: The Ordovician of Estonia, July 15-18, 2023

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Geological Survey of Estonia

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Geology of Estonia: An introduction

Tõnu Meidla

Estonia lies on the east coast of the Baltic Sea, south of the Finnish Gulf, comprising about 45 000 km2 area extending from 57°30'34" to 59°49'12"N and from 21°45'49" to 28°12'44"E.

The topography of this area is generally flat; the area is located about 50 m above sea level on average. Variety of landscapes comprises extensive forests and wetlands intersected by agricultural landscapes, wide depressions surrounding big lakes Peipsi and Võrtsjärv, about 1400 lakes, several thousands of kilometres long coastline and more than 2000 marine islands, most of them very small but more than ten of them being large enough to support the permanent population. The largest islands are Saaremaa, Hiiumaa, Muhu and Vormsi.

Geologically, the area of Estonia corresponds to the southern slope of the Fennoscandian Shield located in the central-western part of the East European Craton. Estonia is located in the area where the Earth's crust is relatively thick (mostly 46–51 km but decreasing to 41–44 km in Saaremaa (Puura and Vaher 1997). The principal features of the crustal structure of the area formed during the Svecofennian orogeny dated about 2.0–1.75 Ga. Most of the crystalline basement belongs to the Palaeoproterozoic (1.8–1.9 Ga) Svecofennian orogenic complex that was also subjected to high-grade metamorphism. This complex is characterised by the gneisses of amphibolite facies in northern Estonia and represents an extension of the major structural units of southern Finland. In southern Estonia, the basement comprises gneisses of granulite facies belonging to the Belarussian–Baltic granulite subdomain.

The metamorphosed rocks of the Svecofennian orogenic complex is intersected by several generations of intrusive bodies, the most important of them being the rapakivi intrusions of the latest Palaeoproterozoic Vyborg Subprovince (the Naissaare, Neeme, Märjamaa and Ereda plutons, 1.62–1.67 Ga) and the huge Riga pluton of the Åland–Riga Subprovince. The Riga rapakivi pluton is of the earliest Mesoproterozoic age (1.54–1.58 Ga) and is associated with a few subvolcanic and volcanic rocks occurring on Saaremaa Island. The crystalline basement was subjected to long-lasting erosion (1.4–0.6 Ga) that resulted in the formation of a peneplane. (Puura et al. 1997). The sedimentary units and magmatic rocks from this period, although known in other parts of the Svecofennian region, are absent in Estonia. The crystalline rocks occasionally display evidence of weathering that may reach up to a depth of 100 m into the basement (Puura 1997; Puura and Vaher 1997).

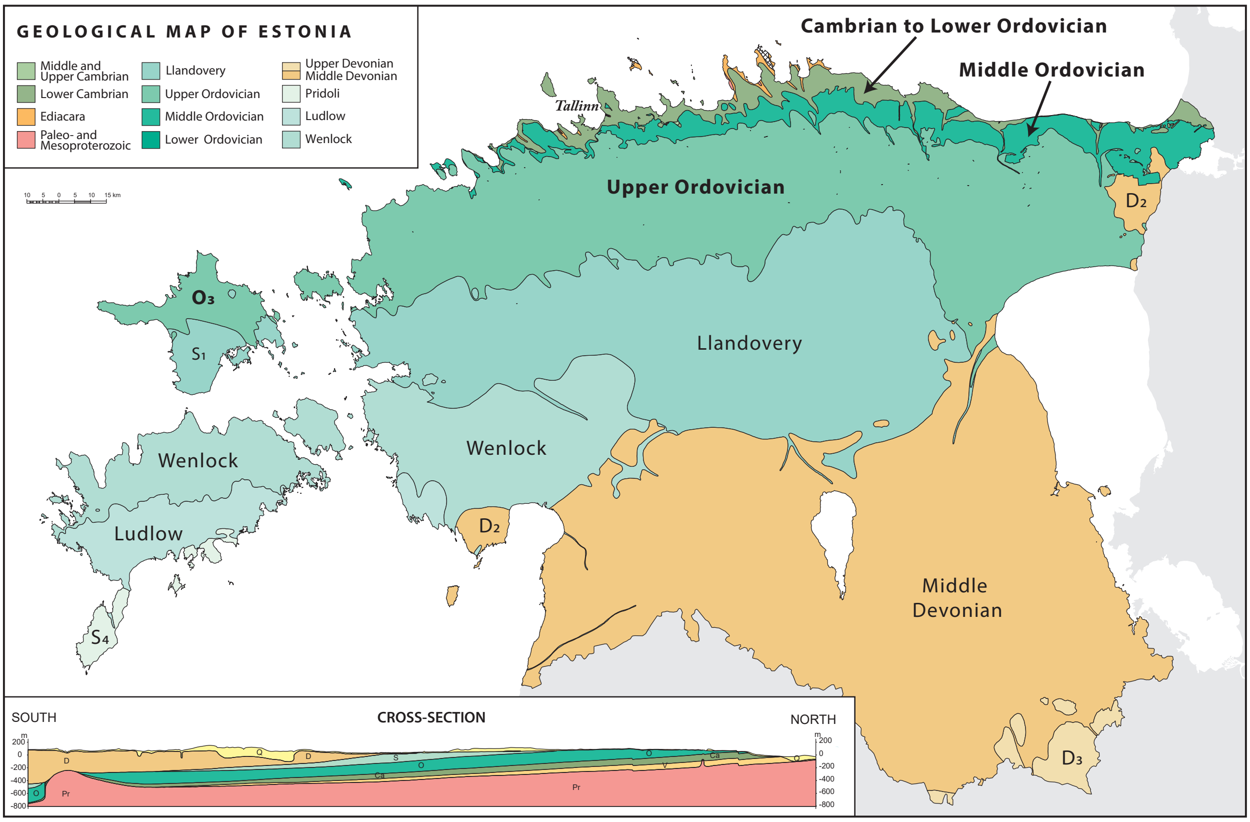

Fig. 1. Generalised bedrock geological map of Estonia with a cross-section, showing outcrop areas of lower and middle Palaeozoic rocks and a NS cross section shaped by the southward dip of the Proterozoic basement (modified from Puura 2008).

The top of the basement lies at a depth ranging from -120m (islands in the Finnish Gulf) up to -780m (the Island of Ruhnu, SW Estonia), dipping gently to the south within most of the territory but becoming slightly elevated again in SE Estonia forming the Mõniste Bedrock Uplift (altitude of the top at -232 m) (Tuuling and Vaher 2018). Because of this southward dipping, the thickness of the sedimentary cover is gradually increasing southwards. The northern border of the distribution area of sedimentary cover reaches the middle of the Gulf of Finland, dividing it into the shield and platform parts.

The sedimentary rocks Estonia are of latest Proterozoic to middle Palaeozoic age. Because of that, Estonia is sometimes called 'a Palaeozoic country'. The Ediacaran–Devonian sedimentary cover is overlain by the sediments of the mid to late Quaternary. The thickness of the pre-Quaternary sedimentary rocks reaches over 100 m in northernmost mainland Estonia and exceeds 800 m in southeastern Estonia (Puura and Vaher 1997), generally reflecting the southward dipping of the upper surface of the crystalline basement. In the outcrop sections, the bedding of the sedimentary bedrock usually looks nearly horizontal but may occasionally show minor local deformations. Because of the gentle dipping of strata, 8–15' (about 2–4.5 m/km) to the south, the outcrop belts of the series and stages display predominantly roughly west-east oriented pattern in the geological map (see Fig. 1).

The Ediacaran System (until the end of the 20th century referred to as the Vendian Complex or the Vendian System) comprises a subsurface unit distributed in northern, northeastern and eastern Estonia. These strata bear a signature of a cool climate as the Baltica Palaeocontinent was located in high latitudes in the late Ediacaran (Cocks and Torsvik 2005). The sandstones and clays prevailing in Estonia comprise a small segment of the latest Ediacaran (Meidla 2017), although a gap has been documented at the lower boundary of the Cambrian. The terrigenous sediments accumulated in a large water body located east of the Estonian area. Estonia comprised a part of its near-coastal zone, and the terrigenous sediments are coarser in the west. The total thickness of the Ediacaran reaches over 120 m, with the maximum in northeasternmost Estonia. Recent advances in the Ediacaran and Cambrian stratigraphy of Estonia are summarised by (Meidla 2017).

The overlying Cambrian is distributed nearly all over Estonia. The Cambrian rocks are predominantly sandstones and siltstones, with a limited supplement of clay, whilst coarser material is rare, occurring at some levels in West Estonia. An exception is the lowermost part of the succession that comprises the late Terreneuvian Blue Clay, a silty clay unit of a remarkable thickness (over 90 m – Meidla et al. 2017). Deposition of the Terreneuvian clays took place in an Ediacaran-like palaeogeographic setting in the course of a marine transgression advancing from the east, but the accumulation of younger Cambrian, Ordovician and Silurian strata was increasingly influenced by the developments along the southern slope of the Fennoscandian Shield. The Cambrian rocks, mostly sandstones, crop out in several coastal and riverside sections, whilst clays are mainly exposed in clay pits near the northern coast. The total thickness of the Cambrian strata is locally exceeding 120 m within the West Estonian archipelago.

The deposition of the Ordovician strata took place in a slowly subsiding marginal part of the East European Craton, initially of weak palaeobathymetric differentiation and slow deposition rate. The Lower Ordovician sandstones and thin clay-rich formations grade into the carbonates in the topmost Lower Ordovician, on the background of progressive depth differentiation due to the development of the Baltic Syneclise. The Middle and Upper Ordovician are represented by limestones that contain thin volcanic interbeds (K-bentonites) at several levels. Late diagenetic dolomitisation is unevenly distributed in limestones. Early Late Ordovician kukersite oil shale is a characteristic feature of northeastern Estonia, whilst Middle and Upper Ordovician red limestone packages and a few thin Upper Ordovician black shale units are known in the subsurface area. In many papers (e.g., Nestor and Einasto 1997) and references therein) the beginning of Katian (middle Upper Ordovician) is reported to mark a transition from cool-water to tropical carbonate sedimentation as the Baltica Palaeocontinent reached the southern tropical latitudes (Cocks and Torsvik 2005). Somewhat controversially, this seems to happen on the background of a gradual temperature decrease throughout the Late Ordovician (Männik et al. 2021). The Ordovician strata are exposed in coastal outcrops and escarpments, active pits and quarries of different ages, but the Upper Ordovician outcrops are mostly small and display only fragments of this unit that occasionally may reach about 100 m thickness. The topmost Ordovician is revealing evidence of the Hirnantian Glaciation, expressed as almost full faunal rearrangement (Nestor et al. 1986) and a major carbon and oxygen isotopic shift (Ainsaar et al. 2010; Männik et al. 2021). The latter feature is more clearly observable in the subsurface because of a gap in the outcrop area caused by the glacioeustatic sea level fall (Brenchley et al. 2003). Recent advances in Ordovician stratigraphy of Estonia and related areas are summarised in (Meidla et al. 2023).

The Silurian System has a more limited distribution, being absent in the northern and eastern parts of Estonia because of erosion. The Llandovery has the widest distribution, occurring both in the western islands and the mainland of Estonia. The distribution areas of the younger series are progressively smaller and gradually shifted to the southwest, to the Baltic Syneclise. The Přidoli Series occurs only in a very small area in southern Saaremaa Island and Ruhnu Island. The limestones and dolomites bear a signature of tropical sedimentation, and a number of K-bentonite beds (mainly lower Wenlock) is indicative of limited volcanic activity in the neighbouring areas. The rocks are locally exposed in the mainland, on Saaremaa Island and in smaller islands of West Estonia. The exposures, however, demonstrate only a minor part of the Silurian succession of over 400 m thickness.

The most recent overview of the Silurian stratigraphy in Estonia is provided by (Männik 2014).

Distribution of the Devonian System is confined to southern, eastern and northeastern Estonia. The latter occurrence represents a small isolated area in northeastern Estonia where the Middle Devonian dolomitic marls and sandstones of rather limited thickness overlie the Upper Ordovician limestones containing the kukersite oil shale commercial deposit. The main distribution area in eastern and southern Estonia represents a transition from the Scandinavian orogenic belt to the Devonian Basin within eastern Laurussia. The Middle Devonian and basal Upper Devonian are mainly represented by sandstones and overlain by a thin succession of Upper Devonian carbonates (mainly dolomites) confined to marginal southeastern Estonia and extending to the south and southeast. The lower Devonian has been recorded in the subsurface only, being confined to a narrow belt near the southern border of Estonia. The Middle and Upper Devonian are often exposed in river valleys of South Estonia and in occasional sand pits. The present state of Devonian stratigraphy in Estonia is summarised in (Mark-Kurik and Põldvere 2012).

The initial thickness of the Ordovician, Silurian and Devonian sedimentary strata may have reached 500-1000 m in North Estonia, and the maximum sediment load was probably reached during the Late Devonian (Kirsimäe et al. 1999). The very long erosional period during Carboniferous-Neogene has created the present-day bedrock topography, shaping bedrock cores of the major uplands of modern topography and depressions of the lakes Peipsi and Võrtsjärv and the Gulf of Finland.

The Quaternary glaciation caused the last stage of erosion of the sedimentary bedrock. The glaciers removed up to 60 m layer from the bedrock surface (Tavast 1997), leaving almost no chance of discovering any strata that might be younger than the Devonian but older than the Quaternary in Estonia.

The accumulation of Quaternary sediments during the Pleistocene and Holocene resulted in the formation of a nearly continuous layer of glacial, glaciofluvial and glaciolacustrine sediments, covered with genetically variable Holocene deposits that are mostly of limited thickness and patchy distribution. The total thickness of Quaternary sediments is usually less than 5 m in North Estonia but generally over 10 m in South Estonia. Thicknesses over 100 m are relatively common in South Estonia (Haanja and Otepää heights) and the Gulf of Finland (Raukas and Kajak 1997), but locally it may exceed 200 m. The bedrock topography, uneven thickness of the Quaternary cover and postglacial land rise have shaped the modern topography of Estonia. Only 10% of the area has an elevation over 100 m a.s.l. The highest point in South Estonia is 318 m a. s. l. but its relative height is only about 60 m (Raukas 1997). A revised stratigraphic chart of the Quaternary sediments in Estonia was recently published by (Hang et al. 2019).

A remarkable feature in Estonian topography is the North Estonian Klint, a nearly continuous escarpment along the northern coast that forms the middle part of the Baltic Klint. It exposes the Cambrian to Middle Ordovician part of the sedimentary succession in numerous outcrops of the lower Palaeozoic strata forming a fairly continuous belt of actively abraded and passive inland escarpments.

Although Estonia is a small country, it still is relatively rich in mineral resources. The most important actively exploited resource is the unique kukersite oil shale that comprises the world's largest exploitable resource of its kind. The Cambrian – Ordovician shelly phosphorite deposit in North Estonia is one of the largest phosphorite deposits within the European Union. It was industrially used between 1924 and 1991 but excluded from the list of active reserves in the late 1990s, mainly because of the past devastating mining and industrial use history. Another potential resource is the Dictyonema argillite which is relatively rich in organic matter (up to 20%) and contains various microelements (Mo, V, etc.) in elevated concentrations. The groundwater in the sedimentary rocks and Quaternary deposits is used as the source of drinking water throughout the country. It formed about 70% of the drinking water consumed in Estonia in the mid-1990s (Vallner and Savitskaja 1997). The Middle–Upper Ordovician, Silurian and Upper Devonian carbonate rocks are widely exploited in numerous quarries. Sand, gravel and peat deposits are in active use. Other resources are less important.

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About the Ordovician System in Estonia

Tõnu Meidla, Leho Ainsaar and Olle Hints

The area of continuous distribution of the Ordovician in the Baltic Sea area and east of it extends from the southern part of the Baltic Sea in the west to the vicinity of Moscow in the east and from the Gulf of Finland or northernmost Estonia in the north to Belarus and Poland in the south. In the northern part of this area, in the eastern coastal region of the Baltic Sea, beds are exposed in sections of the Baltic-Ladoga Klint, sometimes with more than 10 m of strata exposed, which attracted the attention of early investigators, together with other coastal and river bank sections, as well as old and new limestone quarries and open cast pits. Well-accessible successions with well-preserved fossils and sedimentary structures attracted the attention of investigators already in the early 19th century and were addressed in the papers by O. M. L. v. Engelhardt (1820), W. T. H. F. Strangways (1821), E. Eichwald (1825), and others. In particular, the characteristic succession of the Cambrian to Middle Ordovician with a number of distinctive rock units (the Cambrian Blue Clay, phosphatic brachiopod coquina, *Dictyonema* argillite, dark green glauconite sandstone and the succession of distinctive limestone units above) was of great interest.

The thorough monographic paper by F. Schmidt from 1858 brought to attention the main features of Ordovician stratigraphy in Estonia for the first time. The general pattern of his very old geologic map in the same volume is already well demonstrating the most characteristic feature of modern bedrock maps of Estonia —latitudinally orientated outcrop belts of the Ordovician and Silurian stages in northern Estonia. The feature is a result of the generally simple geologic structure of the area, with almost horizontal strata dipping southward only 2–5 m/km.

The Lower Ordovician thin succession of siliciclastics comprises sandstones, argillites and clays (Pakerort and Varangu RSs) overlain by the glauconitic sand- and siltstones (Hunneberg and Billingen RSs). Further up, the main part of the Ordovician succession in northern Estonia is heavily dominated by various kinds of limestones but also contains some intercalations of kukersite oil shale concentrated mainly in the Kukruse Regional Stage (RS). The transition from the terrigenous to carbonate rocks in the basal part of the Toila Formation (topmost Lower Ordovician to basal Middle Ordovician) is marked by the fairly sharp appearance of the first limestone/dolomite beds. The appearance of the first representatives of the numerous characteristic Middle Ordovician fossil groups is recorded in the same transition interval or in the overlying Volkhov Stage.

The Ordovician limestone succession in Estonia and adjacent areas begins with carbonates deposited in a sediment-starved shallow marine basin. Upward the sedimentation rates have increased in obvious correlation with the carbonate carbonate production. In the Upper Ordovician, corals make their first appearance, and the first carbonate buildups appear, emphasising a remarkable change in the overall character of the palaeobasin. Informer publications, change in the type of sedimentation and the character of biofacies is ascribed to a gradual climatic change resulting from the northward drift of the Baltica Palaeocontinent from the temperate climatic zone to the (sub)tropical realm (Nestor and Einasto, 1997). This interpretation, however, is not in full accordance with the results of a pilot study on conodont phosphate oxygen isotope palaeotemperature revealing a continuous cooling trend in the palaeobasin throughout the Middle and Later Ordovician (Männik et al. 2022). Independently of that, the Middle and Upper Ordovician changes resulted in an increase of carbonate production and sedimentation rate on the carbonate shelf where the deposition pattern was obviously controlled by accommodation space available.

The problems of the Ordovician geology in the subsurface area in central and southern Estonia were first revealed in the late1950s when the extensive drilling started in the area. Thanks to the high number of drill cores obtained during a comprehensive drilling programme in the 1950s–1980s, the main correlations problems between the stratigraphic successions in the outcrop area and in southern Estonia were mainly resolved. As a result of the comparison of the eastern Baltic and Scandinavian successions, the concepts of the structural-facies zones (by Männil 1966) or confacies belts (by Jaanusson 1976) were introduced for the Ordovician of Baltoscandia (see Fig. 1). As the term "confacies "is unique (being exclusively used for the Ordovician of Baltoscandia only), a different terminology has been introduced by Harris et al. 2004 (see explanation to the Fig. 1). The micropalaeontological and macrofaunal studies of the core sections also revealed the distinctive biogeographic differentiation pattern, characteristic of the Ordovician rocks (Männil 1966; Männil et al. 1968; Meidla 1996, etc.). Although the biofacies pattern is generally described for the eastern Baltic area, the facies zonation of the entire Baltoscandian area is still imperfectly known. The seismic investigations of the Baltic Sea area, performed in the last decades (Tuuling 1998 and references therein), but also detailed (micro)palaeontological investigations (e.g. Tinn 2002) might produce valuable new information in this field.

The total thickness of the Ordovician reaches up to 190 m, being maximal in central and eastern Estonia and considerably less in the outcrop area, as well as in the southwestern mainland of Estonia. Several correlation problems still persist in the Ordovician of Estonia due to marked biofacies differences between northern and southern Estonia. In part, they are also discussed in a recent monographic overview of Estonian geology (see

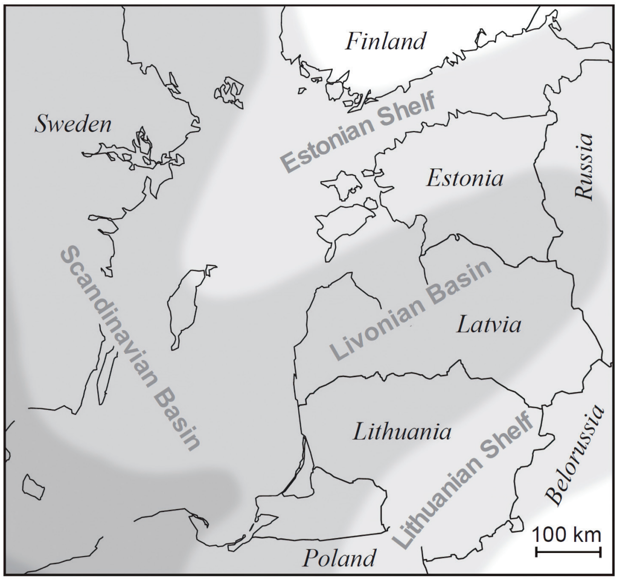

Fig. 2. Post-Tremadocian Ordovician facies zonation according to Harris et al. (2004); from Meidla et al. (2014).

Heinsalu and Viira 1997, Meidla 1997; Hints 1997; Hints and Meidla 1997 in Raukas and Teedumäe, 1997). New prospects in this field have already been opened by stable isotope studies, as the stable carbon isotope curves have demonstrated a good correlation potential (Kaljo et al. 2004, 2007, and references therein; Ainsaar et al. 2004, 2007, 2010).

The development of the stratigraphic classification of the Ordovician strata in Estonia, from the "beds" (*Schichten*) by Schmidt (1858) to the stages in modern meaning, is documented in detail in Männil (1966), Rõõmusoks (1983) and Rõõmusoks et al. (1997). The term "Ordovician" was likely used to describe the Estonian succession for the first time by Bassler (1911) and became widely established in the geological literature of Estonia since Bekker (1921). A number of regional series and subseries for the Ordovician System in Estonia and neighbouring Russia were introduced by Schmidt (1881) and several subsequent authors. Raymond (1916) introduced the traditional American three-fold subdivision of the Ordovician System for this particular area, but this classification was subjected to repeated changes until 1987. Also, the terms "Oeland Series", "Viru Series" and "Harju Series" have been widely used as a basic three-fold classification for the Ordovician System of the area since the 1950s (introduced by Kaljo et al. 1958 and Jaanusson 1960 in a nearly recent meaning). The subseries have been introduced as well (see Männil and Meidla 1994 and Nõlvak et al. 2006 for a summary), but they lost their actuality and are rarely used today.

The modern three-fold classification of the Ordovician System (IUGS 2004) was first used for the Estonian succession by Webby (1998) and is presented here in detail (Fig. 2). In relation to the definition of the GSSP for the base of the Ordovician System in the Green Point section, Newfoundland (Remane, 2003), a revision of the traditional position of the Cambrian-Ordovician boundary at the base of the Pakerort RS in Estonia turned out to be necessary. According to conodont data, the system boundary in the northern Estonian sections lies some metres higher than previously suggested, i.e. in the middle of the Pakerort Stage, within the Kallavere Formation (Puura and Viira 1999). The upper boundary (the lower boundary of the Silurian System) has for a long time been correlated with the major hiatus between the Porkuni and Juuru RSs, corresponding to the maximum regression related to the Hirnantian glaciation, due to the fact that a major faunal overturn is recorded on this level. Recent chemostratigraphic correlations, however, suggest that the falling limb of HICE reaches into the basal part of the Juuru RS (Ainsaar et al. 2010, 2015; Bauert et al. 2014; Meidla et al. 2020, 2023) and the Ordovician–Silurian boundary is located within the beds formerly attributed to the basal Silurian.

The term "(Regional) Stage", first applied by Bekker (1921), has become the principal category in the chronostratigraphic classification of the Ordovician System in Estonia.

The main features of the chronostratigraphic classification of the Ordovician System were established already by Männil (1966). Only minor changes were introduced in the later decades: the Ceratopyge RS was renamed the Varangu RS (Männil, 1990), the Latorp RS was replaced by the Hunneberg and Billingen RSs (Hints et al., 1993) and a new unit, the Haljala RS, is used instead of the Idavere and Jõhvi RSs (following Jaanusson, 1995 and Nõlvak, 1997). Hints and Nõlvak (1999) brought the concept of boundary stratotypes ("golden spike") into the Estonian stratigraphy, proposing a stratotype — the Pääsküla outcrop — for the lower boundary of the Keila RS. However, as stratigraphic hiatuses on the stage boundaries are very common in northern Estonia (remarkable faunal changes are usually related to hiatuses), wide usage of this concept for the stage boundaries in this area looks rather complicated.

The lithostratigraphic classification of the Ordovician rocks was introduced by Orviku (1940) for the upper Middle Ordovician. This approach was widely accepted by subsequent authors and led to the compilation of a series of detailed correlation charts approved by the Interdepartmental Stratigraphic Committee of the former USSR (Resheniya... 1965, 1978, 1987 and a related paper by Männil and Rõõmusoks, 1984). The last version of such a formal correlation chart (the edition of 1987) was, in a slightly emended form, published also in English in the series of the IUGS publications (Männil and Meidla, 1994).

The correlation chart in Fig. 2 contains some recent improvements compared to this publication, the most recent ones being introduced by Ainsaar and Meidla (2001), Nõlvak et al. (2006), Meidla et al. (2020 and references therein) and Paiste et al. (2022, 2023). Some more versions of the Ordovician correlation charts for Estonia have also been published by Hints et al. (1993), Nõlvak (1997) and Meidla et al. (2014).

Ordovician stratigraphy in Estonia, 2023

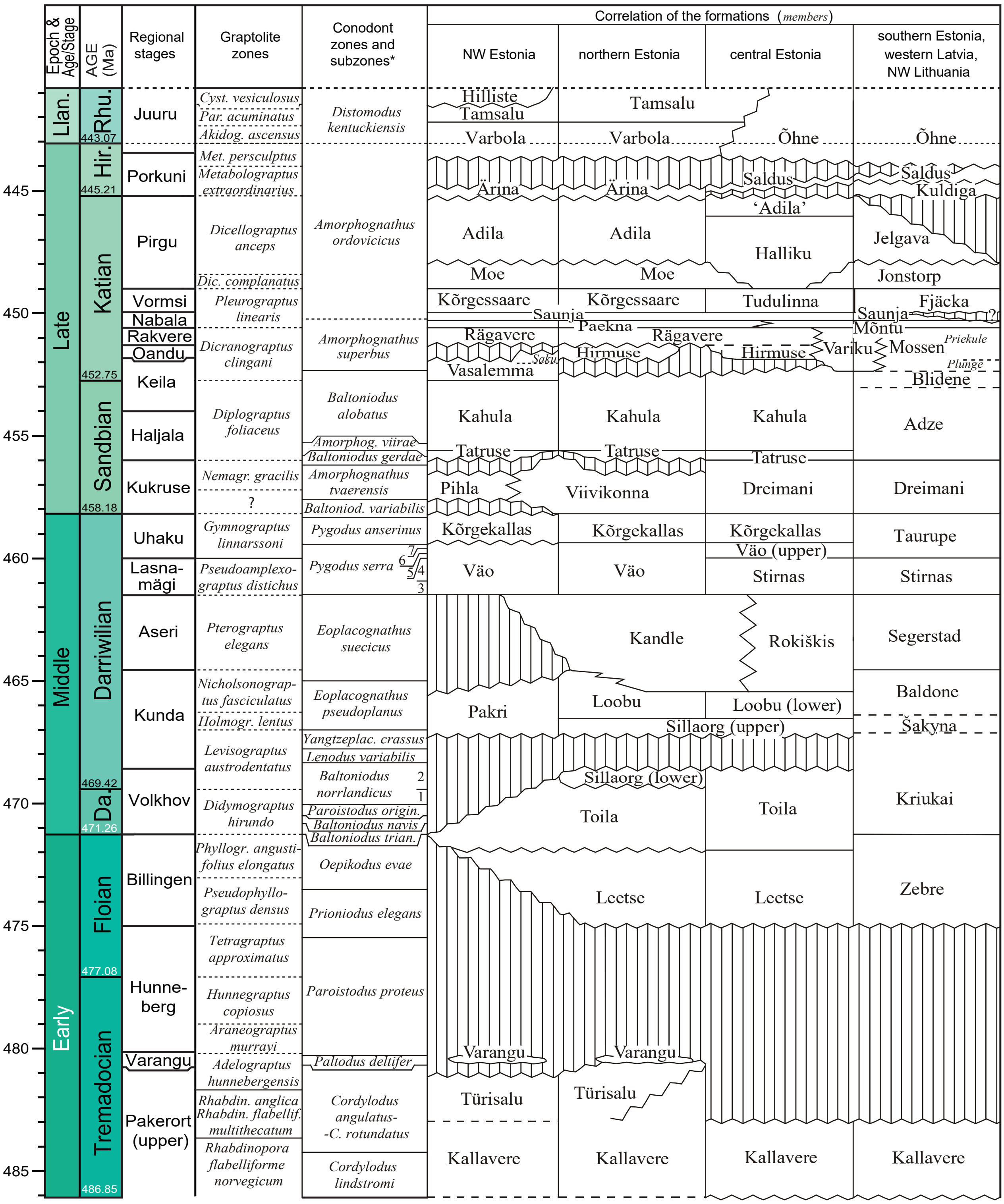

Fig. 3. Ordovician stratigraphy of Estonia. Graptolite zonation according to Kaljo & Vingissaar, 1969, Kaljo et al., 1986, Männil, 1976, Resheniya..., 1987, Männil & Meidla, 1994, Nõlvak et al., 2006, conodont zones according to Männik in Nõlvak et al. 2006, Paiste et al. 2020, 2022 and Meidla et al. 2023. Numbers in the column of the conodont zonation correspond to the conodont subzones as follows: subzones of the *Baltoniodus norrlandicus* Zone: 1 – *Trapezognathus quadrangulum* Subzone, 2 – *Lenodus antivariabilis* Subzone; subzones of the *Pygodus serra* Zone: 3 - *Eoplacognathus foliaceous* Subzone, 4 - *Eoplacognathus reclinatus* Subzone, 5 - *Eoplacognathus robustus* Subzone, 6 - *Eoplacognathus protoamosus* Subzone, 7 - *Eoplacognathus lindstroemi* Subzone. Abbreviations: Llan., Llandovery; Da.,Darriwilian; Hir., Hirnantian; Rhu., Rhuddanian; *Cyst., Cystograptus; Par., Parakidograptus; Met., Metabolograptus; Dic., Dicellograptus; Nemagr., Nemagraptus; Holmogr., Holmograptus; Phyllogr., Phyllograptus; Rhabdin, Rhabdinopora; flabellif., flabelliforme; Amorphog., Amorphognathus; Baltoniod., Baltoniodus; Yangtzeplac., Yangtzeplacognathus; origin., originalis; trian., triangularis.*

The composition and textures of the Ordovician carbonate rocks and the principal differences between the confacies belts were summarised by Põlma (1982 and references therein).

The monographic studies on Ordovician palaeontology started already in the 19th century. After the comprehensive review of the Ordovician and Silurian strata (in modern meaning) by Schmidt (1858 and several subsequent monographic papers), a number of important monographic papers were published by F. B. Rosen, W. Dybowski, A. Pahlen, G. Holm, A. Mickwitz, O. Jaeckel, J. H. Bonnema and R. F. Bassler. The tradition of palaeontological investigations on the Ordovician material of Estonia was continued by A. Öpik (1930, 1934 and others) and, later on, by the recent generation of palaeontologists. Monographs and extensive monographic papers were published on the Ordovician brachiopods, corals, stromatoporoids, chitinozoans, scolecodonts, ostracods, conodonts, etc. Summaries on the palaeontological investigations on virtually all fossil groups recorded from the Ordovician of Estonia are published in the recent monograph "Geology and mineral resources of Estonia" (Raukas and Teedumäe 1997).

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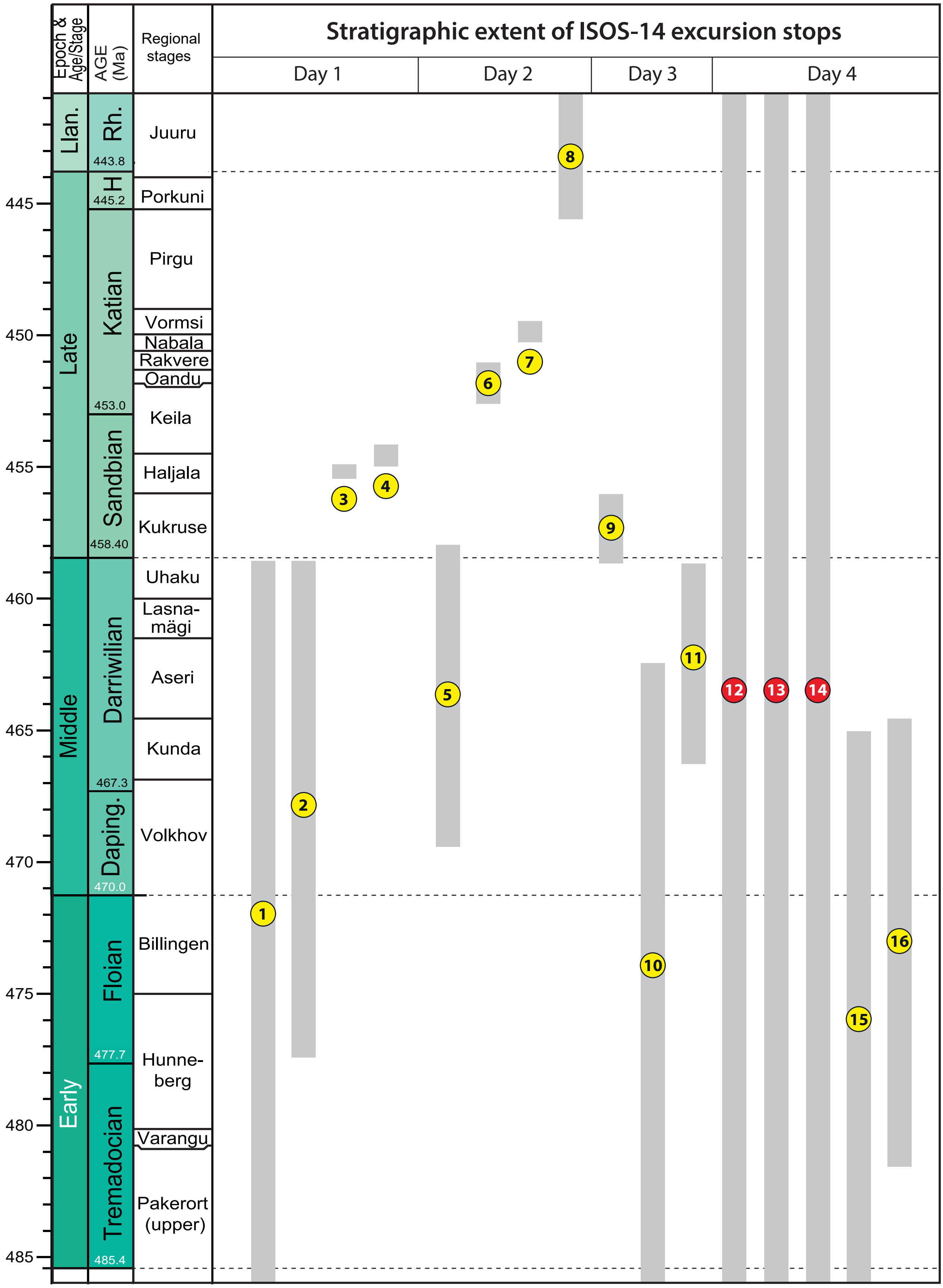
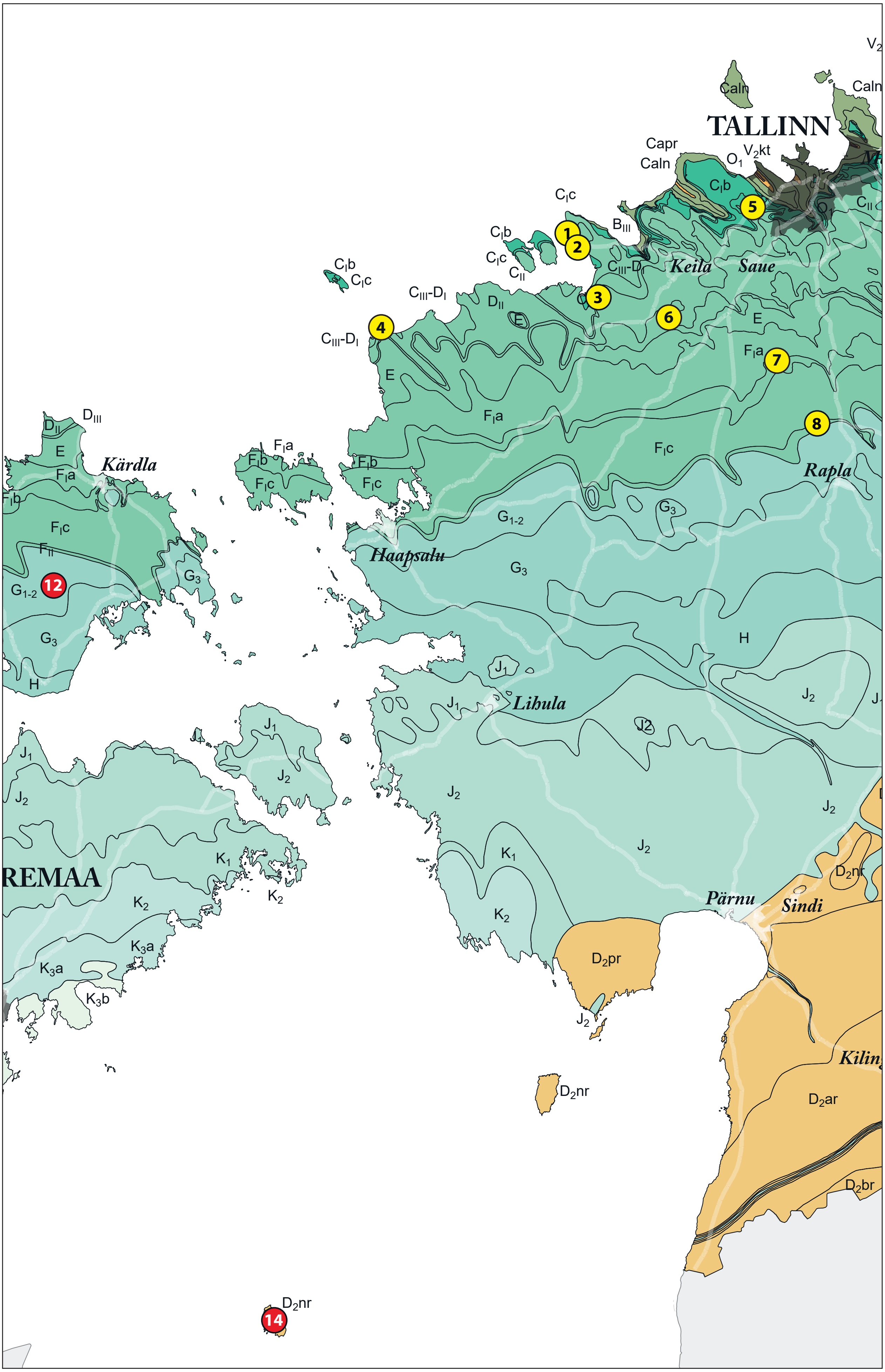
Excursion timeline

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K2
K3a
K3b
D2pr
D2nr
D2ar
D2br

Excursion Day 1

Stop 1: Pakerort cliff, Pakri Peninsula

Olle Hints

Location: Latitude 59.37747°N, longitude 24.03648°E; Harju County, NW Estonia.
Stratigraphy: From Cambrian Series 2 to Darriwilian, Pakerort to Uhaku regional stages.
Status: Cliff is under nature protection; no hammering, but loose material may be collected.
More information: https://geoloogia.info/en/locality/13546

Coastal cliffs on the Pakri Peninsula, ca 50 km west of Tallinn, provide the best exposures of Cambrian to Middle Ordovician rocks in NW Estonia. These cliffs are part of the Baltic Klint – a nearly 1200 km long escarpment that runs from Öland (Sweden) through the Baltic Sea and North Estonia to NW Russia (see also Stop 10 below). The sections on the Pakri Peninsula and the nearby Pakri islands have been well-known since the 1840s, nowadays regularly visited by geology students and geological field excursions (Hints 2014). The up-to-24-m-high Pakerort cliff is also an important geotourism site in Estonia.

The western coast of the Pakri Peninsula constitutes a nearly continuous outcrop subdivided into the Paldiski, Uuga and Pakerort cliffs (Fig. 1.1). This is one of the few places in Estonia where the gentle southward dip of bedrocks (ca 3–4 m per km) can be directly observed. The Pakerort cliff in the north is the etymon for the Pakerort Regional Stage and provides an opportunity to study the lower Cambrian (Series 2) to Tremadocian strata. The Floian to Darriwilian succession is best accessed at the Uuga cliff, close to the Paldiski Northern Port (see Stop 2 below).

Fig. 1.1. Locality map of cliff sections on Pakri Peninsula, NW Estonia (from Hints 2014). The Pakerort Regional Stage is named after Cape Pakerort.

Fig. 1.2. Tremadocian to Darriwilian succession of the 24-m-high Pakerort Cliff, Cape Pakri in distance. Photo: Olle Hints, 2015.

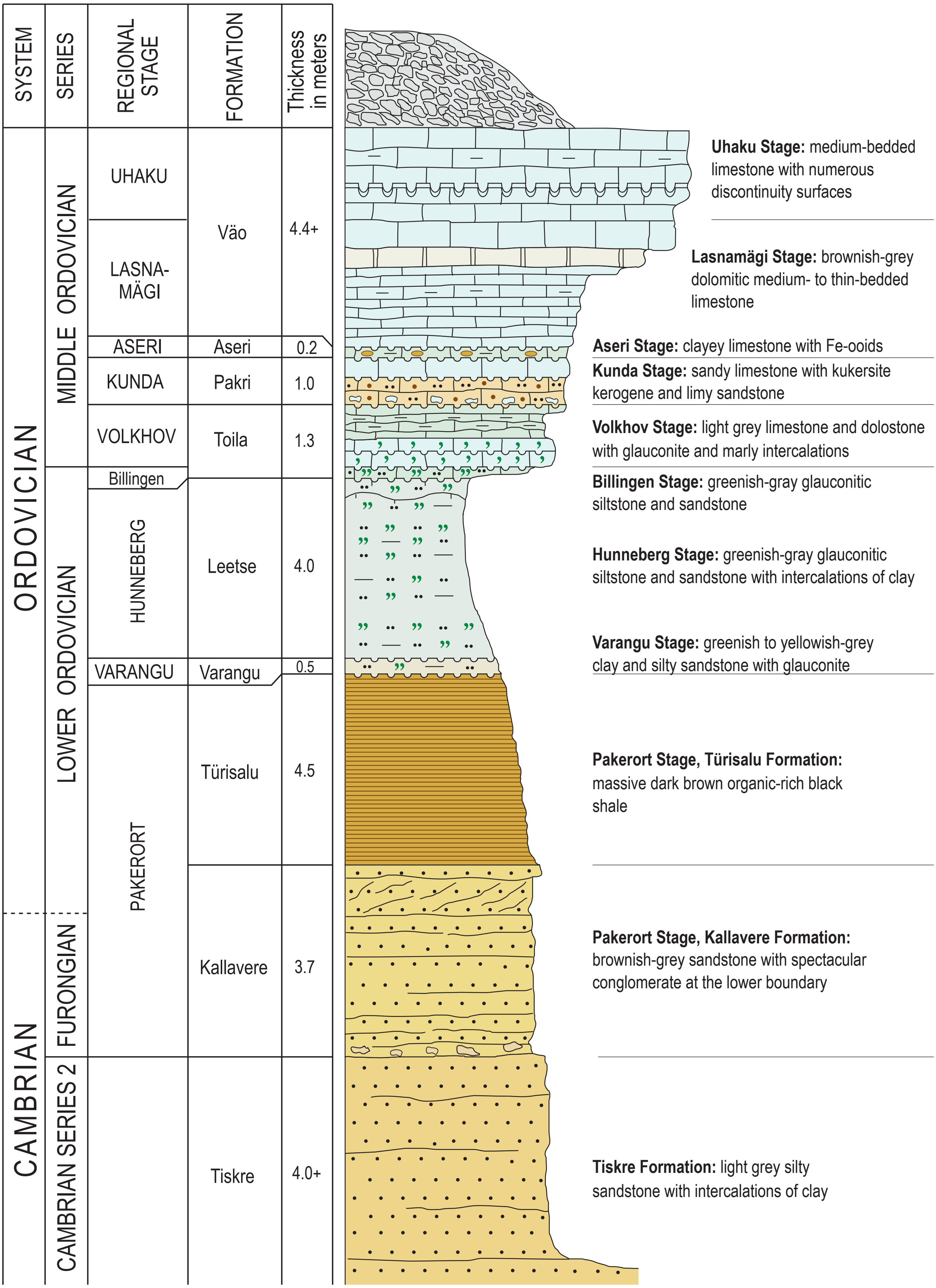

Fig. 1.3. Composite section of the cliffs on Pakri Peninsula, NW Estonia. After Mens and Puura (1996).

The composite section on the Pakri Peninsula (Fig. 1.2, 1.3) is characterised below, based on the descriptions and data by Mens et al. (1996, 1999), Nemliher and Puura (1996), Hints et al. (2014), Löfgren et al. (2005), Põldsaar and Ainsaar (2014), Tammekänd et al. (2010), Einasto and Rähni (2005), Mens and Puura (1996), Orviku (1940).

Fig. 1.4. Basal conglomerate on the boundary of the Cambrian Series 2 Tiskre Formation and the Furongian-Lower Ordovician Kallavere Formation. Photo: Olle Hints, 2020.

Fig. 1.5. The Cambrian-Ordovician boundary on Pakri Peninsula can be approximated with the base of the Suurjõgi Member within the Kallavere Formation indicated by the right hand of the student. Photo: Olle Hints, 2019.

Fig. 1.6. The topmost part of the Kallavere Formation just below the black shale is strongly pyritised ("Pyrite layer") and sometimes preserves ripple marks. Photo: Rutt Hints, 2015.

(1) The **Tiskre Formation** (4+ m, lower Cambrian) is composed of light grey sandy siltstones with interbeds of shaly siltstones and clays. Based on drill core data, the entire thickness of the formation reaches ca 18 m. Ripple marks are common in the upper part of the formation (Mens et al. 1996).

(2) The **Kallavere Formation** (ca 3.7 m, Furongian to Tremadocian) is represented by yellowish fine- to medium-grained sandstones with interbeds of dark brown kerogenous shale in the lower part. The contact with the underlying Tiskre Formation is sharp, marked by a conspicuous basal conglomerate (Fig. 1.4). This conglomerate comprises (1) loose cobbles and boulders of the Tiskre Formation, up to ca 40 cm in diameter and (2) dark-coloured flat pebbles and cobbles cemented with pyrite, apatite and carbonates (Nemliher and Puura 1996). The upper part of the Kallavere Formation (Suurjõgi Member) is represented by cross-bedded sandstones and a strongly pyritised sandstone layer on the top, sometimes with ripple marks (Fig. 1.6). The formation contains scattered debris of lingulate brachiopods, mostly belonging to the genus *Ungula* (Nemliher and Puura 1996).

Conodont and acritarch evidence suggest that the basal conglomerate formed slightly before or during the *Cordylodus proavus* time (Mens et al. 1996, 1999). Thus, the base of the Pakerort Stage, drawn at the appearance of *Cordylodus andresi* in Estonia (see Puura and Viira 1999), coincides with the base of the Kallavere Formation in the Pakerort section. The base of the Ordovician System cannot be precisely correlated on the Pakri Peninsula, but unpublished finds of conodonts and the age of the Suurjõgi Member elsewhere in Estonia allow us to approximate it with the base of the cross-bedded sandstones of the Suurjõgi Member (Fig. 1.5).

(3) The **Türisalu Formation** (4.5 m, Pakerort Regional Stage, Tremadocian) consists of homogenous dark brown kerogenous shale (commonly referred to as graptolite argillite, previously known as the "Dictyonema Shale") containing graptolites *Rhabdinopora flabelliformis flabelliformis* and *Rhabdinopora flabelliformis* cf. *norvegica* in Pakri sections (Mens et al. 1996). The formation is characterised by a high content of organic matter (10–20%), authigenic K-feldspar, pyrite and redox-sensitive trace elements, such as V, U and Mo. Based on microfabrics studies (Hints et al. 2014 and references therein), it has been suggested that dynamic sedimentation events, rather than slow net sedimentation, may have been the dominant mechanism behind the accumulation of these beds. Storm-related near-bottom flows and the bed-load transport of mud particles were likely common distribution

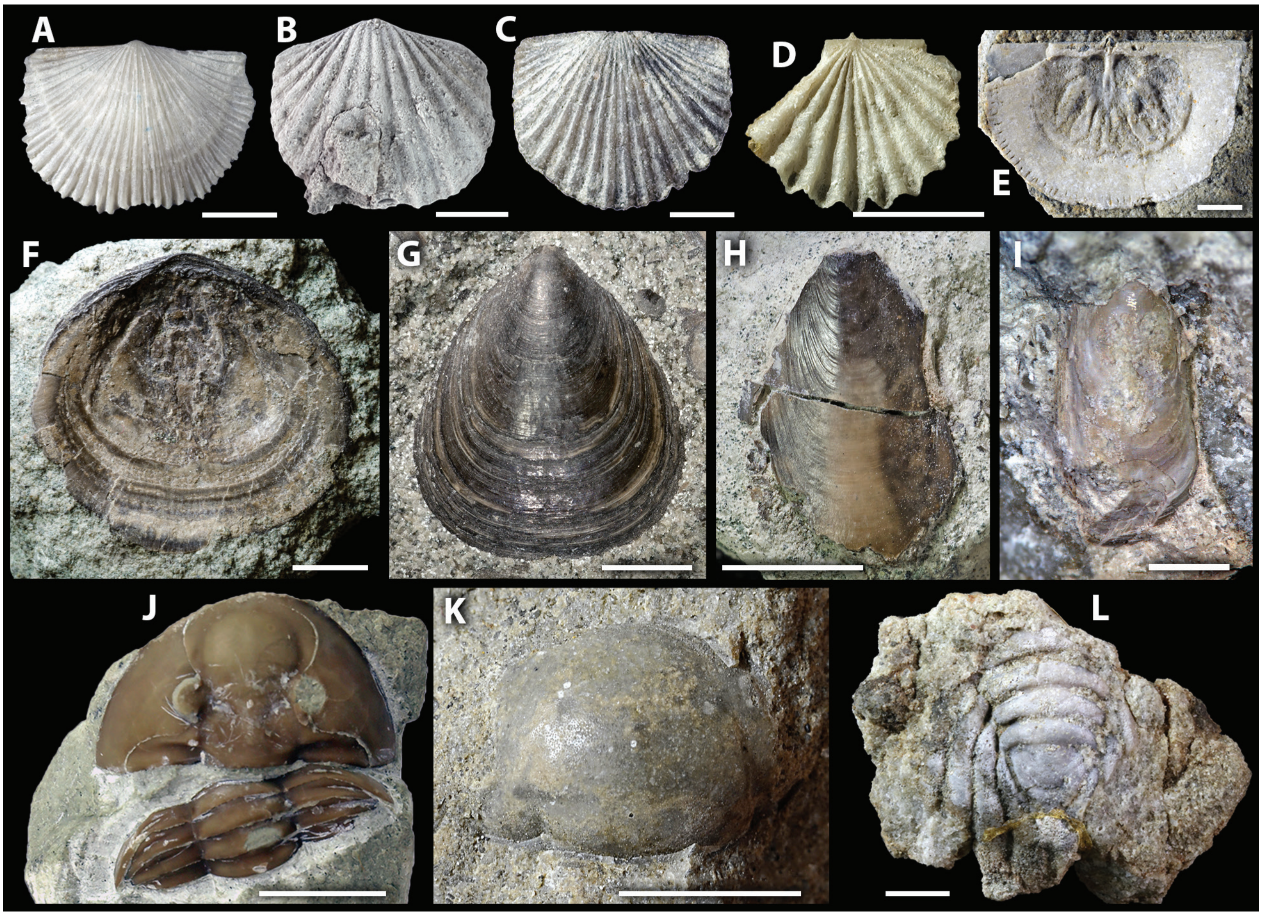

Fig. 1.7. Selected fossils from the Pakri Peninsula and Pakri islands. Scale bars: J – 1 cm; A–H, K, L – 5 mm; I – 1 mm. **A–I** – brachiopods; **A** – *Panderina pakriensis*, Väike-Pakri Cliff, Toila Formation (Dapingian), GIT 125-47; **B** – *Rogorthis pakriensis*, Väike-Pakri Cliff, Pakri Formation (Darriwilian), GIT 125-102; **C** – *Orthambonites fundata*, Paldiski, Pakri Formation (Darriwilian), GIT 125-89; **D** – *Nicolella pterygoidea*, Pakri, Pakri Formation (Darriwilian), GIT 125-174; **E** – *Ingria pakriana*, Väike-Pakri Cliff, Pakri Formation (Darriwilian), GIT 675-29; **F** – *Thysanotos siluricus*, Paldiski, Leetse Formation; GIT 275-86; **G** – *Leptembolon lingulaeformis*, Leetse, Leetse Formation; GIT 275-63; **H** – "*Lingulella*" *nitida*, Paldiski, Leetse Formation; GIT 275-70; **I** – lingulid *Rowellella* inside *Trypanites sozialis* boring, Uuga Cliff, Väo Formation (Darriwilian); TUG 1393-186. **J–L** – trilobites; **J** – *Paraptychopyge pahleni,* Väike-Pakri Cliff, Toila Formation (Dapingian), TUG 1355-410; **K** – *Panderia,* Väike-Pakri Cliff, Pakri Formation (Darriwilian), GIT 437-417; **L** – *Pliomera fisheri*, Väike-Pakri Cliff, Pakri Formation (Darriwilian), GIT 435-23.

agents of organic-rich mud, which can be viewed as a near-shore tongue of the Scandinavian Alum Shale complex.

(4) The **Varangu Formation** (0.5 m, Varangu Regional Stage, Tremadocian) is represented by greenish-grey to beige clay and silty sandstone with glauconite. It contains the zonal conodont *Paltodus deltifer deltifer* (Löfgren et al. 2005).

(5) The **Leetse Formation** (ca 3.9 m, Hunneberg and Billingen regional stages, Tremadocian to Floian) is composed of greenish-grey weakly lithified glauconitic sandstone (20–40% glauconite grains). The type locality of the formation is the Leetse cliff on the eastern coast of the Pakri Peninsula. The Leetse Formation corresponds to the *Paroistodus proteus* conodont Zone, and the base of the Floian Global Stage is identified within the lower third of this unit on the Pakri Peninsula (Löfgren et al. 2005). The upper ca 20 cm of the formation is distinguished as the Mäeküla Member, which becomes calcareous and corresponds to the *Oepikodus evae* conodont Zone. The *Prioniodus elegans* Zone seems to fall into a gap in this area (Löfgren et al. 2005). The transition to the overlying Toila Formation is gradual, characterised by increasing carbonate content.

(6) The **Toila Formation** (ca 1.3 m, Billingen and Volkhov regional stages, Floian to Dapingian) is represented by grey glauconitic limestones (packstones and wackestones). The lower ca 10 cm of the formation (Päite Member) corresponds to the *Oepikodus evae* conodont Zone (Löfgren et al. 2005) and is overlain by a distinct and geographically widespread discontinuity surface (hardground), informally known as the "Püstakkiht" in Estonia (Fig. 2.2). This surface indicates a regional hiatus. It is taken as the base of the Volkhov Regional Stage in northern Estonia and correlated with the base of the Dapingian. Conodonts of the Volkhov Regional Stage are insufficiently known on the Pakri Peninsula, but the top of the formation seems to fall into the *Paroistodus originalis* Zone (Hints et al. 2012). This suggests that the upper part of the Volkov Stage corresponds to a gap in NW Estonia.

(7) The **Pakri Formation** (ca 1.0 m, Kunda Regional

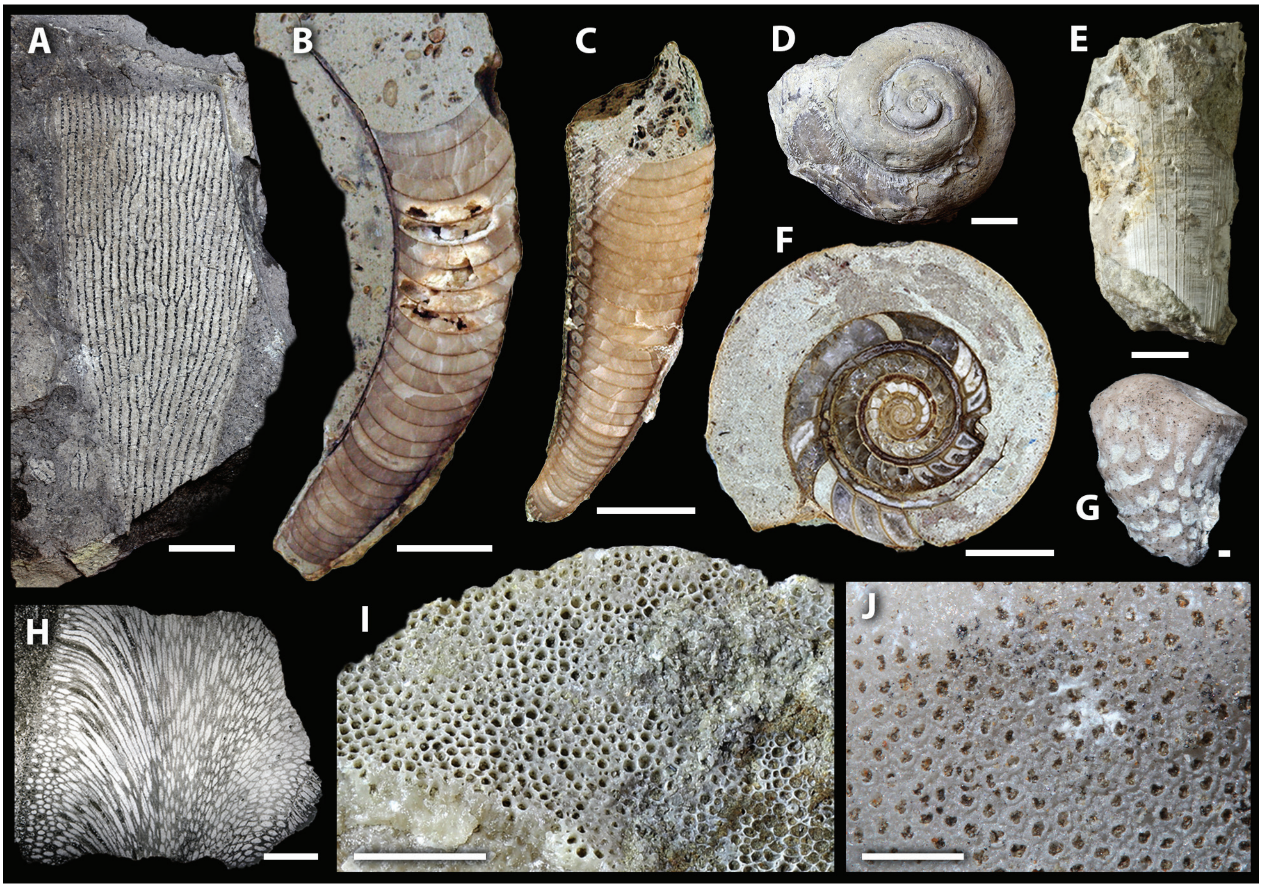

Fig. 1.8. Selected fossils from the Pakri Peninsula and Pakri islands. Scale bars: A, F–D – 1 cm; B–E, H, I – 5 mm; G, J – 1 mm. **A** – graptolite *Rhabdinopora flabelliformis flabelliformis*, Pakri, Türisalu Formation (Tremadocian), GIT 398-1034. **B**, **C**, **F** – cephalopods; ***B*** – *Richardsonoceras goldmanni,* Uuga Cliff, Kandle Formation (Darriwilian), TUG 1285-51; ***C*** – *Paldoceras paldiskense*, Uuga Cliff, Kandle Formation (Darriwilian), TUG 1285-10; **F** – *Trocholites depressus*, Väike-Pakri Cliff, Väo Formation (Darriwilian), GIT 145-1. **D** – gastropod *Proturritella cingulata*, Paldiski, Pakri Formation (Darriwilian), GIT 404-400. **E** – hyolith *Hyolithes gerhardi*, Paldiski, Väo-Kõrgekallas formations (Darriwilian), GIT 387-2. **G** – eocrinoid *Bolboporite*s (*Bolboporites*) *uncinatus*, Pakri, Pakri Formation (Darriwilian), GIT 468-76. **H–J** – bryozoans; **H–I** – *Dianulites pakriensis*, Väike-Pakri Cliff, Pakri Formation (Darriwilian), GIT 537-1294; **J** – *Pakripora cavernosa***,** Väike-Pakri Cliff, Pakri Formation (Darriwilian), GIT 537-1227-1.

Stage, Darriwilian) is composed of sandy limestone to limy sandstone (up to ca 80% quartzose sand according to Põldsaar and Ainsaar 2014). These sediments are spread in a limited area in NW Estonia, probably representing one of the few remains of a near-shore facies in the Ordovician Baltoscandian Basin. The unit contains numerous soft-sediment deformation structures (such as load casts, flame structures, ball-and-pillow morphologies, sedimentary dykes, autoclastic breccias, and sand volcanoes) that indicate large-scale liquefaction and fluidisation of the unconsolidated and water-saturated sediments, probably by a large earthquake (Põldsaar and Ainsaar 2014). The coincidence of a deformation event and the Middle Ordovician meteoritic bombardment period, and the occurrence of shock metamorphic features and extraterrestrial chromite in the Pakri Formation suggest that a meteorite impact might have caused such an earthquake (Alwmark et al. 2010). The basal part of the Kunda Stage corresponds to a gap in NW Estonia, and thus the base of the Darriwilian coincides with the Volkhov–Kunda stage boundary on the Pakri Peninsula. The upper part of the formation corresponds to the *Eoplacognathus pseudoplanus* conodont Zone and the *Cyathochitina regnelli* chitinozoan Zone. The Pakri Formation also contains several strong pyritic discontinuity surfaces, the oldest kukersite kerogen in the region and is rich in shelly faunas.

(8) The **Kandle Formation** (ca 0.1 m, =Aseri Formation in some previous publications; Aseri/Lasnamägi regional stages, Darriwilian) is composed of argillaceous limestone with brown or white ooids. In the Uuga cliff, this unit contains the zonal conodont *Yangtzeplacognathus foliaceus*, which is considered to indicate the lower Lasnamägi age. If this is true, the Aseri Regional Stage may be entirely missing in some parts of the Pakri Peninsula and other places in NW Estonia (Hints et al. 2012).

(9) The **Väo Formation** (ca 5.1 m, Lasnamägi and Uhaku regional stages, Darriwilian) is represented by grey thin- to medium-bedded limestones (wacke- to packstones), a discrete layer of dolostone (Pae Member) and numerous phosphatic and pyritic discontinuity surfaces. The dolomitic Pae Member is characterised by a positive magnetic susceptibility anomaly likely because of fluid migration, which produced secondary iron input and/or rearrangement of existing iron and precipitation of ferroan dolomite crystals (Plado et al. 2016). The age of the Väo Formation and individual members are well-constrained by conodont and chitinozoan biostratigraphy, the most useful being subzones of the *Pygodus serra* conodont Zone. The base of the Uhaku Regional Stage is drawn at the appearance of *Gymnograptus linnarssoni*, but as only a single find of this species comes from the Uuga cliff, the appearance of the conodont *Baltoplacognathus robustus* provides a more helpful level (Hints et al. 2012). The upper part of the Väo Formation, starting from the Pae Member, constitutes the so-called Building Limestone, which is widely quarried and utilised all over northern Estonia. Many of the individual layers are specifically named by local quarrymen, and some of these layers can be recognised over hundreds of kilometres (Einasto and Rähni 2005).

(10) The **Kõrgekallas Formation** (1.0+ m, Uhaku Regional Stage, Darriwilian) is composed of grey limestones, which are relatively more argillaceous than the underlying Väo Formation. The boundary between the formations is marked by six distinct successive discontinuity surfaces.

Younger rocks belonging to the Kukurse and Haljala regional stages, basal Sandbian, are distributed (but not well exposed) in the central part of the Pakri Peninsula.

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Stop 2: Uuga cliff, Pakri Peninsula

Olle Hints

Location: Latitude 59.36138°N, longitude 24.03941°E; Harju County, NW Estonia.
Stratigraphy: From Tremadocian-Floian to Darriwilian, Hunneberg to Uhaku regional stages.
Status: Cliff is under nature protection, no hammering.
More information: https://geoloogia.info/en/locality/13545

The Uuga cliff is located close to the Paldiski Northern Port, where the cliff gradually emerges and gains height toward the north. It is possible to walk along the coast to the Pakerort cliff (Stop 1) and observe the gentle southwards dip of the layers (due to that, successively older rocks get exposed northwards). At the Uuga cliff, the upper part of the Leetse Formation and the oldest carbonate rocks of the Toila, Pakri, Kandle, Väo and Kõrgekallas formations are accessible. These are characterised in detail above (Stop 1).

The Uuga cliff succession has been analysed for microfossils (Fig. 2.4; Tammekänd et al. 2010; Hints et al. 2012), geochemistry, magnetic properties, as well as sedimentology (Põldsaar and Ainsaar 2014). A prominent hardground at the base of the Volkhov Regional Stage, coinciding with the base of the Dapingian, can be observed within the glauconite-rich limestones of the Toila Formation (Fig. 2.2).

The Pakri Formation, Kunda Regional Stage, lower Darriwilian, is characterised by sandy limestones to calcareous sandstones with soft-sediment deformations (Fig. 2.3).

Fig. 2.1. Succession of Tremadocian-Floian glauconitic sandstone (Leetse Formation) and Dapingian-Darriwilian carbonate rocks at the Uuga Cliff near the Northern Port of Paldiski. Photo: Olle Hints, 2020.

Fig. 2.2. A characteristic hardground ("Püstakkiht") at the base of the Volkhov Regional Stage (coinciding with the base of the Dapingian). The same surface with *Gastrochaenolites* borings can be traced from NW Russia to Öland Island, Sweden. Left – outcrop photo, right – polished slab GIT 362-538.

Fig. 2.3. Soft-sediment deformations (load casts and flame structures, Põldsaar & Ainsaar 2014) in the Pakri Formation, Kunda Regional Stage. Photo: Gennadi Baranov, 2011.

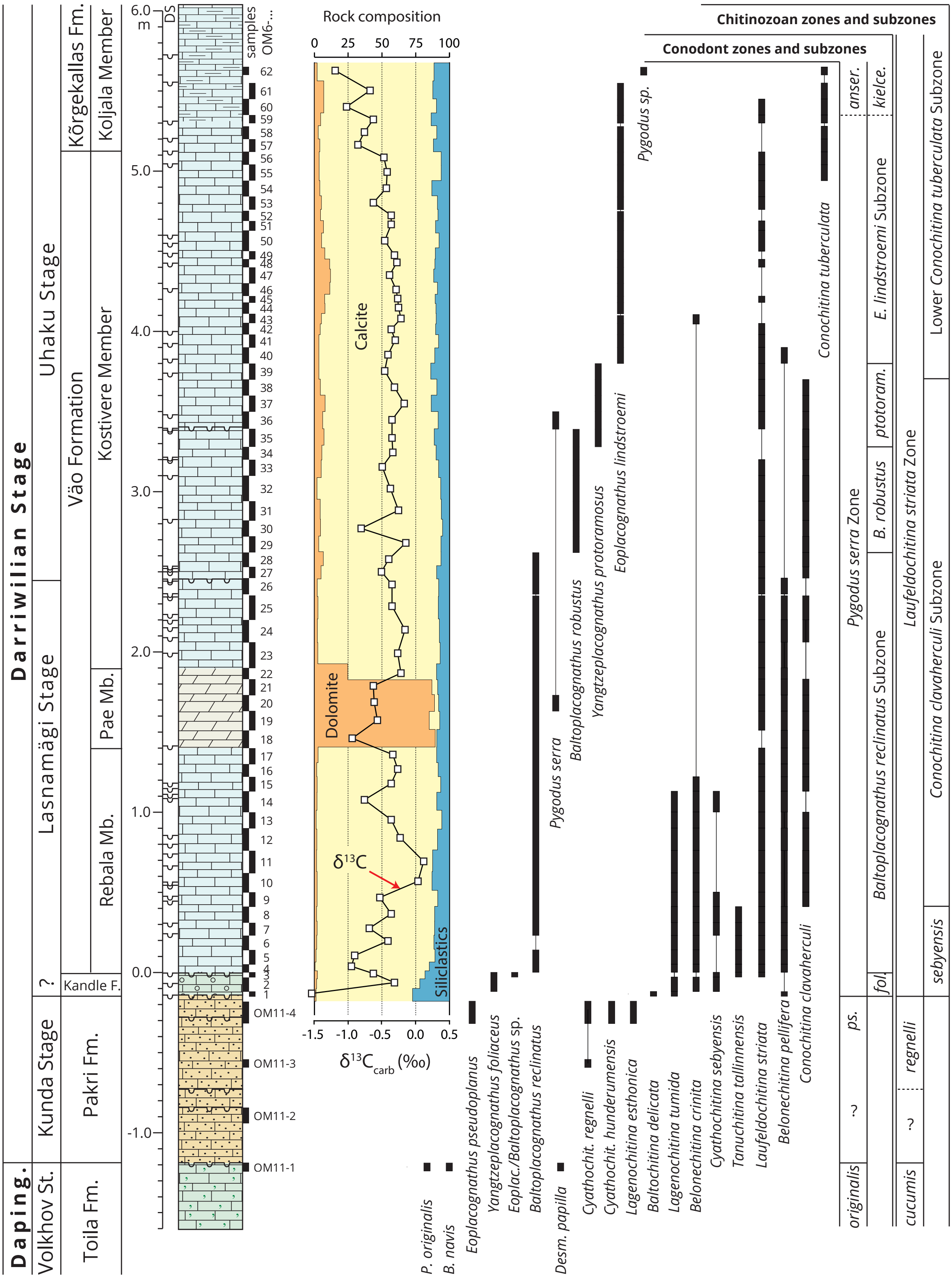

Fig. 2.4. Distribution of key conodonts and chitinozoans in the Uuga Cliff (from Hints et al. 2012).

Stop 3: Madise escarpment

Oive Tinn

Location: Latitude 59.29083°N, longitude 24.12194°E; Harju County, NW Estonia.
Stratigraphy: Sandbian, Haljala Regional Stage, Kahula Formation.
Status: No hammering of the outcrop, but fossil collecting is allowed.
More information: https://geoloogia.info/en/locality/10030

The Madise outcrop is a 500 m long and ca 3.5 m escarpment in the Madise village, near the Mattias' (St. Matthiew's) church of Harju-Madise, exposing Sandbian argillaceous limestones and marls. At present, the escarpment is located about 0.6 km from the sea, but it formed as a coastal cliff during an earlier developmental stage of the Baltic Sea, known as Littorina Sea – a brackish water reservoir which existed 7500 to 4000 BP (Alar Rosentau, pers. comm).

The Madise escarpment is the stratotype of the Madise Member, the middle part of the Kahula Formation, Haljala Regional Stage. Historically, the Haljala Regional Stage was separated into the Jõhvi and Idavere stages, but due to relatively minor faunal differences and problems distinguishing the two units in subsurface sections in central and southern Estonia, the new unit – Haljala Regional Stage – was proposed by Jaanusson (1995). The former Idavere and Jõhvi stages can be used in the rank of substages (Hints 1997).

In northern and central Estonia, the upper part of the Haljala Regional Stage and the lower part of the Keila Regional Stage comprise a complex of beds with cyclically alternating content of terrigenous material – the Kahula Formation (Ainsaar 1993). The Madise outcrop (Fig. 3.1, 3.2) opens about 1 m of marls and marly limestone of the Pagari Member at the base and the overlying more calcareous limestones (wackestones and packstones) of the Madise Member.

The argillaceous rocks of the Kahula Formation are rich in shelly faunas, and many fossils can also be found in the Madise section (Fig. 3.3, 4.8). Among these are trilobites (representatives of genera *Asaphus*, *Atractopyge*, *Autoloxolichas*, *Cybelella*, *Hemisphaerocoryphe*, *Illaenus*, *Reraspis*, *Toxochasmops*); some of the oldest rugose corals worldwide (*Primitophyllum*, *Lambephyllum*); sponges (*Carpospongia*), gastropods (*Subulites*, *Salpingostoma*, *Megalomphala*, *Lophospira*, *Lesueurilla*, *Kokenospira*, *Holopea*, *Cymbularia*, *Bucania*, *Brachytomaria*), brachiopods (*Alichovia*, *Vellamo*, *Porambonites*, *Platystrophia*, *Orthisocrania*, *Leptaena*, *Cyrtonotella*, *Clitambonites* etc.), echinoderms (*Hemicosmites*, *Hoplocrinus*) and bryozoans (*Diplotrypa*, *Trigonodictya*, *Tarphophragma*). Also, calcareous algae (*Cyclocrinites*, *Mastopora*) and several ichnofossils (*Arachnostega*, *Conichnus*, *Cochlichnus*, *Palaeophycus*, *Sanctum*) have been collected from the Madise escarpment.

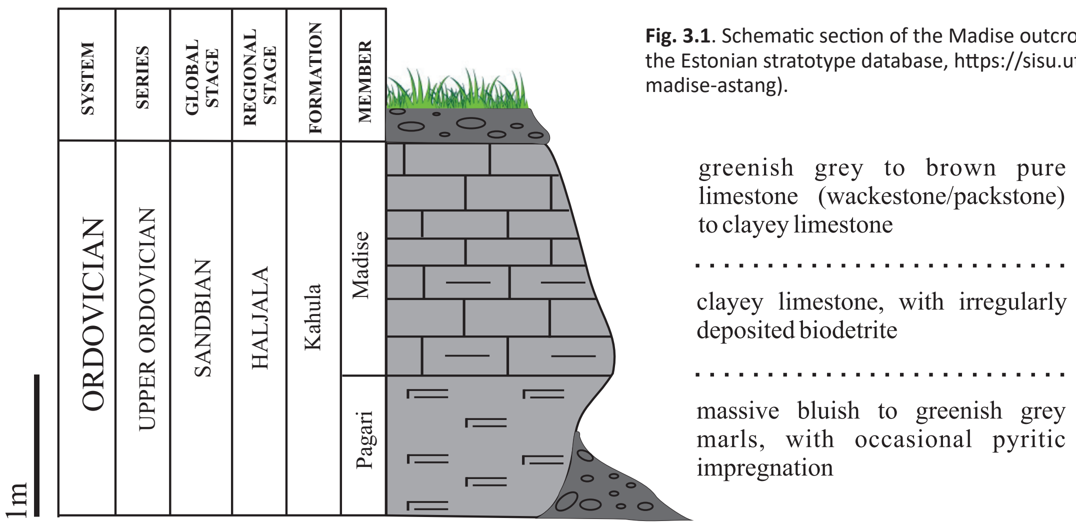

Fig. 3.1. Schematic section of the Madise outcrop (modified from the Estonian stratotype database, https://sisu.ut.ee/stratotuup/o-madise-astang).

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Fig. 3.2. Overview of the Madise escarpment. Photo: Leho Ainsaar, 2008.

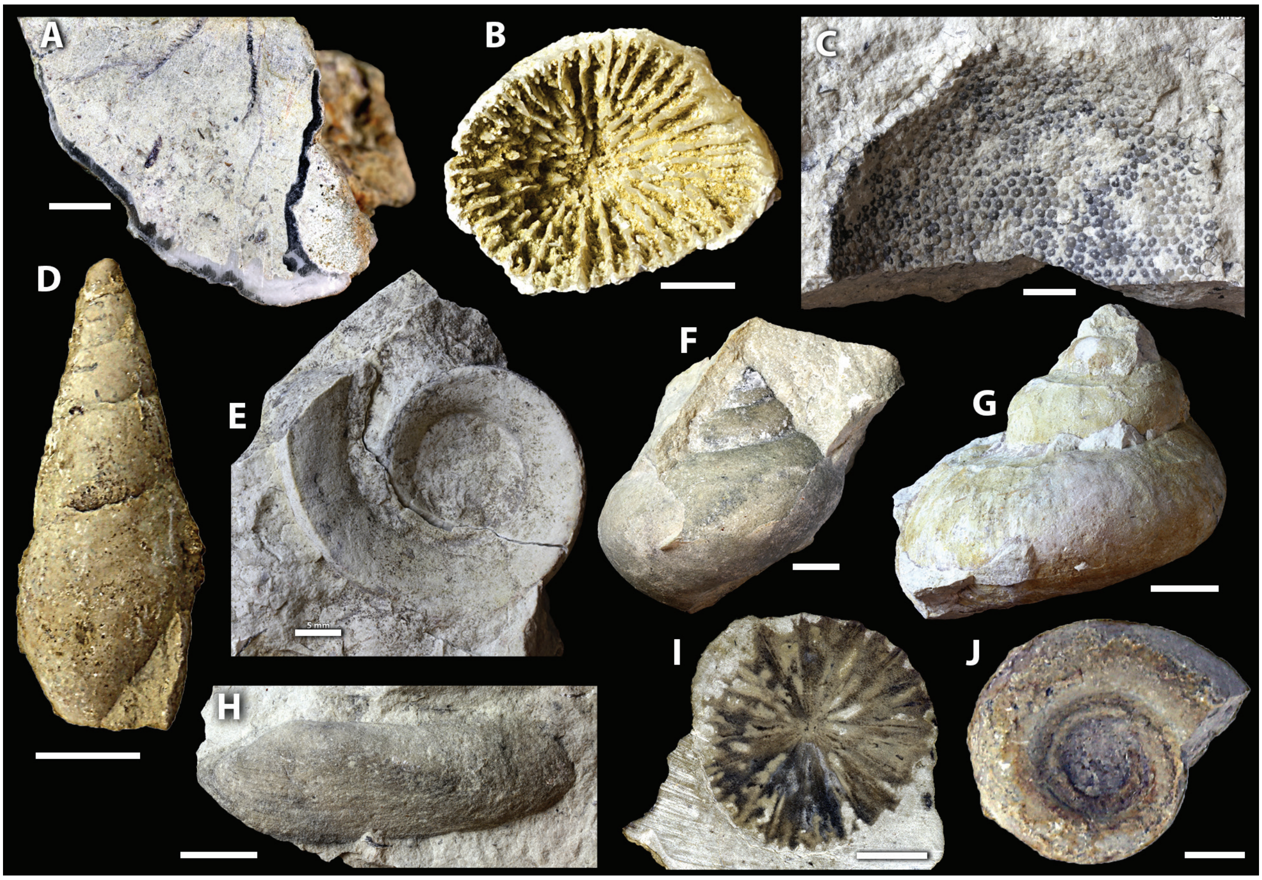

Fig. 3.3. Selected fossils from the Madise scarplet, Haljala Regional Stage (Sandbian). Scale bars: D, G–I – 1 cm; A–C, E, F, J – 5 mm. **A**–**B** – rugose corals; **A** – *Primitophyllum primum*, GIT 77-2; **B** – *Lambelasma dybowskii*, GIT 398-954. **C** – dasycladacean algae *Mastopora concava*, GIT 339-756. **D**–**G**, **J** – gastropods; **D** – *Subulites amphora*, TUG 72-222; **E** – *Lesueurilla marginalis spiralis*, GIT 404-456; **F** – *Lophospira* GIT 404-450; **G** – *Lophospira prisca*, GIT 404-449; **J** – *Megalomphala cycloides*, TUG 2-370. **H** – bivalve *Orthonota*, GIT 694-64-1; **I** – sponge *Carpospongia castanea*, GIT 413-100.

Stop 4: Põõsaspea cliff

Olle Hints

Location: Latitude 59.226065°N, longitude 24.03648°E; Lääne County, NW Estonia.
Stratigraphy: Sandbian, Haljala and Keila regional stages, Kahula Formation and Kinnekulle K-bentonite.
Status: Cliff is under nature protection, no hammering, but loose material may be collected.
More information: https://geoloogia.info/en/locality/12690

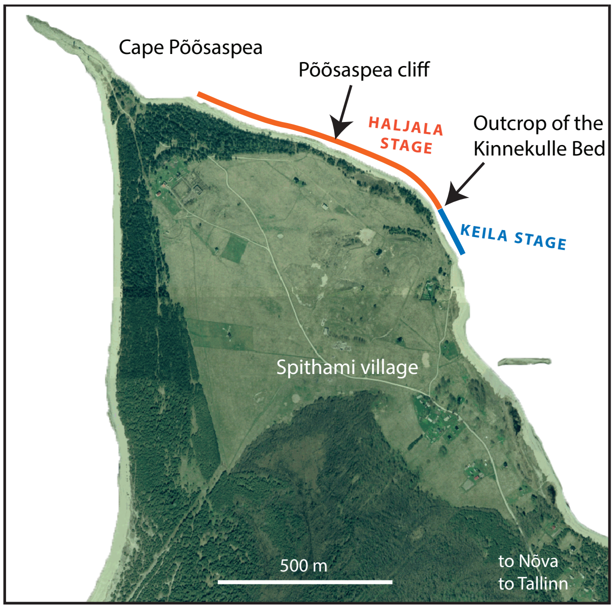

Fig. 4.1. Locality map showing the Põõsaspea cliff with late Sandbian limestone and the outcrop of the Kinnekulle K-bentonite (after Hints et al. 2008).

The bedrock outcrop on the eastern coast of Põõsaspea Cape, in the village of Spithami (historically Spitham or Spithamn), was well known already to Friedrich Schmidt (1881). He described several fossils from the locality and used Spithamn as a reference site in his geological cross-section (Schmidt 1881, p. 58).

According to Rõõmusoks (1970), the low cliff at Põõsaspea Cape exposes ca 1.5 m of variably argillaceous limestones of the Jõhvi Stage (now substage of the Haljala Regional Stage). It was discovered much later that the southern part of the section also hosts the Kinnekulle K-bentonite and limestones of the Keila Regional Stage, in total thickness of more than 1 m (Hints et al. 2008; Perrier et al. 2012; further details below). The Põõsaspea cliff is thus complementary to the Madise section (Stop 3), being slightly younger in the southernmost part.

The Põõsaspea cliff is richly fossiliferous; some examples are shown in Fig. 4.3. Rõõmusoks (1970, Table 13) lists 47 taxa of brachiopods, bryozoans, gastropods, trilobites, echinoderms, conulariids, calcareous algae and graptolites. In addition, cephalopods are common mac-

Fig. 4.2. Overview of the Põõsaspea coastal outcrop. The low cliff is exposing fossiliferous argillaceous limestones of the Kahula Formation, Haljala and Keila regional stages. Photo: Gennadi Baranov, 2023.

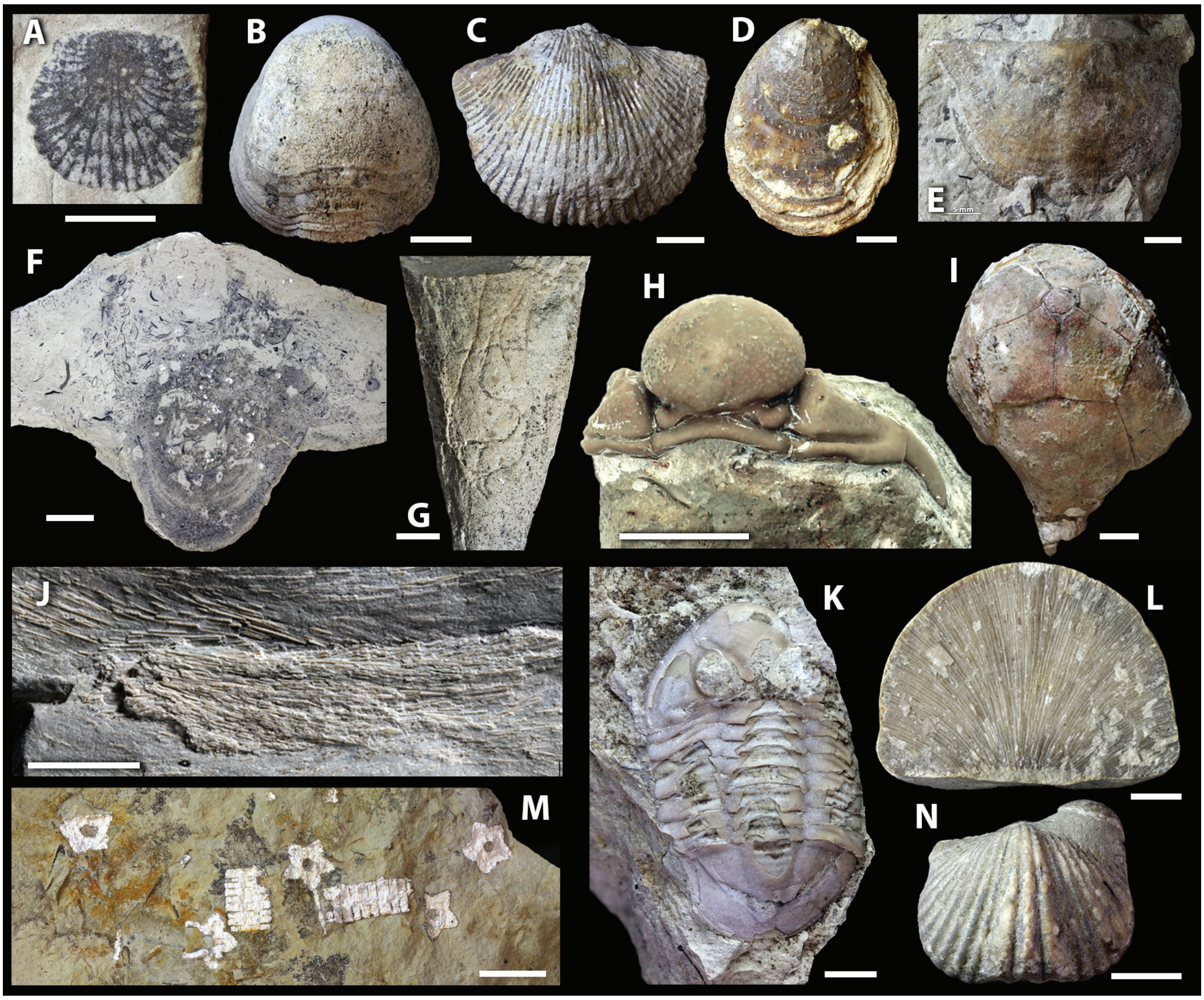

Fig. 4.3. Selected fossils from the Madise scarplet and Põõsaspea outcrop, Haljala and Keila regional stages (Sandbian). Scale bars: B, F, H, J, M – 1 cm; A, C–E; G, I, K, L, N – 5 mm. **A–E** – brachiopods from the Madise scarplet, Haljala Regional Stage; **A** – *Orthisocrania curvicosta*, GIT 772-136; **B** –*Porambonites* (*Equirostra*) *baueri*, GIT 619-553; **C** – *Cyrtonotella kuckersiana frechi*, GIT 400-21; **D** – *Alichovia ramispinosa*, GIT 811-6; **E** – *Clinambon anomalus*, GIT 543-1114. **F–G** – trace fossils from the Madise scarplet, Haljala Regional Stage; **F** – polished vertical section of *Conichnus conicus*, 362-328; **G** – feeding trace *Cochlichnus* on the hyolith steinkern, GIT 696-49-1. **H**, **K** – trilobites from the Madise scarplet, Haljala Regional Stage; **H** – *Hemisphaerocoryphe pseudohemicranium*, TUG 1085-87; **K** – *Asaphus* (*Neoasaphus*) *jewensis*, GIT 453-763. **I** – crinoid *Hoplocrinus estonus* from the Madise scarplet, Haljala Regional Stage, GIT 104-15. **J** – problematic sponge *Pyritonema subulare*, fragment of a root tuft, composed of long needle-like spicules, Põõsaspea, Haljala Regional Stage, GIT 413-82. **L** – bryozoan *Mesotrypa orientalis* from the Põõsaspea Cliff, Haljala Regional Stage, GIT 537-4271. **M** – silicified columnals of echinoderm *Baltocrinus*, Põõsaspea, Haljala Regional Stage, GIT 690-49. **N** – brachiopod *Platystrophia dentata trapezoidalis*, Põõsaspea, Keila Regional Stage, GIT 525-126.

rofossils, but their preservation is usually poor. Recent microfossil studies have identified 71 species of ostracods (Perrier et al. 2012) and 23 species of chitinozoans (Hints et al. 2017) from the upper part of the Põõsaspea succession. Among chitinozoans, the biozonal *Angochitina multiplex* has been identified in a few samples ca 1 m above the Kinnekulle K-bentonite.

The Põõsaspea cliff is one of few places in the eastern Baltic region where the Kinnekulle K-bentonite is exposed (Hints et al. 2008). It is the thickest K-bentonite in the Baltic Ordovician and an excellent time marker for the entire Baltoscandian region (Bergström et al. 1995; Kiipli et al. 2007), serving as the primary criterion for the base of the Keila Regional Stage (Hints et al. 1997, 1999). The bed has been dated radiometrically at 454.9 ± 4.9 Ma in Estonia (Bauert et al. 2014); and using a more precise method in Norway at 454.52 ± 0.50 Ma (Svensen et al. 2015). The thickness of the Kinnekulle K-bentonite decreases eastwards, from more than a metre in southern Scandinavia to a few cm in NW Russia (Fig. 4.7; Bergström et al. 1995).

In the Põõsaspea section, the Kinnekulle Bed is ca 40 cm thick and composed of the following parts (after Hints et al. 2008; starting from the base):

(1) 2–5 cm of dark greyish plastic clay containing hard particles. The basal contact with underlying limestones of the Haljala Regional Stage is sharp.

(2) 2–3 cm of light grey, in places yellow, hard layer of uneven distribution; its topmost part is rich in large biotite phenocrysts.

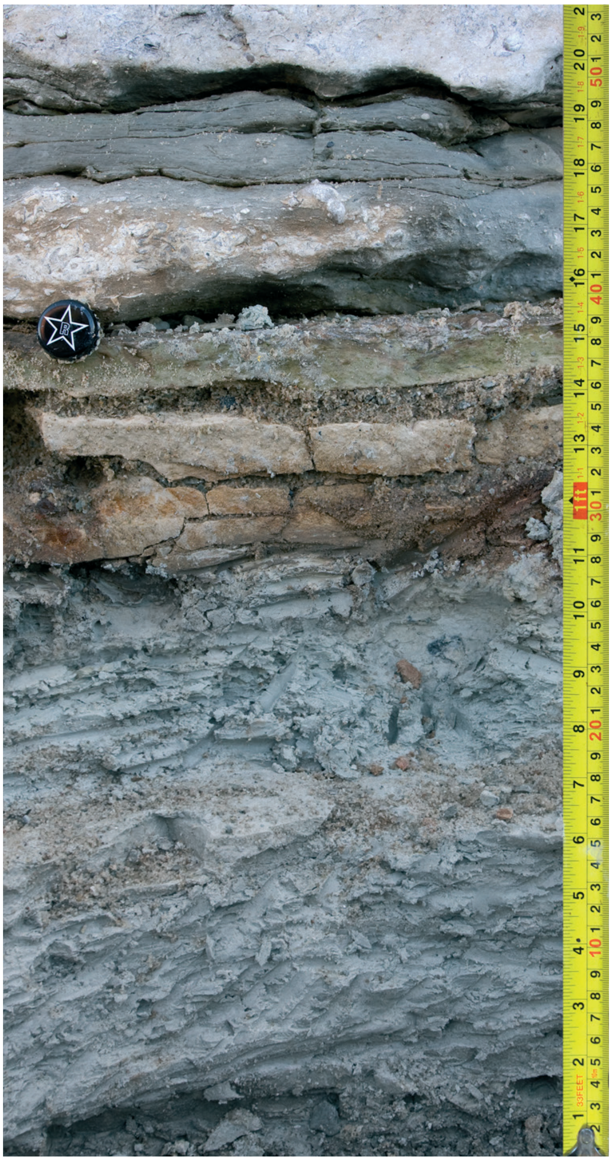

Fig. 4.4. Põõsaspea cliff is one of few localities where the Kinnekulle K-bentonite is exposed in Estonia. Photo: Olle Hints, 2008.

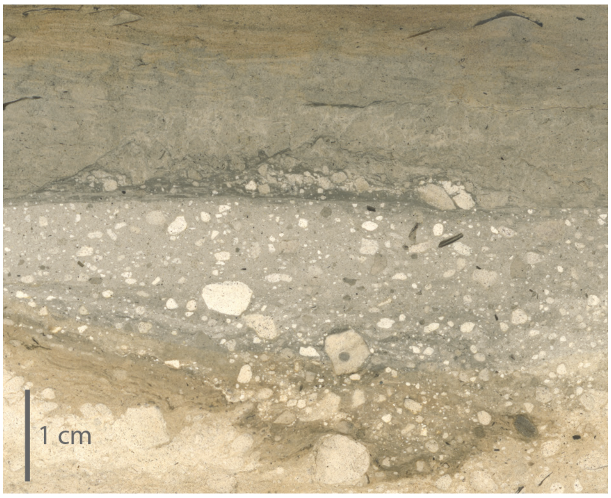

Fig. 4.5. The upper part of the Kinnekulle K-bentonite contains a brecciated layer, indicating early lithification of the volcanic ash. Photo from Hints et al. (2008).

Fig. 4.6. Silicified nodules with calcitic infill are common, alongside with the silicification of fossils. The silica is thought to have derived from the Kinnekulle volcanic ash. Photo: Olle Hints, 2023.

(3) 21–23 cm of light grey (almost white when dry) plastic clay, which embodies irregularly distributed rounded and flattened, almost white nodules of hard variety, up to 10 cm in size. Some nodules display microlamination resulting from varied content of biotite; sometimes, they are bioturbated, burrows are filled with darker material. Angular hard particles are also encountered within the clay.

(4) 5–7 cm of light yellowish to brownish hard feldspathitic layer, occasionally containing elongated or irregularly shaped concretions of pyrite reaching 5 cm in size, bioturbated in places. The top 0.5–3 cm is a distinct breccia with greyish cement containing angular particles from sub-mm to 1 cm in size (Fig. 4.5). The clasts are mostly lighter in colour; no size gradation can be observed. The lower contact of the breccia is irregular, whilst the upper surface is mostly flat and more distinct.

(5) few cm of darker brownish and slightly carbonaceous rock, with abundant brachiopod shells and fragments in the upper part. This is overlain by 10–14 cm of greyish-brown to dark brown kerogenous mudstone containing accumulations of shelly faunas in the lower part and microlaminated kerogenous rock in the upper part. In this interval, the material from volcanic ash is mixed with carbonates and organic matter, and thus the upper boundary of the K-bentonite bed cannot be identified precisely.

The mineral composition of the Kinnekulle Bed at Põõsaspea is dominated by authigenic K-feldspar and illite-smectite (Fig. 4.8; Perrier et al. 2012).

It has been shown that the Kinnekulle volcanic ash-fall had a strong influence on marine biotas (Hints et al. 2003). Even though the extinction of only a few species among ostracods is known (e.g., *Tetrada memorabilis*), both benthic and planktonic communities were stressed and got significantly reorganised after the ash-fall (Perrier et al. 2012; Hints et al. 2017).

Põõsaspea Cape is also famous for a particular type of erratic boulders that are eroded from the uplifted and brecciated basement rocks of the nearby Neugrund meteorite crater (Suuroja and Suuroja 2010). These boulders can be observed on the coast.

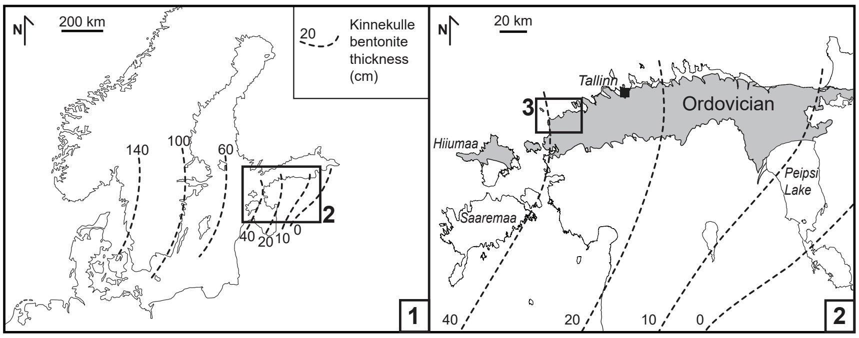

Fig. 4.7. Thickness of the Kinnekulle K-bentonite in Baltoscandia and Estonia (after Perrier et al. 2012).

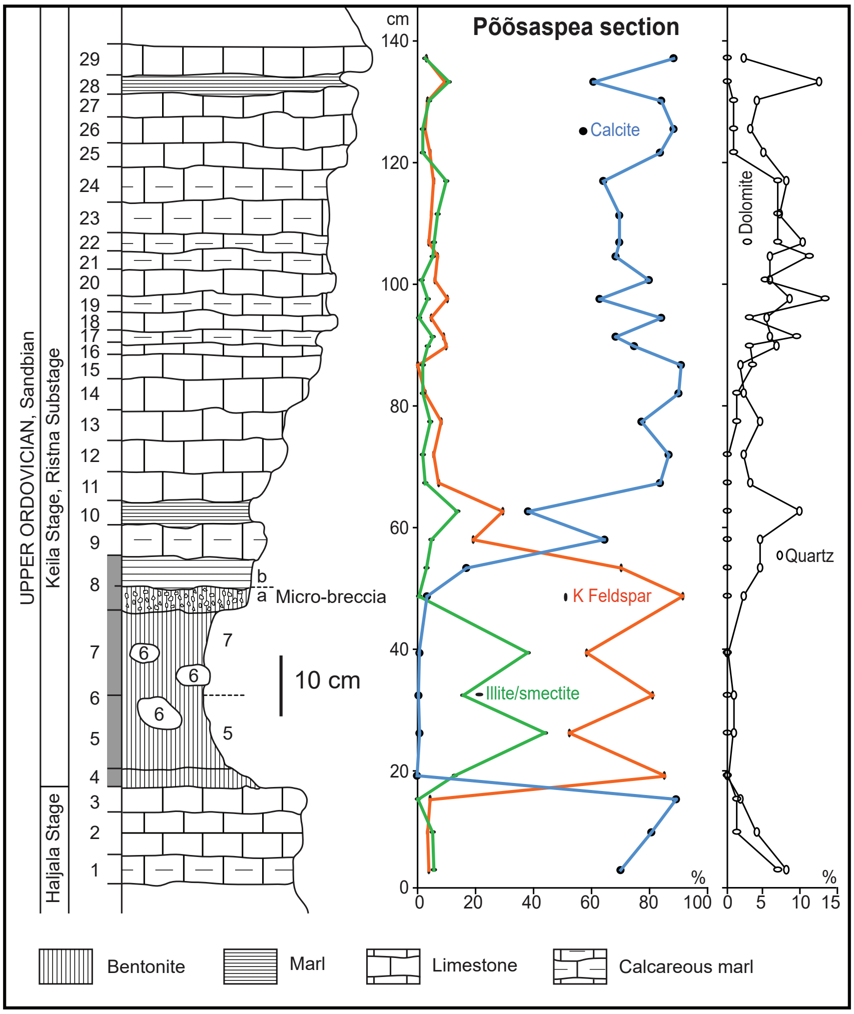

Fig. 4.8. Mineralogical composition of the Kinnekulle K-bentonite and adjacent limestones in the Põõsaspea section (after Perrier et al. 2012).

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Excursion Day 2

Stop 5: Harku quarry

Ursula Toom and Olle Hints

Location: Latitude 59.39837°N, longitude 24.56378°E; Harju County, northern Estonia.
Stratigraphy: Dapingian to Sandbian, Volkhov to Kukruse regional stages.
Status: Active quarry – follow safety instructions; sampling and fossil collecting welcome!
More information: https://geoloogia.info/en/locality/14672

The Harku quarry is an active limestone quarry located on the northwest edge of Tallinn, Hüüru Village, Harjumaa County. Investigations of Ordovician limestones as a building material near Tallinn intensified in 1933. Orviku (1940) gave the first description of the old Harku quarry, and since 1953, the Harku area has been continuously subject to mineral exploration. The company "Kombinaat No. 469" started quarrying limestone in 1984. Since 1994, the quarry has been operating under the company "Harku Karjäär AS". The limestone from the Harku quarry is mainly used to produce crushed stone for the construction industry. Today, the Harku quarry extends about 1.8 km in the N–S and 0.8 km in the W–E direction, being one of the largest limestone quarries in Estonia (Fig. 5.1).

The Ordovician rocks are exposed in a thickness of ca 14 m, constituting the entire Darriwilian succession and the lowermost beds of the Sandbian. The oldest strata are observable only in drainage ditches and occasional deeper excavations below the main quarry floor (Fig. 5.2). They include the topmost Toila Formation, Volkhov Regional Stage, Dapingian, and the complete Kunda Stage, Darriwilian. The main quarry walls (Fig. 5.3) constitute the Lasnamägi and Uhaku regional stages (Darriwilian), and the lowermost Kukruse Regional Stage (basal Sandbian).

Fig. 5.1. Overview of the southern part of the Harku limestone quarry. Photo: Gennadi Baranov, 2023.

The Middle Ordovician limestones are famous building stones around the Baltic Sea (Knaust 2021). They have been classically named 'Orthoceratite Limestones' due to their characteristic fossils, the orthocone cephalopods. The lower parts of the 'Orthoceratite Limestone' (corresponding to the Kunda Regional Stage, lower Darriwilian) are strongly dominated by endocerids (Kröger 2012). However, orthocerids are the dominant group in the Lasnamägi and Uhaku stages (upper Darriwilian). This is expressed in historical local stratigraphical terms such as the 'Endoceras Limestone' in the Oslo area, 'Vaginatumkalk' or 'Vaginatum limestone' in Sweden, 'Vaginatenkalk' in the East Baltic region and the southern coast of the Baltic Sea where the rocks are found as erratic boulders. These informal terms are occasionally still in use.

The 'Orthoceratite Limestone' lithofacies is widely interpreted as being deposited on a wide flat-bottomed, near-shore carbonate shelf. Water depth fluctuated but rarely fell below the photic zone (Jaanusson 1973; Chen & Lindström 1991). The concentration and distribution of cephalopod conchs in some beds indicate that these were deposited extremely rapidly. However, numerous significant breaks within the sequence are believed to represent periods of subaerial emergence. The average deposition rate of the 'Orthoceratite Limestone' was very low, perhaps 1–3 millimetres per thousand years (Jaanusson 1973).

Formations exposed in the Harku quarry

The Toila Formation (ca 0.4 m, Volkhov Regional Stage, Dapinginan) is composed of grey glauconitic limestones in the upper boundary, partly sandy or conglomeratic (Fig. 5.4D), which is assumed to represent the youngest part of the Toila Formation. The upper boundary of the formation (contact with the Pakri Formation) shows variable lithology in the Harku quarry, similar to what has been described from the Pakri Peninsula and Pakri islands, and, in particular, the Osmussaar Island (Alwmark et al. 2010).

The Pakri Formation (up to 0.2 m, Kunda Regional Stage, Darriwilian) comprises bioturbated limy sandstone to sandy limestone. The infill of burrows is brownish due to the admixture of kukersite (Fig. 5.4C, E). Calcareous sandstones of the Pakri Formation occur in a limited area in NW Estonia. Eastwards, the limestones of the Sillaoru and Loobu formations fully replace the Pakri Formation laterally. The Pakri formation is thin and irregular, partly occurring as bored sandstone pebbles with pyritic impregnation. The upper boundary of the formation is marked by bored pyritic hardground (Fig. 5.4B).

Fig. 5.2. The Volkhov and Kunda regional stages (Dapingian to lower Darriwilian) are cropping out only in ditches and few deeper excavations. Photo: Olle Hints, 2023.

The Pakri Formation contains numerous soft-sediment deformations, sedimentary dykes, and breccias. An earthquake (Põldsaar & Ainsaar 2014) or meteorite shower (Alwmark et al. 2010; Ainsaar et al. 2007) are discussed as possible causes for the liquefaction and fluidisation of the unconsolidated and water-saturated sediments.

The Loobu Formation (ca 0.2 m, Kunda Regional Stage, Darriwilian) consists of limestone with fine pyritic skeletal sand with rare glauconite grains. Numerous

Fig. 5.3. The main wall in the southern part of the Harku limestone quarry is exposing the succession from the Aseri Regional Stage to the basal part of the Kukruse Regional Stage (correlated with the base of the Sandbian), including complete Lasnamägi and Uhaku regional stages (Väo and Kõrgekallas formations). Photo: Gennadi Baranov, 2023.

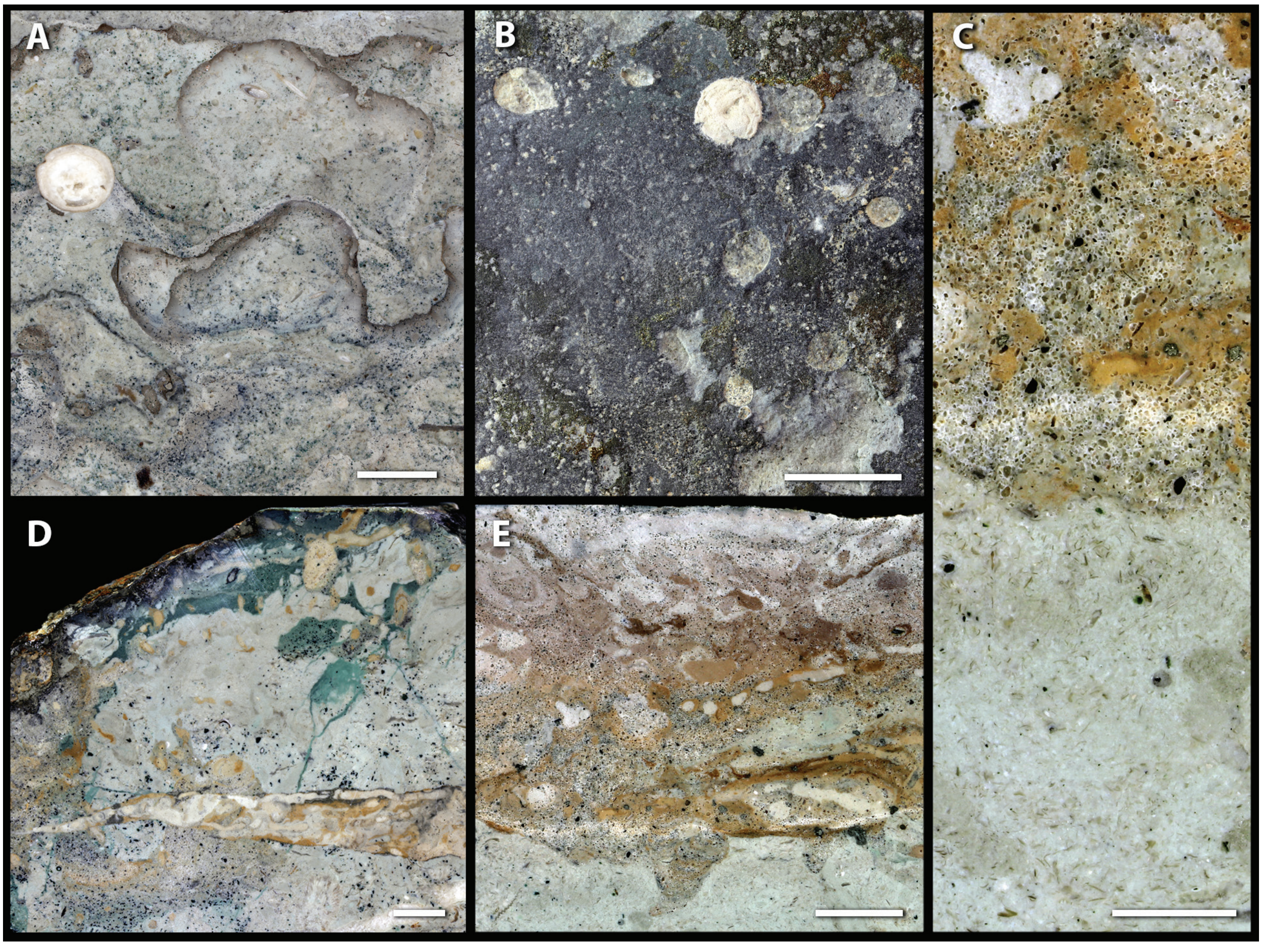

Fig. 5.4. Selected samples of Darriwilian limestones from the Harku quarry. Scale bars: A, D, E – 1 cm, B, C – 5 mm. **A** – rough discontinuity surfaces with phosphatic impregnation characteristic for the Loobu Formation, GIT 695-58-1; **B** – hardground with strong pyritic impregnation on the top of the Pakri Formation, demonstrating *Trypanites* borings and small bryozoan holdfast, GIT 362-925; **C** – detail from the Toila and Pakri formations boundary bed marked by wavy surface, GIT 362-717; **D** – vertical section from the top of the Toila Formation demonstrates partly sandy and conglomeratic glauconitic limestones with strong pyritic hardground, detail from GIT 362-922; **E** – bioturbated limy sandstone of the Pakri Formation in total thickness, GIT 362-922.

rough discontinuity surfaces with phosphatic impregnation can be observed (Fig. 5.4A). The boundary between the Loobu and Kandle formations in the Harku quarry is marked by an even phosphatic hardground surface with deep burrows (Fig. 5.5D).

The Kandle Formation (ca 0.3–0.4 m, Aseri Regional Stage, Darriwilian) consists of bioclastic limestones with unevenly distributed brown iron ooids. The upper boundary of the formation is marked by an uneven discontinuity surface and is overlain by hard and unsorted skeletal limestone with numerous small light phosphatic ooids (cf. Sturesson and Bauert 1994) in the basal portion (Fig. 5.5H).

The Väo Formation (ca 5 m, Lasnamägi and Uhaku regional stages, Darriwilian) consist of medium to thick-bedded light grey limestones (wacke- to packstones) with occasional interbeds of brownish dolostones with a large number of burrowed discontinuity surfaces and bored and burrowed hardgrounds (Fig. 5.5B). The Väo Formation is subdivided into three members; the middle and upper members represent the 'Lasnamägi Building Limestone'. The most remarkable complex of discontinuity surfaces and hardgrounds marks the upper boundary of the Väo formation (Fig. 5.5C). The boundary between the Lasnamägi and Uhaku stages can be identified biostratigraphically using the FAD of *Gymnograptus linnarssoni* or FAD of the conodont *Baltoplacognathus robustus*. It falls into the Väo Formation and is marked by a discontinuity surface within the bed named 'Raudsüda'.

The Kõrgekallas Formation (ca 6.5 m, Uhaku Regional Stage, Darriwilian) is represented by wavy-bedded to seminodular argillaceous limestone. Impregnated and bored discontinuity surfaces and hardgrounds are characteristic, but less common than in the Väo Formation. In the upper part of the formation, kukersite kerogen occurs as infill of borings (Fig. 5.5A) and thin layers.

The Viivikonna Formation (1.5 m?, Kukruse Regional Stage, Sandbian) is represented in the Harku area by marly limestones with thin beds and dispersed kukersite kerogen. It is tentatively identified in the southern part of the quarry, but the beds are weathered and not easily accessible due to the high quarry walls. Moreover, the whole succession still awaits biostratigraphic study.

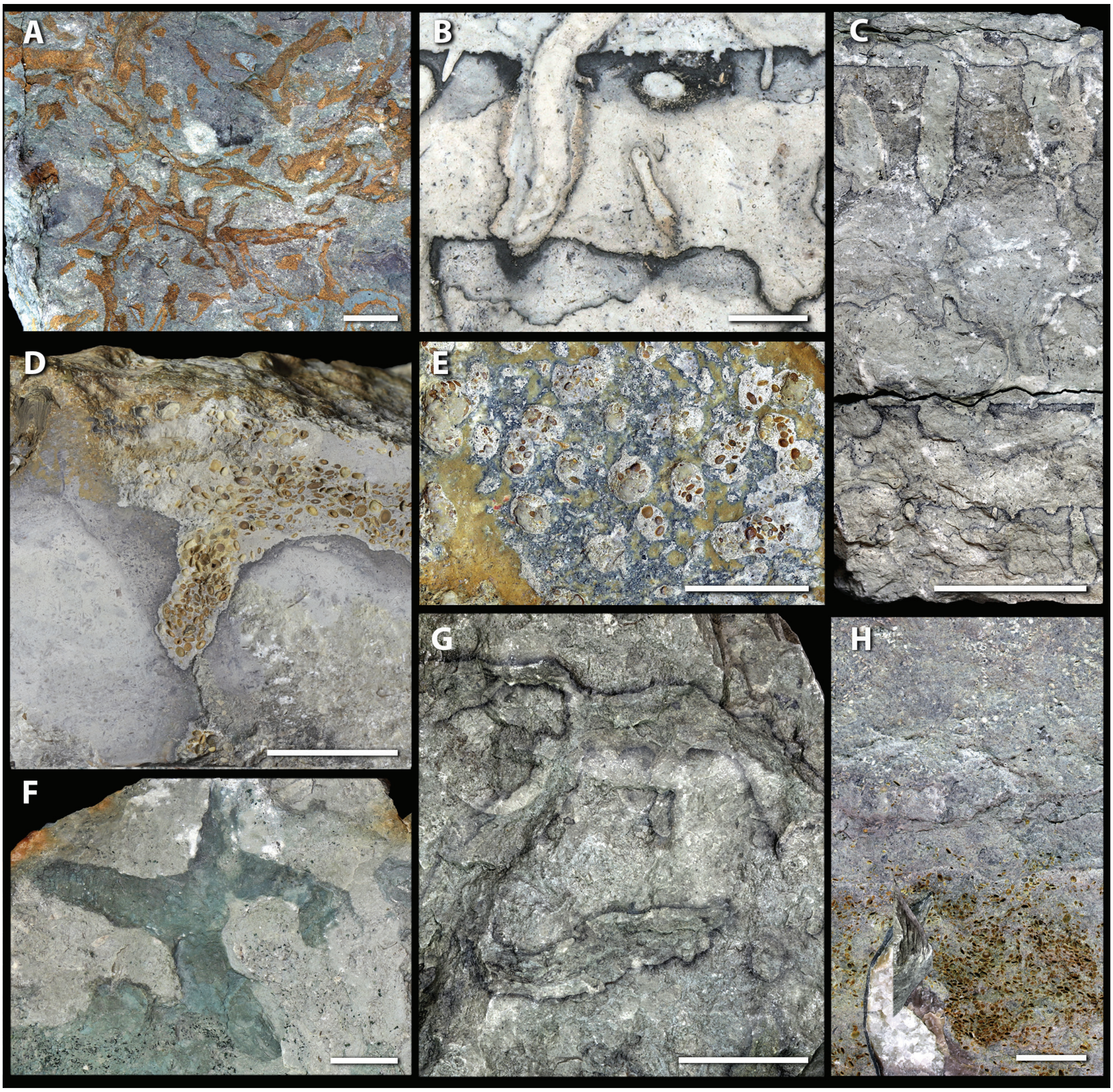

Fig. 5.5. Selected samples of Darriwilian limestones from the Harku quarry. All scale bars are 1 cm, and only B is 5 cm. **A** – *Chondrites* borings filled with kukersite, Kõrgekallas Formation, Pärtilioru Member, GIT 362-972-1; **B** – detail of burrowed and bored pyrite-stained hardgrounds, Väo Formation, GIT 362-720; **C** – complex of discontinuity surfaces and hardgrounds with *Balanoglossites triadicus* burrows and *Trypanites sozialis* borings, from the boundary beds of Väo and Kõrgekallas formations, GIT 362-915; **D** – *Balanoglossites triadicus* burrow from Loobu and Kandle formations boundary bed, filled with brown iron ooids, GIT 362-920; **E** – bedding-plane view of Loobu and Kandle formations boundary bed. Dense accumulation of *Trypanites sozialis* borings on top of the surface, borings are filled with iron ooids, GIT 362-917; **F** – bedding-plane view of *Balanoglossites triadicus* filled with glauconite, Toila Formation, GIT 362-920; **G** – bedding-plane view of *Balanoglossites triadicus*, Loobu Formation, GIT 362-921; **H** – upper boundary of the Kandle Formation, demonstrating brown iron ooids of the Kandle Formation and light phosphatic ooids of the Väo Formation, sample GIT UT23-1.

Ichnofabrics with *Balanoglossites* and *Trypanites*

Ichnofabrics with *Balanoglossites* and T*rypanites* are typical of the Darriwilian limestones in Estonia (Knaust et al. 2023). *Balanoglossites triadicus* show U- and Y-shaped components in cross-section, irregular outline, highly variable tube diameter, and net-like appearance on the bedding planes (Fig. 5.5B, C, D, F, G). The trace maker could simultaneously bioerode and burrow (Knaust & Dronov 2013). Short and straight *Trypanites sozialis* borings (Fig. 5.5B, E; 5.4B) are common on the hardgrounds. Usually, the borings are densely placed on positive features of the surface topography.

Macrofauna

In the outcrop area, large nautiloids are characteristic of the Loobu Formation. The trench in the Harku quarry is well-known for yielding excellent phosphatised cephalopod remains of the Kunda Regional Stage (e.g., Mutvei

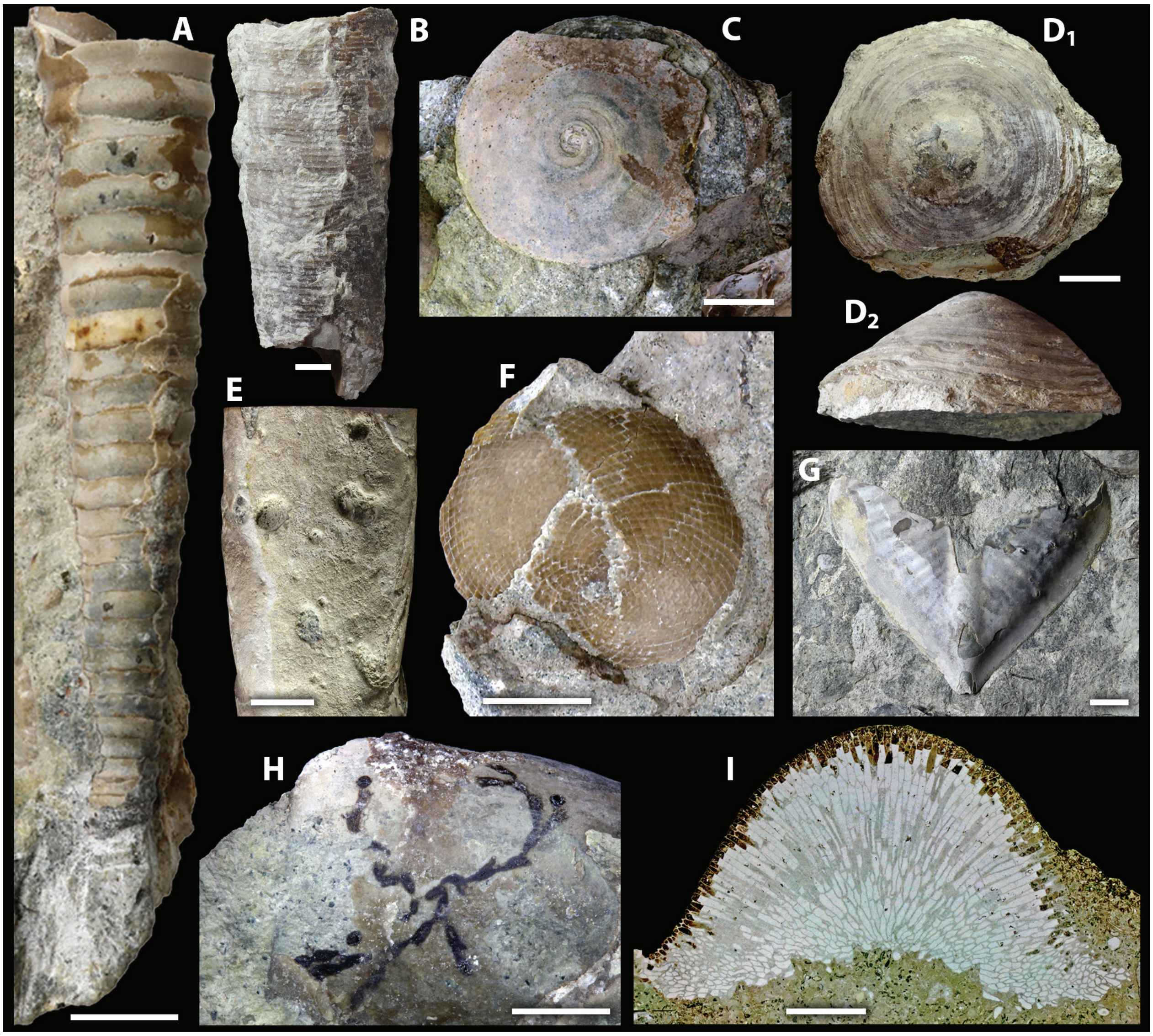

Fig. 5.6. Selected fossils from the Harku quarry, Loobu Formation (Darriwilian). Scale bars: A, C, D, F, G – 1 cm; B, E, H, I – 1 mm. **A–B** – cephalopods; **A** – *Proterovaginoceras incognitum*, TUG 1612-32; **B** – *Anthoceras vaginatum*, GIT 695-53. **C** – gastropod *Pararaphistoma qualteriata*, TUG 1585-71. **D** – monoplacophorian *Metoptoma siluricum*, GIT 815-2. **E** – steinkern of *Proterovaginoceras incognitum* with *Trypanites sozialis* borings, GIT 858-7. **F** – retceptaculitid *Fisherites orbis*, TUG 1644-8. **G** – trilobite *Megistaspis* (*Heraspis*) *heroica*, 398-950-1. **H** – graptolite *Hormograptus*? attached to the internal surface of a nautiloid conch, GIT 494-41-1. **I** – bryozoan *Dianulites collucatus*, GIT 494-41-1.

1996, 1997, 2002; Kröger 2012; King 2014; Pohle et al. 2019). Endocerids *Anthoceras vaginatum*, *Dideroceras wahlenbergi* and *Suecoceras barrandei*; bisonoceratid *Proterovaginoceras incognitum*; ormocerid *Adamsoceras holmi* and tarphycerids *Tragoceras falcatum* and *Estonioceras* are reported from the Loobu Formation. Lithified steinkerns exposed on the seafloor were colonised by boring organisms or filled with small faecal pellets of *Coprulus oblongus*. Large shells of Ordovician cephalopods host cryptic faunas, mainly represented by bryozoans and cornulitids. From the Harku quarry a rare crustoid graptolite *Hormograptus*? lithoimmured inside a nautiloid conch was described (Vinn et al. 2019). Bryozoans are not common, but recent study by Ernst (2022) brought out five genera (*Dianulites collucatus, Revalotrypa gibbosa, Mesotrypa bystrowi, Orbipora acanthophora, Orbipora* aff. *distinca* and *Sonninopora*). Due to phosphatisation, not only nautiloid shells, but also gastropods (e.g., *Pararaphistoma qualteriata* and *Salpingostoma locator*, retseptaculitids (*Fischerites orbis*), and rare tergomyans (e.g., *Metoptoma siluricum*) are exceptionally well preserved. Trilobites are abundant in the upper part of the Loobu Formation. Helje Pärnaste has identified *Megistaspis (Heraspis) heroica* and *Pterygometopus sclerops.*

Rõõmusoks (1970) listed various macrofossils from the Lasnamägi and Uhaku regional stages from the Harku area. The faunas were dominated by sedentary forms, particularly articulate brachiopods e.g., *Christiania oblonga, Clitambonites schmidti septatus, Clitambonites squamatus*, *Porambonites* (*Equirostra*) *deformatus*, *Estlandia marginata marginata*, *Leptestia musculosa, Orthisocrania planissima*, Sowerbyella (*Sowerbyella*) *orvikui*, *Sowerbyella* (*Sowerbyella*) *uhakuana*. In addition, bryozoans, orthocerid cephalopods, and blastozoan *Echinosphaerites* occur.

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Stop 6: Vasalemma quarry

Björn Kröger and Ursula Toom

Location: Latitude 59.23337°N, longitude 24.33032°E; Harju County, NW Estonia.
Stratigraphy: Early Katian, Keila to Rakvere regional stages, Kahula and Vasalemma formations.
Status: Active quarry; please follow safety instructions. Sampling and fossil collecting are welcome!
More information: https://geoloogia.info/en/locality/12431

The Vasalemma quarry is an active quarry located c. 28 km south-west of Tallinn, near Keila, Harju County. The large quarry exposes in its northern part, mainly the Kahula Formation, and in its southern part, the Vasalemma Formation, Keila Regional Stage (Sandbian, Ordovician). Locally, the overlying strata of the Oandu and Rakvere regional stages (Katian, Ordovician) are exposed.

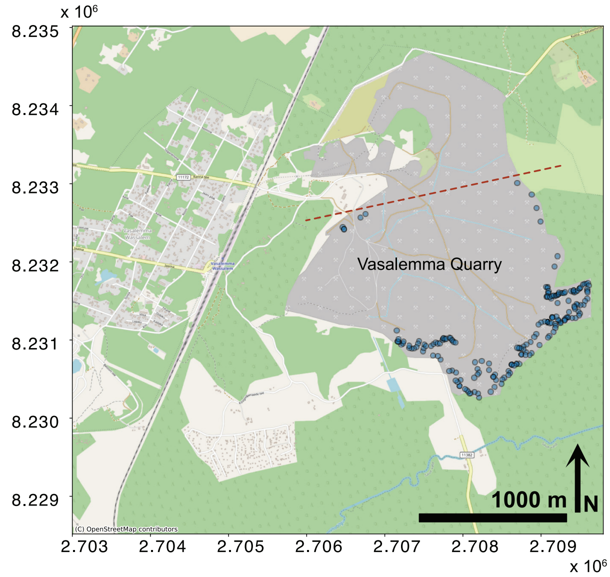

Fig. 6.1. Vasalemma quarry with mapped reef positions (blue dots) (westernmost corner of the quarry is unmapped). Red line indicates the maximum northward extension of the Vasalemma Formation, late Sandbian. Coordinate system: Web Mercator.

History

The echinoderm limestone of the Vasalemma Formation has been quarried for centuries and is known in the region as the "Vasalemma Marble". The limestone was described and named in a stratigraphical context by Eichwald (1854) and Schmidt (1881). The names "Hemicosmitenkalk" (Eichwald 1854) and "cystoid limestone" (Männil 1960) refer to the rock-building abundance of echinoderm intraclasts (mainly of the genus *Hemicosmites*, Rhombifera). Within the massive echinoderm limestone beds, echinoderm-bryozoan-receptaculitid reefs are abundant (Fig. 6.1). Together, the echinoderm grainstone and the reefs form the "Wasalemm'sche Schicht" of Schmidt (1881), which is synonymous with the Vasalemma Formation of subsequent authors (e.g., Männil and Rõõmusoks 1984; Hints and Midel 2008).

In Schmidt's system, the Vasalemma Formation was designated as D3, the topmost layer of sequence D, and thus formed the stage above the "Kegel'sche Schicht" (Keila Regional Stage, D2). In a series of field guides, Linda Hints and colleagues (Hints 1990, 1996; Hints et al. 2004; Kröger et al. 2014b) published several drill core sections and outcrop details. A comprehensive review and reappraisal of the stratigraphy and sedimentology of the formation was published by Kröger et al. (Kröger et al. 2014b, 2014c). Today, the Vasalemma Formation is stratigraphically placed within the Keila Regional Stage, being of late Sandbian age (Meidla et al. 2023).

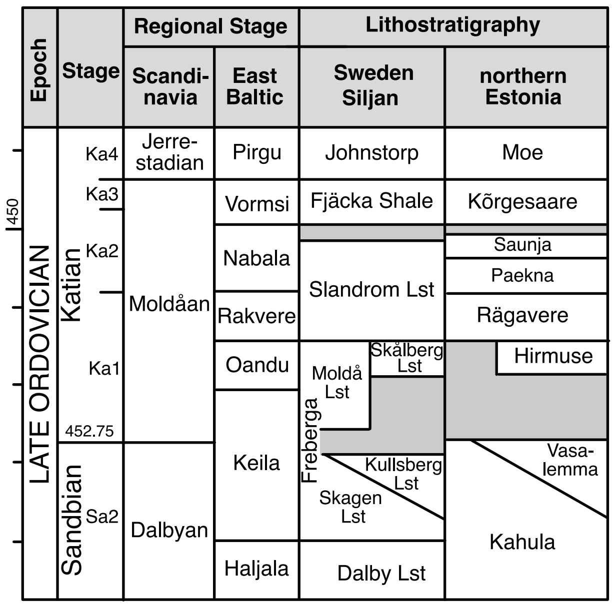

Fig. 6.2. Stratigraphic scheme of early Late Ordovician in northern Estonia compared with selected units from Scandinavia. Lithostratigraphic units are formations if not otherwise marked. Subdivisions in Stage column are Ordovician time slices (after Bergström et al. 2009). Compiled from Calner et al. (2010), Meidla et al. (2023), Nielsen et al. (2023). Lst, Limestone. Regio., Regional. Numbers give Million years ago. Grey fields are sedimentary hiati.

Stratigraphy

The Vasalemma Formation is a partly discontinuity-bounded unit. The lower and the upper boundaries are diachronous. From the combined drill core and outcrop data, it is known that in the southern part of the Vasalemma quarry, the base is marked by a prominent hardground on top of the Pääsküla Member, Kahula Formation (Kröger et al. 2014b, 2014c). In other places, the base is less than a few meters above this hardground, within the overlying Saue Member of the Kahula For-

Fig. 6.3. A latest Sandbian reef body in the southern wall of the Vasalemma quarry, North Estonia. Photo: Olle Hints, 2023.

mation (Kröger et al. 2014a). Laterally the echinoderm limestone of the Vasalemma Formation grades into the skeletal wacke- to packstone lithologies of the Saue and Lehtmetsa members of the Kahula Formation. This gradual lateral change is exposed along the kilometre-long quarry wall of the Vasalemma quarry.

The top of the formation is formed by a distinct hardground surface on top of the reefs, which locally also represents an erosional surface, which cuts into the reefs and the echinoderm limestone. This upper surface is overlain by the argillaceous sediments of the Hirmuse Formation, Oandu Regional Stage, or locally by yellowish micritic limestone of the Rägavere Formation (Kröger et al. 2014a, 2014c).

The Vasalemma Formation is within the *Amorphognathus tvaerensis* conodont zone (Männik 2017). $\delta^{13}C_{carb}$ data from drill cores of the Vasalemma Formation record the rising limb of the upper Sandbian Guttenberg Isotopic Carbon Excursion (GICE; see e.g., Meidla et al. 2023) and a sharp drop of values at its upper discontinuity, indicating that the main interval of the GICE is younger than the formation (Fig. 6.2; Kröger et al. 2014a, 2014c).

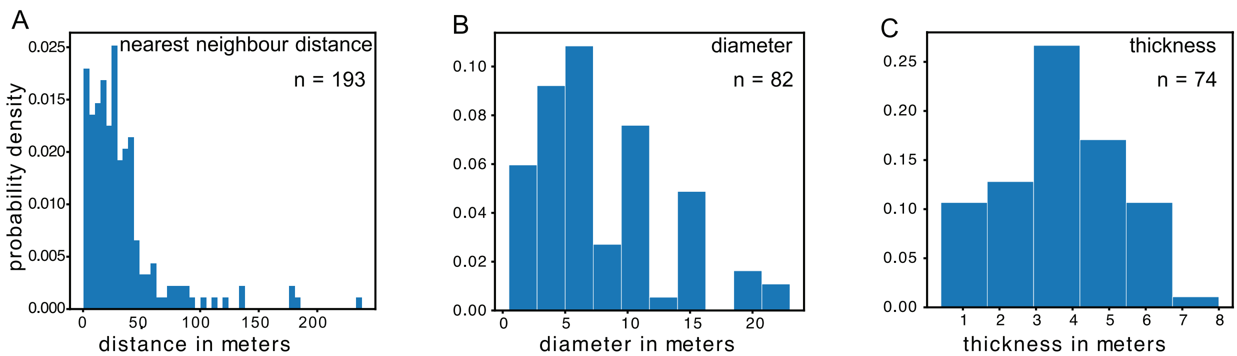

Fig. 6.4. Histograms of selected features of the reefs of the Vaselemma quarry, Vasalemma Formation, late Sandbian. **A** – Nearest neighbour distance; **B** – Reef diameter; **C** – Reef thickness.

Geological Setting and Sedimentology

The Vasalemma Formation occurs along c. 20 km E–W stretched belt with a N–S extension of c. 5 km. Toward the north, it is partly limited by an erosional front. The formation has a thickness of up to 15 m and consists mainly of a massive echinoderm grainstone with, in its central areas, concentrations of patch reefs. The echinoderm limestone is a massively bedded grainstone, almost completely composed of *Hemicosmites* ossicles held together by syntaxial cement (Fig. 6.5C). Ripple waves and crossbedding are widespread features within

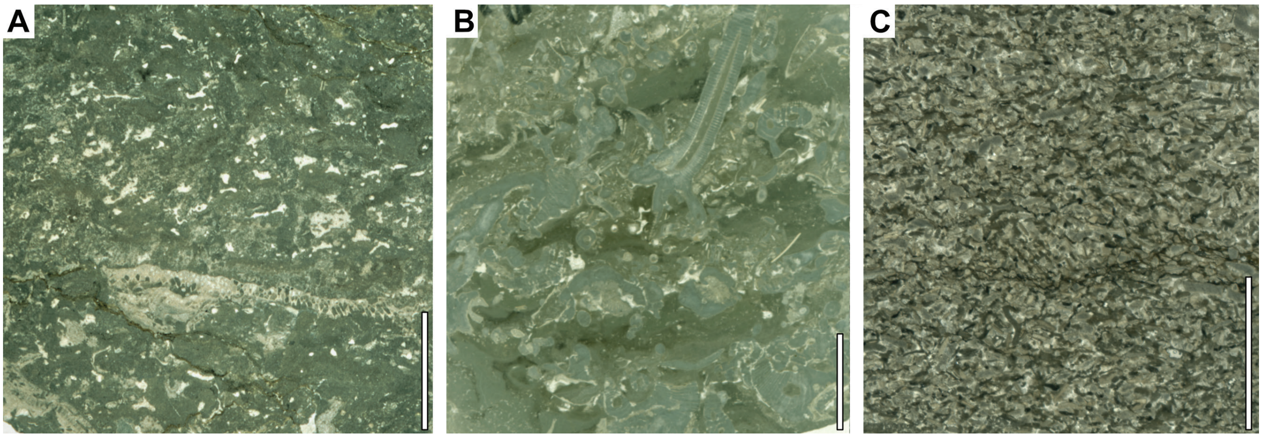

Fig. 6.5. Examples of microfacies of Vasalemma Formation, late Sandbian. **A** – Reef core limestone with encrusting bryozoan and clotted micrite as matrix; **B** – Reef core with abundant *Hemiscosmites* roots and clotted micrite as matrix; **C** – *Hemicosmites* grainstone with syntaxial cements. Note the abundance of sparitic fenestrae in A and B. Scale 10 mm.

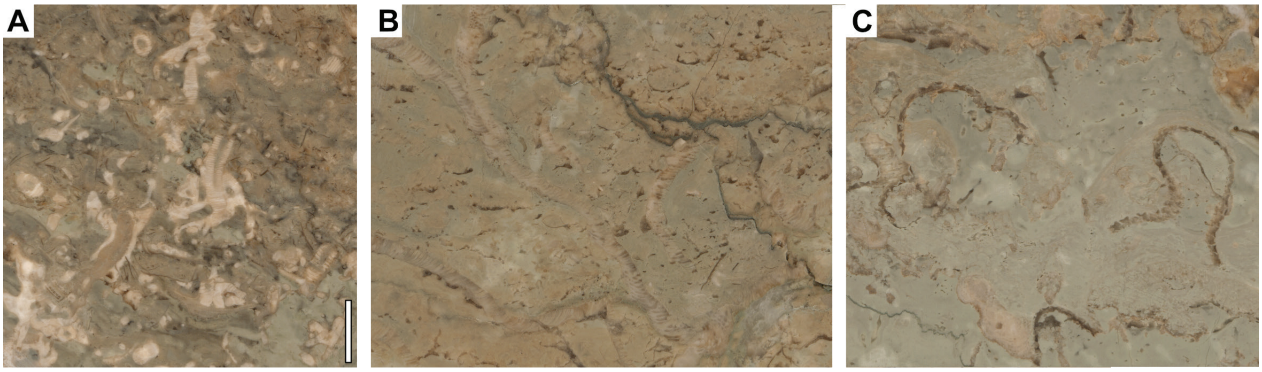

Fig. 6.6. Examples of polished slabs of reef core facies from Vasalemma quarry, Vasalemma Formation, late Sandbian; **A** – Area with abundant *Hemicosmites* roots; **B** – Area with abundant encrusting bryozoan colonies; **C** – Area with abundant receptaculitids. Scale 10 mm in A–C.

the echinoderm limestone. The reefs are up to c. 10 m thick and up to 50 m wide, and their cores are formed by a matrix-rich boundstone (50–80% matrix), with abundant echinoderms, bryozoans, and receptaculitids as main skeletal components and abundant fenestral fabric (Kröger et al. 2014a) (Fig. 6.5A–B, 6.6). Associated with the reef cores are commonly pockets, preserving locally restricted siliciclastic (marl, silt) and microbial limestone facies. In the north-eastern part of the quarry, the base of the formation forms the top hardground of the Pääskula Member, which here exposes a ripple surface and which is partly highly bioeroded with borings of *Trypanites*. The ripple-marks have a mean wavelength of c. 0.4 m and a NE/SW direction (Hints & Miidel 2008). The top of the Vasalemma Formation is formed by an iron (pyrite) impregnated and bioeroded hardground and erosional surface, which is locally covered by a conglomerate with highly rounded, pyrite-impregnated clasts from the Vasalemma Formation.

Sea level and paleoclimate

The top Vasalemma discontinuity reflects a major regional sea level drop (corresponding to the base of the depositional sequence VIII of Dronov et al. 2011, the Lower Wesenberg Sequence of Dronov 2017, and the Frognerkilen Lowstand Event of Nielsen 2011). This discontinuity and its associated facies and faunal change mark a massive change in the regional sedimentation regime and faunal composition during the late Keila to Rakvere time that has been termed Mid-Caradoc Event (Meidla et al. 1999) or Middle Caradoc Facies and Faunal Turnover (Ainsaar et al. 2004). The interval has been interpreted as related to climate change and associated changes in ocean circulation (Ainsaar et al. 2004). Oxygen isotope data suggest that the Mid-Caradoc Event (late Haljala – Keila stage) was an interval of global cooling that climaxed during the Frognerkilen Lowstand Event (Männik et al. 2021).

Fauna

The Vasalemma Formation contains extraordinarily rich and abundant fauna. Dozens of species of bryozoans were described from the Vasalemma Formation by Bassler (1911), Männil (1959), Modzalevskaya (1953),

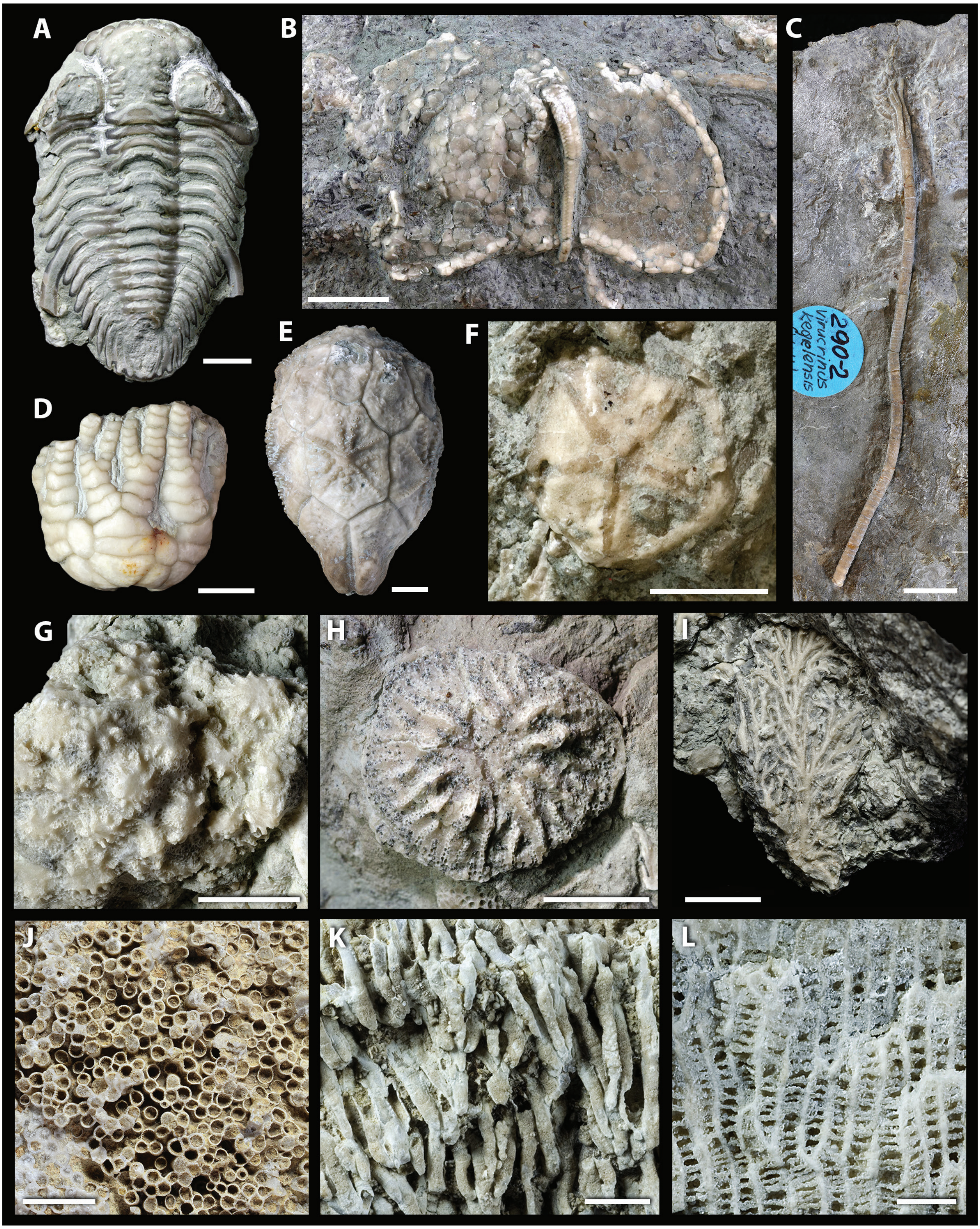

Fig. 6.7. Selected fossils from the Vasalemma quarry, Vasalemma Formation (Katian). Scale bars: A, D–H, L – 5 mm; B, C, I–K – 1 cm. **A** – trilobite *Atractopyge kutorgae*, TUG 1393-1. **B** – solutan echinoderm *Maennilia estonica*, GIT 609-1-1. **C**, **D** – crinoids; **C** – *Virucrinus kegelensis*, GIT 290-2; **D** – *Tintinnabulicrinus estoniensis*, GIT 653-3. **E** – blastozoans *Hemicosmites*, GIT 633-206. **F** – edrioasteroid *Cyathocystis rhizopora*, GIT 643-11-1. **G**, **I** – bryozoans; **G** – *Revalopora revalensis*, GIT 222-202; **H** – *Inconobotopora*, GIT 222-205; **I** – *Phylloporina*, GIT 222-204. **J**, **K**, **L** – tabulate corals; **J**, **K** – *Eoflecheria orvikui*, **J** – GIT 180-94, **K** – GIT 94-10; **L** – *Saffordophyllum tulaensis*, GIT 94-10.

Pushkin (1990) and Gorjunova & Lavrentjeva (1993). A thorough revision of the bryozoan fauna is still needed. The echinoderm fauna is strongly dominated by *Hemicosmites*, but locally edrioasteroids (*Cyathocystis*, Rozhnov 2004), rare solutans (Rozhnov & Jeffries 1996), asteroids (Blake & Rozhnov 2007) and crinoids (Ausich et al. 2015; Rozhnov 1990, 2012; Wright & Toom 2019) are worth mentioning. The reefs of the Vasalemma Formation contain rugose corals, such as *Lambelasma carinatum* which are among the oldest of the region.

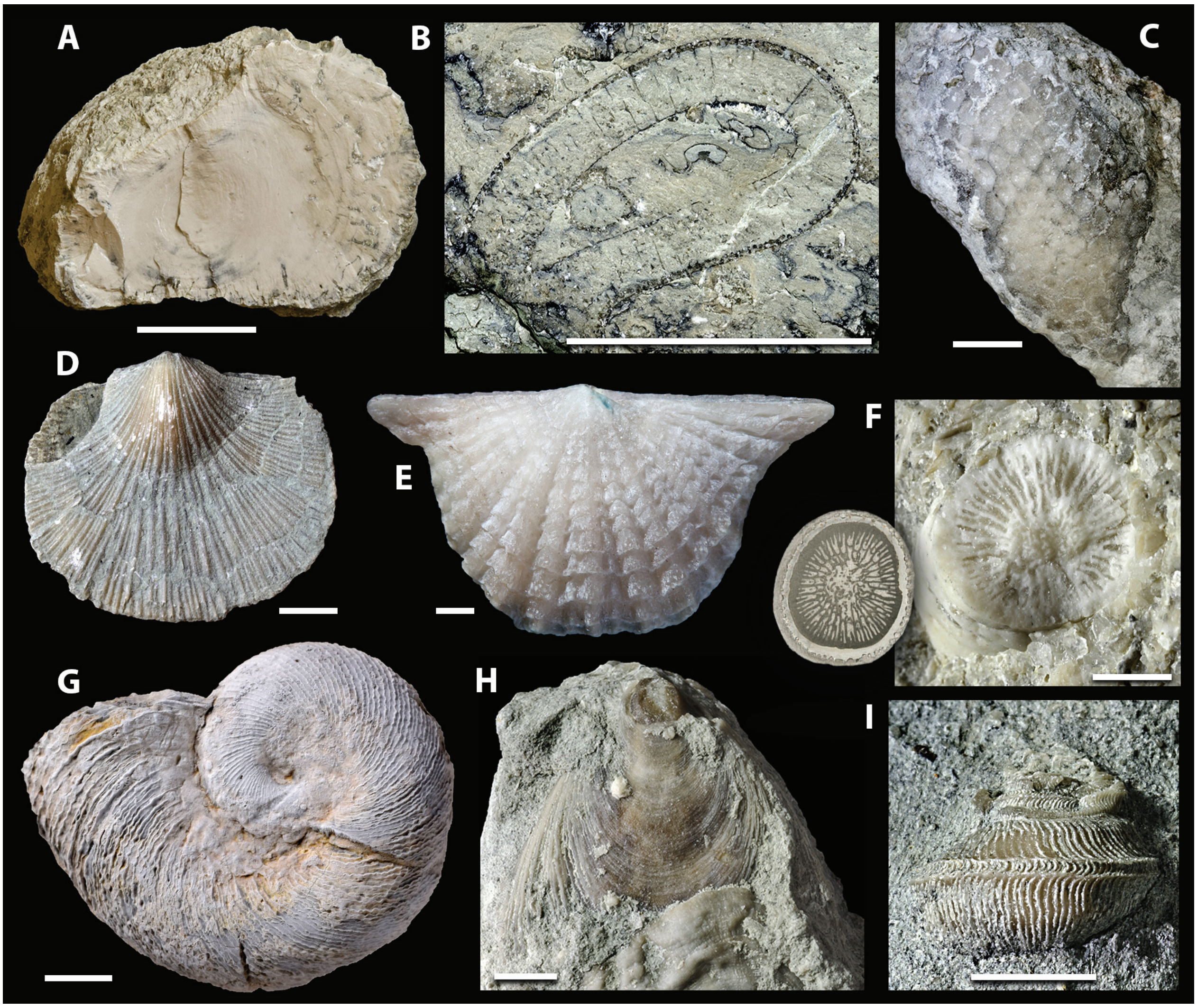

Fig. 6.8. Selected fossils from the Vasalemma quarry, Vasalemma Formation (Katian). Scale bars: A–D, F–J – 5 mm, E – 1 mm. **A** – *Solenopora*, GIT 339-1043. **B,C** – retceptaculitid *Receptaculites poelmi*; B – GIT 413-166, C – GIT 413-163. **D, E** – Brachiopods; D – *Horderleyella kegelensis*, GIT 207-2021; **E** – *Bassetella alata*, GIT 595-1. **F** – rugose coral *Lambelasma carinatum*, TUG 1393-7. **G** – cephalopod *Discoceras vasalemmense*, TUG 939-76. **H** – monoplacophorian *Pilina*, GIT 222-122-1. **I** – gastropod *Brachytomaria baltica*, GIT 222-114.

Receptaculites poelmi from the Vasalemma Formation has been described by Miagkova (1981). The chaetetid sponge *Solenopora* is locally common within the reefs. Bryozoans, echinoderms, receptaculitids and *Solenopora* form complex, partly densely intergrown assemblages (Vinn et al. 2018). Locally, the uppermost sections of the reefs contain large colonies of tabulate corals *Eofletcheria orvikui*, *Saffordophyllum tualensis* and *S. grande* (Klaamann 1975); also crusts of stromatoporoids such as *Cystistroma sakuaense* occur. The reefs contain a rich macrofauna with monoplacophorans (*Pilinia* sp.) and gastropods (*Brachytomaria baltica* and *Cyclonema lineatum*). The trilobites of the Vasalemma Formation are not systematically studied yet but the most common representatives include *Asaphus, Chasmops, Stenopareia* and *Toxochasmops*. A rich cephalopod fauna has been described by Kröger & Aubrechtová (2017). Cephalopods, trilobites and echinoderms occur frequently as concentrations in pockets associated with the reefs. Dense cornulitid infestations of the reef and echinoderm-limestone on the capping hardground surface are remarkable (Vinn & Toom 2015). In addition, the Hirmuse Formation contains a rich association of cornulitids and other calcareous tubicolous organisms (Vinn et al. 2023). Brachiopods *Estlandia pyron silicificata, Bassettella alata, Saukrodictya, Horderleyella kegelensis,* and *Apatorthis* sp. occur mainly in the argillaceous interlayers of the lower half of the Vasalemma Formation. Additionally, two forms of noncalcified algae have been discovered from dolomitic mudstone layers associated with the reefs.

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Stop 7: Sutlema quarry

Björn Kröger and Ursula Toom

Location: Latitude 59.17410°N, longitude 24.61958°E; Rapla county, central northern Estonia.
Stratigraphy: mid-Katian, Nabala and Vormsi regional stages, Saunja and Kõrgessaare formations.
Status: Active quarry, follow safety rules; sampling and fossil collecting welcome!
More information: https://geoloogia.info/en/locality/16318

The Sutlema quarry is an active quarry c. 30 km south of Tallinn, west of Kohila, Rapla County (Fig. 7.2). The quarry exposes the upper c. 7 m of the Nabala Regional Stage and c. 4 m of the overlying Vormsi Regional Stage, middle Katian (Fig. 7.1). The Sutlema quarry is operated by the company "Kiirkandur AS"; the production is mainly used for road construction.

Stratigraphy

The boundary between the Nabala and Vormsi regional stages in northern Estonia is marked by a prominent discontinuity surface, interpreted as a paleo-karst horizon (Calner et al. 2010). The massive limestone underlying the discontinuity surface belongs to the Saunja Formation, and the relatively high $\delta^{13}C_{carb}$ values (up to 2.39 ‰, Meidla & Ainsaar 2014) are indicative of the Saunja Carbon Isotope Excursion (Baltic Chemostratigraphic Zone BC10, Ainsaar et al. 2010). The Saunja Excursion has been correlated with the middle Katian Waynesville Excursion in North America (Bergström et al. 2012; Meidla & Ainsaar 2014). The overlying strata of the Vormsi Regional Stage correspond to the middle Katian *Amorphognatus ordovicicus* Conodont Zone (Meidla et al. 2023).

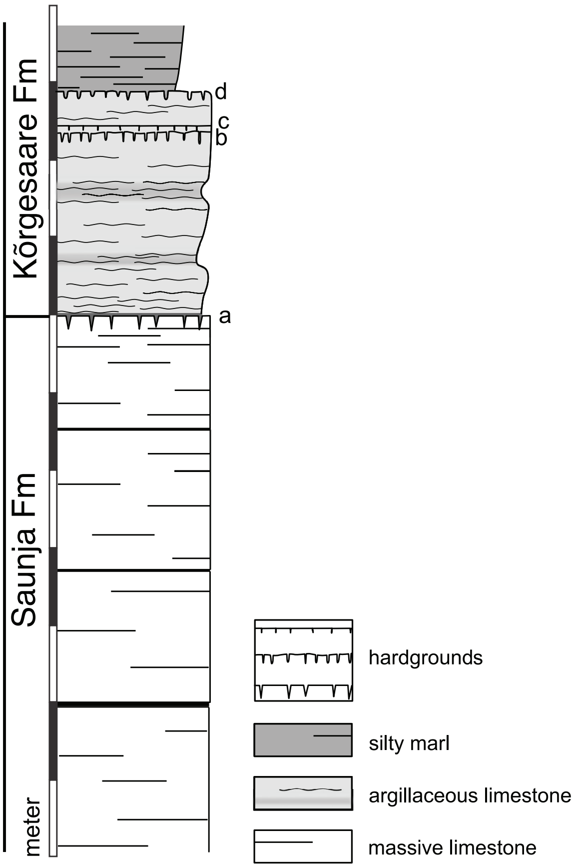

Fig. 7.1. Stratigraphy and lithology of the Sutlema quarry outcrop. Abbrevations: Fm, formation; a-d, denote individual hardground horizons.

Fig. 7.2. Overview of the Sutlema quarry, showing mining of the Saunja limestone (carbonate mudstone), Nabala Regional Stage, Mid-Katian. Photo: Olle Hints, 2022.

Sedimentology

Saunja Formation

The Saunja Formation at Sutlema consists of bedded (10–40 cm), fine-grained (lithographic), and bioturbated limestone with very thin (<1 cm) interlayers. Few interlayers with thickness of more than one centimetre can be used to distinguish individual 1–2 m thick strata within the formation. Rhythmic bedding of argillaceous and carbonaceous beds is visible on fresh quarry walls (Fig. 7.3A, 7.4). Similar limestone and marl alternations are interpreted as resulting from diagenetic processes (Munnecke et al. 2023). The microfacies can be described as a lime-mudstone to skeletal grainstone with common echinoderm ossicles, microgastropods and fragments of bryozoans and skeletal green algae (Fig. 7.3). The lithology of the Saunja Formation has been described as Baltic limestone facies, in which calcitarchs are common (Kröger et al. 2019). At Sutlema, the abundant and well-preserved burrows of, e.g., *Chondrites*, *Phycodes* and *Planolites* are remarkable (Fig. 7.7C).

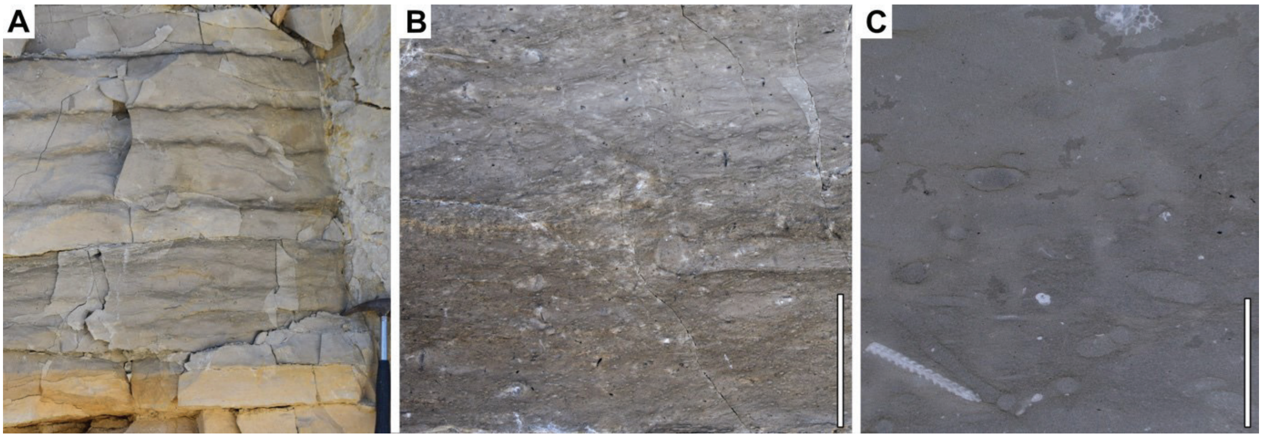

Fig. 7.3. Burrowed limestone of the Saunja Formation, Nabala Regional Stage, Katian, from the Sutlama quarry, Estonia. **A** – field perspective of a fresh outcrop; **B** – Detail of A, note the nested burrow pattern, scale 5 cm; **C** – thin section, with a fragment of brachiopod (lower left), *Coelospheridium* sp. (upper margin), and a micro-gastropod (center right), scale 5 mm.

Fig. 7.4. Limestone of the Saunja Formation, Nabala Regional Stage, Katian, from the Sutlema Quarry, Estonia. Photo: Olle Hints, 2020.

Kõrgessaare Formation

The Kõrgessaare Formation at Sutlema consists of a grey to greenish coloured, wavy bedded to nodular limestone-marl alternation of argillaceous skeletal wackestone (Fig. 7.5, 7.6) and marl. The base of the formation is a flat discontinuity surface formed by a hardground on the top of the Saunja Formation. This hardground is heavily burrowed and bored by *Balanoglossites* and *Trypanites* trace-makers and shows signs of karstification (Fig. 7.7B). The burrows reach down to 7 cm into the Saunja Formation and are partly filled with argillaceous wackestone of the Kõrgessaare Formation. The exposed part of the Kõrgessaare Formation consists of a thickening-up sequence with a series of prominent hardgrounds at its top (levels b, c, d in Fig. 7.1). The

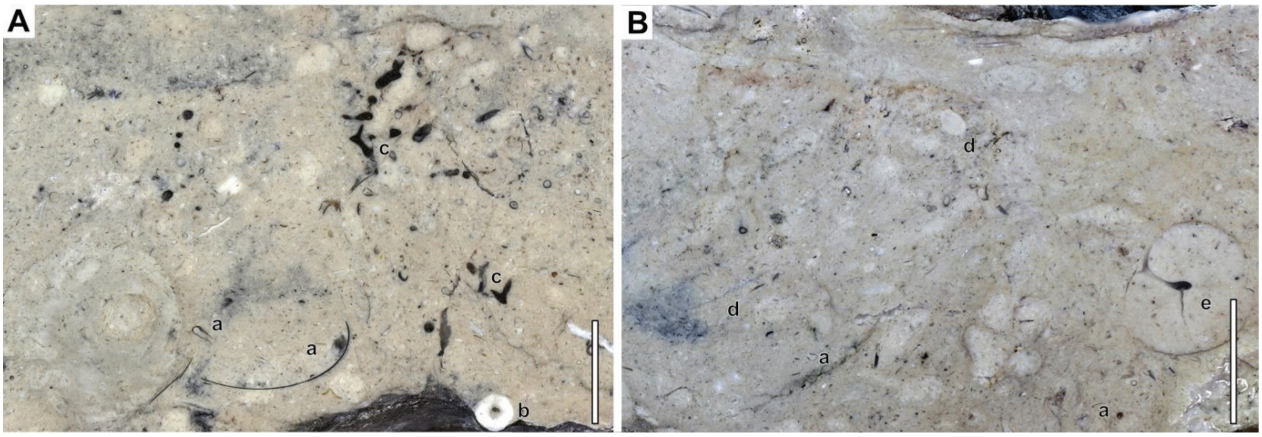

Fig. 7.5. Polished cross section of a burrowed skeletal wackestone from c. 1 m above base of the Kõrgessaare Formation, Vormsi Regional Stage, Katian, from the Sutlama quarry, Estonia. **A** – Detail with abundant trilobite carapace fragments (a), echinoderm ossicle (b) and a hydroid? Colony (c); **B** – Detail with abundant trilobite carapace fragments, bryozoan colony (d) and gastropod (e). Scale bars correspond to 1 cm.

Fig. 7.6. Limestone of the Kõrgessaare Formation, Vormsi Regional Stage, Katian, from the Sutlema Quarry, Estonia. Photo: Gennadi Baranov, 2021.

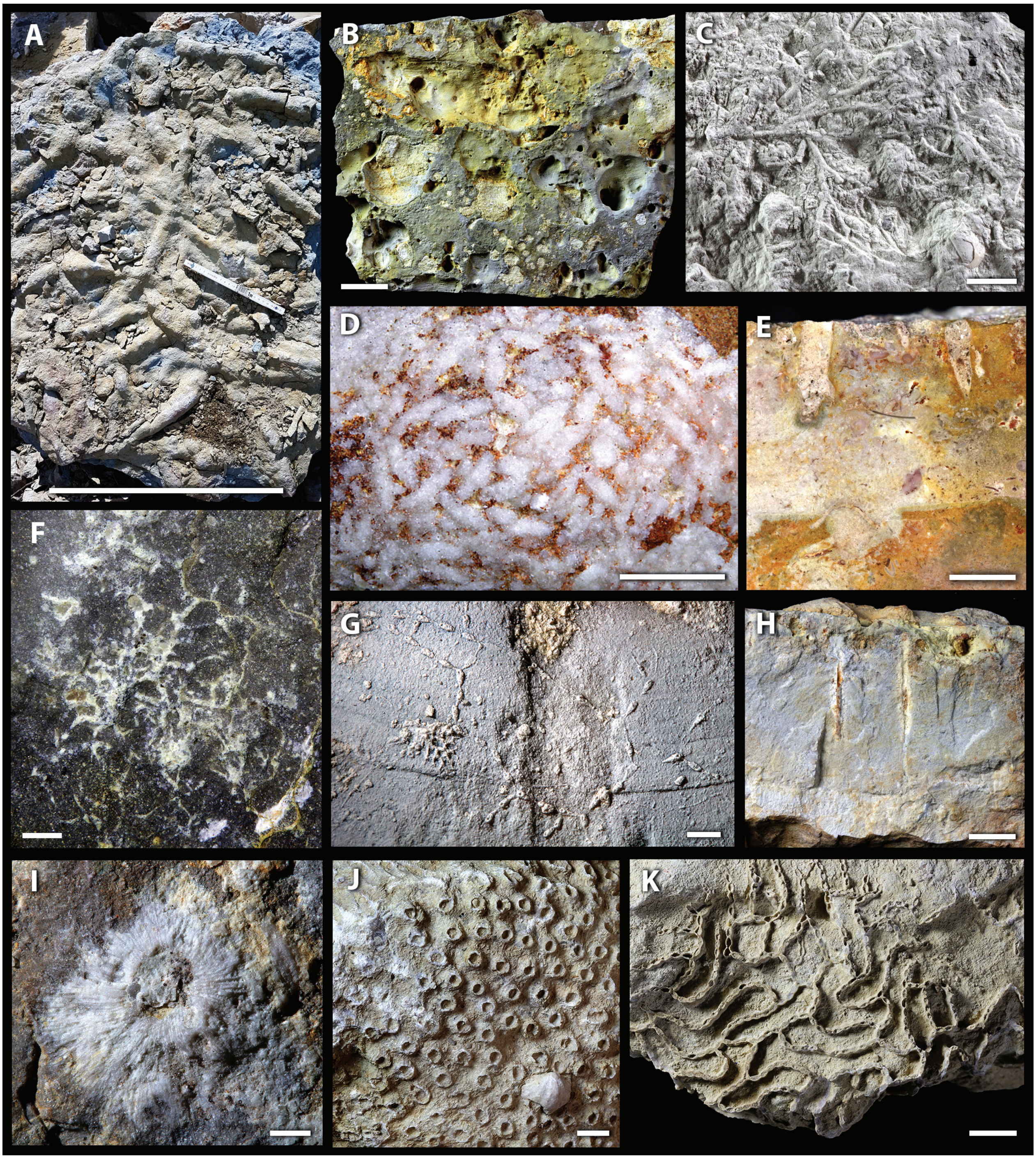

Fig. 7.7. Selected fossils from the Sutlema quarry, Kõrgessaare and Saunja formations (Katian). Scale bars: A – 50 cm, B, C, H, J, K – 1 cm; E – 5 mm; F, D, G, I – 1 mm. **A** – large borings of *Thalassinoides suevicus* from the Kõrgesaare Formation, field image. **B** – bored, bioeroded and karstified hardground on the top of the Saunja Formation, GIT 881-9. **C** – abundant trace fossil *Chondrites intricatus* on the bedding plane, Saunja Formation, GIT 362-912. **D** – clusters of small faecal pellets of *Coprulus oblongus* filling gastropod, Saunja Formation, GIT 404-686-1. **E** – bioerosional trace fossil *Trypanites sozialis* on hardground, Kõrgesaare Formation, GIT 362-865-2. **F** – algal bioerosional traces, hardground on the top of the Saunja Formation, GIT 881-27-3. **G** – bryozoa *Corynotrypa delicatula* encrusting large brachiopod *Porambonites*, Kõrgessaare Formation, GIT 812-74-1. **H** – bioerosional trace fossil *Trypanites weisei*, hardground on the top of the Saunja Formation, GIT 881-28. **I** – bryozoan holdfast encrusting hardground on the top of the Saunja Formation, GIT 881-26-2. **J**, **K** – tabulate corals from the Kõrgessaare Formation; **J** – *Sarcinula*, GIT 649-9; **K** – *Catenipora,* GIT 734-78**.**

double hardground (levels b and c) is also heavily burrowed, bored, and probably karstified. The uppermost hardground of this sequence (level d) is rough and weakly bored; it is impregnated with phosphatic minerals and partly stained with glauconite. Above this hardground a c. 1 m thick wavy bedded, silty, grey marly layer occurs, rich in rhynchonelliformean brachiopods.

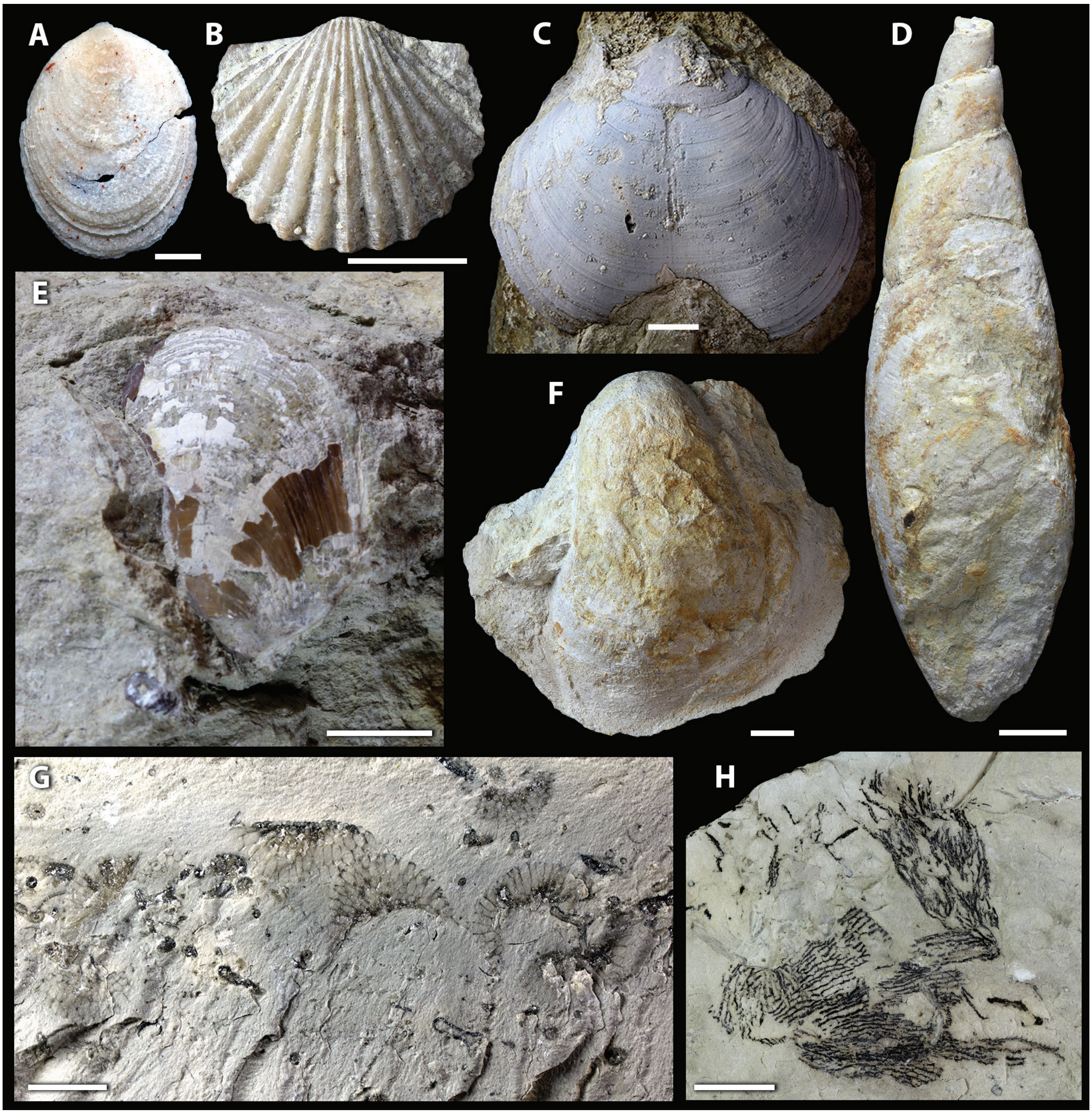

Fig. 7.8. Selected fossils from the Sutlema quarry, Kõrgessaare and Saunja formations (Katian). Scale bars: C–H – 1cm, B – 5 mm, A – 0.5 mm. **A–C**, **E** – brachiopods from the Kõrgessaare Formation; **A** – *Pseudopholidops*, GIT 737-254; **B** – *Sulevorthis lyckholmiensis*, GIT 673-488; **C** – *Porambonites gigas*, GIT 673-489; **E** – *Pseudolingula quadrata* in the life position, GIT 810-177. **D–F** – gastropods from the Kõrgessaare Formation; **D** – *Subulites subula*, GIT 812-114; **F** – *Salpingostoma kokeni*, GIT 812-100. **G** – algae *Vermiporella* and *Coelosphaeridium* from the Saunja Formation, GIT 812-54. **H** – dendroid *Dictyonema* from the Saunja Formation, GIT 812-1-2.

Fauna and flora

Fossils are relatively rare but highly diverse in the Saunja Formation. A rich flora of calcareous skeletal algae occurs (e.g., a form provisionally assigned to *Coelospheridium*, the green algae *Vermiporella*, and the receptaculite *Tettragonis sulcata* (Fig. 7.9C). Poriferans are abundant. Molluscs are relatively well preserved with gastropods (e.g., *Murchisonia*, *Subulites*), cephalopods (e.g., *Striatocycloceras*), and bivalves present. Well-preserved dendroid graptolites, tentaculids such as *Palaenigma wrangeli* and enigmatic carbonaceous remains of colonial organisms, here tentatively identified as hydroids (Fig. 7.9A) are remarkable.

Fossils are abundant in the Kõrgessare Formation. Large gastropods are common (e.g., *Hormotoma*, *Fusispira*, *Megalompha*, *Subulites*, *Salpingostoma*, *Sinuites*). They are most abundant in the layer c. 10 cm above the base of the formation. Cephalopod occurrences include endocerids and the orthocerid *Striatocycloceras*. From the marly horizons within the Kõrgessare Formation, a rich fauna of cornulitids has been described (Vinn et al. 2022). Coral occurrences include tabulates (e.g., *Catenipora*, *Heliolites*, *Protaraea*, *Propora*, *Sarcinula*) and rugosans (Fig. 7.7). Small craniid *Pseudopholidops* and the large linguliid *Pseudolingula quadrata*, which occurs

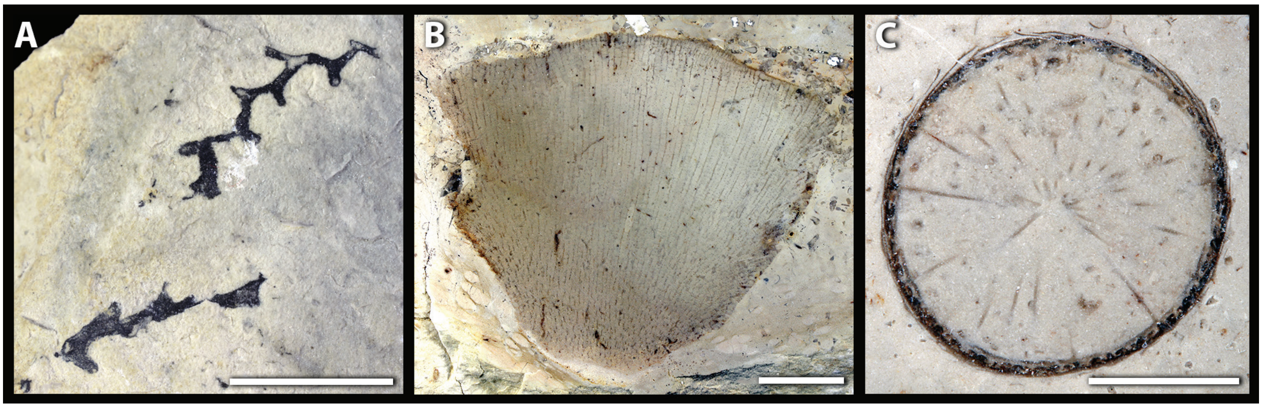

Fig. 7.9. Selected fossils from the Sutlema quarry. Saunja Formation (Katian). Scale bars: A, B – 1 cm; C – 5 mm. **A** – remains of colonial organisms, tentatively determined as hydroids, GIT 812-39. **B** – anthaspidellid sponge, GIT 812-24. **C** – retceptaculitid *Tettragonis sulcata*, GIT 812-23.

in life position (Fig. 7.8E), are common. Rhynchonelliformeans collected from the Kõrgessare Formation in the Sutlema quarry include, e.g., *Bekkeromena*, *Boreadorthis recula*, *Glyptorthis*, *Kiaeromena* (*Bekkeromena*) *vormsina*, *Neoplatystrophia*, *Nicollela*, *Plaesiomys saxbyana, Porambonites gigas*, *Sampo hiiuensis*, *Sulevorthis lyckholmiensis*, *Triplesia* and *Vellamo verneuilii*. Several shelly fossils are encrusted by bryozoans of *Corynotrypa delicatula* (Fig. 7.7G).

The epizoans of the hardgrounds include cornulitids, crinoids, bryozoans, brachiopods, and tabulate corals. The bioerosional ichnofauna of the hardgrounds is abundant, consisting of the shallow-marine firmground trace fossil *Balanoglossites triadicus.* The hard-substrate boring *Trypanites* and algal bioerosional traces are most common (Fig. 7.7E, F, H). The ichnogenus *Trypanites* is represented by three species, shallow *T. socialis,* elongated *T. weisei,* and course-changing *Trypanites* isp.

The degree of bioturbation of the Kõrgesaare Formation is high, with a characteristic branching burrow system of *Thalassinoides*. Gastropods of the Saunja and Kõrgessaare formations are frequently filled with small faecal pellets. They occur as massive clusters of ichnospecies *Coprulus oblongus* and more rarely represent the ichnogenus *Tubularina* (i.e., burrows filled with sparry calcite and coprolites). Ichnogenera recorded from steinkerns of gastropods are *Pilichnus* and *Palaeophycus*.

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Stop 8: Reinu quarry

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Location: Latitude 59.08768°N, longitude 24.74044°E; Rapla County, central northern Estonia.
Stratigraphy: Latest Katian to Rhuddanian; Pirgu to Juuru regional stages, Adila, Ärina, Varbola and Tamsalu Fm.
Status: Active quarry with high walls – be careful; hammering and fossil collecting are welcome!
More information: https://geoloogia.info/en/locality/16317

The Reinu quarry is located in northern Estonia, 40 km south of Tallinn. The early Silurian limestone of the Varbola Formation, Juuru Regional Stage, has been quarried for crushed stone production since 2007. Today the quarry is operated by the infrastructure construction and maintenance company TREV-2 Grupp. The limestone aggregates from the Reinu quarry are used mainly in road construction.

The locality has been visited by geologists since the first bedrocks were quarried, and it has served as an excellent and fossiliferous outcrop for the Varbola Formation (Einasto et al. 2007). A number of studies have been published on the material from the Reinu succession, notably on important palaeontological finds (Ausich et al. 2020; Wright & Toom 2017; Jeon et al. 2022), but also on chemostratigraphy (Gul et al. 2021). The Ordovician–Silurian boundary interval was first exposed in the quarry in 2020 within a small rounded excavation used for water drainage and pumping. In 2022, Ordovician rocks were opened on a larger scale, and they started contributing to the quarry's production. Since then, the topmost Pirgu (latest Katian) and the entire Porkuni (Hirnantian) regional stages have been accessible in the Reinu quarry. This is now the second outcrop of the Ordovician–Silurian boundary interval in Estonia, the other being the Neitla quarry (Männik & Nõlvak 2023). Hirnantian rocks are well known in a few additional sites, notably the old Porkuni quarry (Hints et al. 2000, Hints & Männik 2014).

Studies on Hirnantian strata in the Reinu quarry are currently underway, with only some preliminary results on microfossils and chemostratigraphy published (Hints & Tonarova 2023; Meidla et al. 2023b). The main units identified in the quarry are briefly characterised and discussed below.

(1) The **Adila Formation** (0.3 m; Pirgu Regional Stage, Latest Katian) consists of gray wackestones with several pyritsed discontinuity surfaces. It is the lowermost stratigraphic unit exposed only in the deepest part of the quarry. The formation contains organic-walled microfossil assemblage typical of the Pirgu Regional Stage in Estonia, including rare *Spinachitina coronata*, *Cyathochitina campanulaeformis*, *C. kuckersiana*, and *Belonechitina micracantha*. However, no specific zonal chitinozoans were found in the few samples studied. Additionally abundant scolecodonts, melanosclerites and foraminiferans (*Blastammina* sp.) were found.

Fig. 8.1. Overview of the Reinu quarry, showing Hirnantian reefs (Ärina Formation, Porkuni Regional Stage) in the lower escarpment and overlying limestones of the Varbola Formation (Hirnantian to Rhuddanian, Juuru Regional Stage). Photo: Olle Hints, 2022.

Fig. 8.2. Ordovician-Silurian boundary beds in the Reinu quarry. Hand points to the Koigi Member. Photo: Olle Hints, 2022.

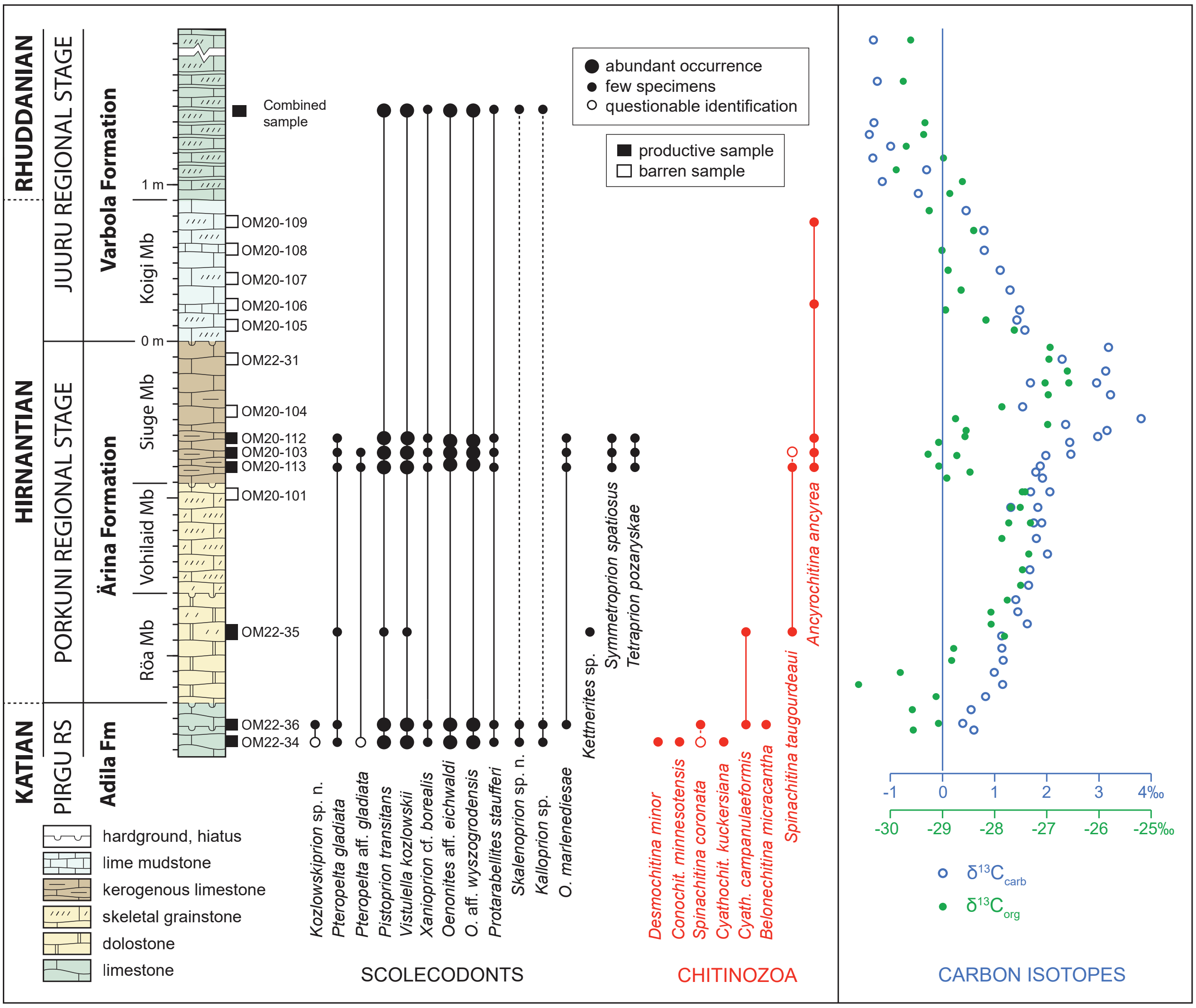

Fig. 8.3. Ordovician-Silurian boundary beds in the Reinu quarry. Distribution of selected scolecodonts is modified from Hints & Tonarova (2023), chitinozoan data by Jaak Nõlvak (unpublished), carbon isotopes from Meidla et al. (2023). Note that the isotope data points are adjusted to fit the boundaries between lithological units, due to the fact that thickness of individual beds varies between the sampling sites within the quarry.

Fig. 8.4. Dolomitised Hirnantian reef the Reinu quarry. The reefal limestone is usually assigned into the Tõrevere Member of the Ärina Formation. Here the reefs are laterally replaced by the kerogenous Siuge Member in distance of few meters. Photo: Olle Hints, 2022.

(2) The **Ärina Formation** (c. 2.5 m; Porkuni Regional Stage, Hirnantian) consists of various shallow-marine carbonates. The formation is distributed in northern and central Estonia and considered to be primarily early Hirnantian in age, bound by stratigraphic gaps (Meidla et al. 2023a, 2023b). It is commonly divided into the dolostone (**Röa** Member), skeletal grainstone (**Vohilaid** Member), kerogenous limestone (**Siuge** Member) and, in places, dolomitised reef limestone members (**Tõrevere** Member). Ainsaar et al. (2015) showed that the Vohilaid, Siuge and Tõrevere units are reef-related lithotypes rather than true members. In the Reinu quarry, all these units can be identified (Fig. 8.2, 8.3, 8.4, 8.5), but their lateral distribution and thickenss varies between sites, particularly due to organic buildups and uneven erosion during the Hirnantian. A single reef body c. 20 m in diameter was exposed in 2022 (Fig. 8.4) showing a gradual lateral transition from the dolomitised reef limestone (Tõrevere Member) into the kerogenous limestone of the Siuge Member (Fig. 8.1). Shelly fossils are common in the Vohilaid and Siuge members (Fig. 8.7). The Siuge Member is characterised also by abundant benthic microfossil assemblage. The most abundant Ordovician polychaete fauna from Baltoscandia was recently reported from the Siuge Member in the Reinu quarry, with well over 5000 scolecodonts per kg of rock (Hints & Tonarova 2023). Ostracods show similarly rich fauna, study of which is currently in progress. The most kerogenous part of the Siuge Member (sample OM20-113) contains the zonal chitinozoan *Spinachitina taugourdeaui*, confirming the early Hirnantian age of the unit (Kaljo et al. 2008). *S. taugourdeaui* was also identified from the Röa Member (Fig. 8.3); thus, the entire Ärina Formation in the Reinu quarry corresponds to the S. *taugourdeaui* Zone.

(3) The **Varbola Formation** (ca 11 m, Juuru Regional Stage, Hirnantian–Rhuddanian) is represented mainly by the alternation of packstones/grainstones and marl beds. The formation contains abundant tabulate corals, stromatoporoids, rugosans, brachiopods, echinoderms and other shelly fossils (Fig. 8.6). Microfossil samples have revealed an abundance of benthic forms, notably scolecodonts. However, chitinozoans and conodonts and very rare and of very low diversity indicating strong impact of the Hirnantian extinction to these groups.

The lowermost part of the formation, the **Koigi Member**, is usually represented by lime mudstones, but in the Reinu quarry, the grainstones overlying the Siuge / Tõrevere lithotypes are also assigned to the Koigi Member. Fig. 8.5 shows the lower boundary of the unit and succession of three rock varieties: (1) brown kerogenous Siuge wackestone, (2) 5-cm-thick grainstone bed, overlain by (3) fine-grained mudstone unit, typical of the Koigi Member. In places, the basal part of the Koigi Member contains a conglomerate with pebbles several cm in size and large fragments of corals and stromatoporoids.

Conventionally, the Ordovician–Silurian boundary has been drawn below the Varbola Formation (and Koigi Member). However, carbon isotope chemostratigraphy, has shown that the Koigi Member represents the falling limb of the Hirnantian Carbon Isotope Excursion. This pattern is also visible in the Reinu succession (Fig. 8.3), where the highest $\delta^{13}C$ values are recorded in the Siuge Member, and the overlying Koigi strata show a gradual decline in $\delta^{13}C$. Biostratigraphic evidence to identify the base of the Silurian is limited in the Reinu quarry. Most likely, the Koigi Member is of late Hirnantian age, whereas the main part of the Varbola formation belongs

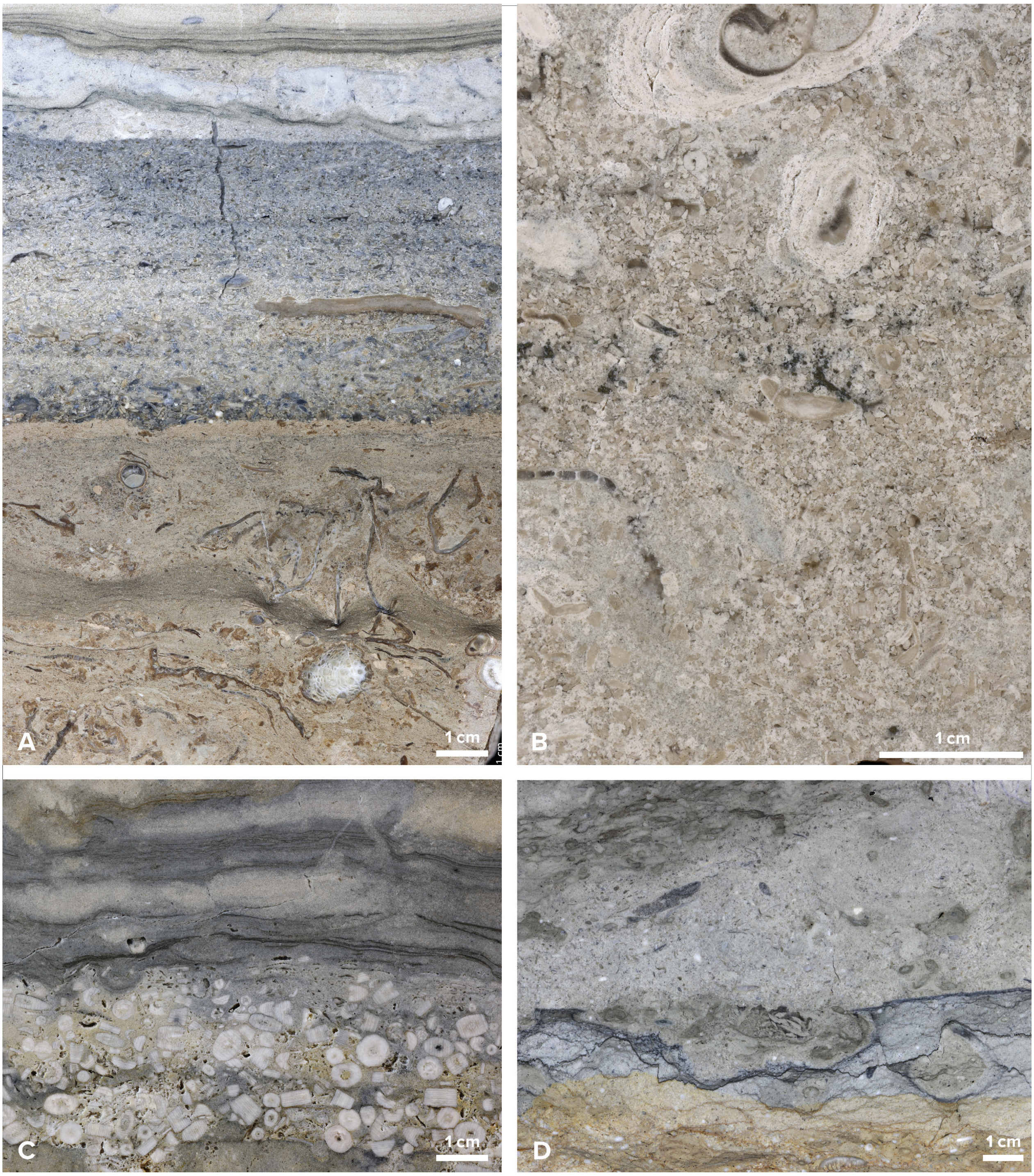

Fig. 8.5. Examples of latest Katian and Hirnantian rocks from the Reinu quarry. **A** – Boundary between kerogenous Siuge Member of the Ärina Formation and grainstone and carbonate mudstone of the Koigi Member, Varbola Formation. **B** – Grainstone of the Vohilaid Member, Ärina Formation. Note the oncolithic overgrowths on some shells. **C** – Dolostone with abundant echinoderm ossicles, Röa Member, Ärina Formation. **D** – Wackestone with a pyritised discontinuity surface, Adila Formation, Pirgu Regional Stage, latest Katian. Sample from the collection of TalTech Department of Geology.

to the Rhuddanian (Gul et al. 2021; Meidla et al. 2023a). Here we correlate the Ordovician–Silurian boundary with the upper boundary of the Koigi Member.

(4) The **Tamsalu Formation** (Juuru Regional Stage, Rhuddanian) overlying the Varbola Formation has a thickness of less than a metre. It consists of Borealis-limestone – essentially a coquina of brachiopod *Borealis borealis borealis* (Fig. 8.6N) containing in places also abundant corals and stromatoporoids. This rock unit is characterised by very high CaO content and is therefore, a valuable resource for the chemical industry. It is quarried in several localities in central Estonia, notably in the Karinu and Võhmuta quarries (Ainsaar 2004).

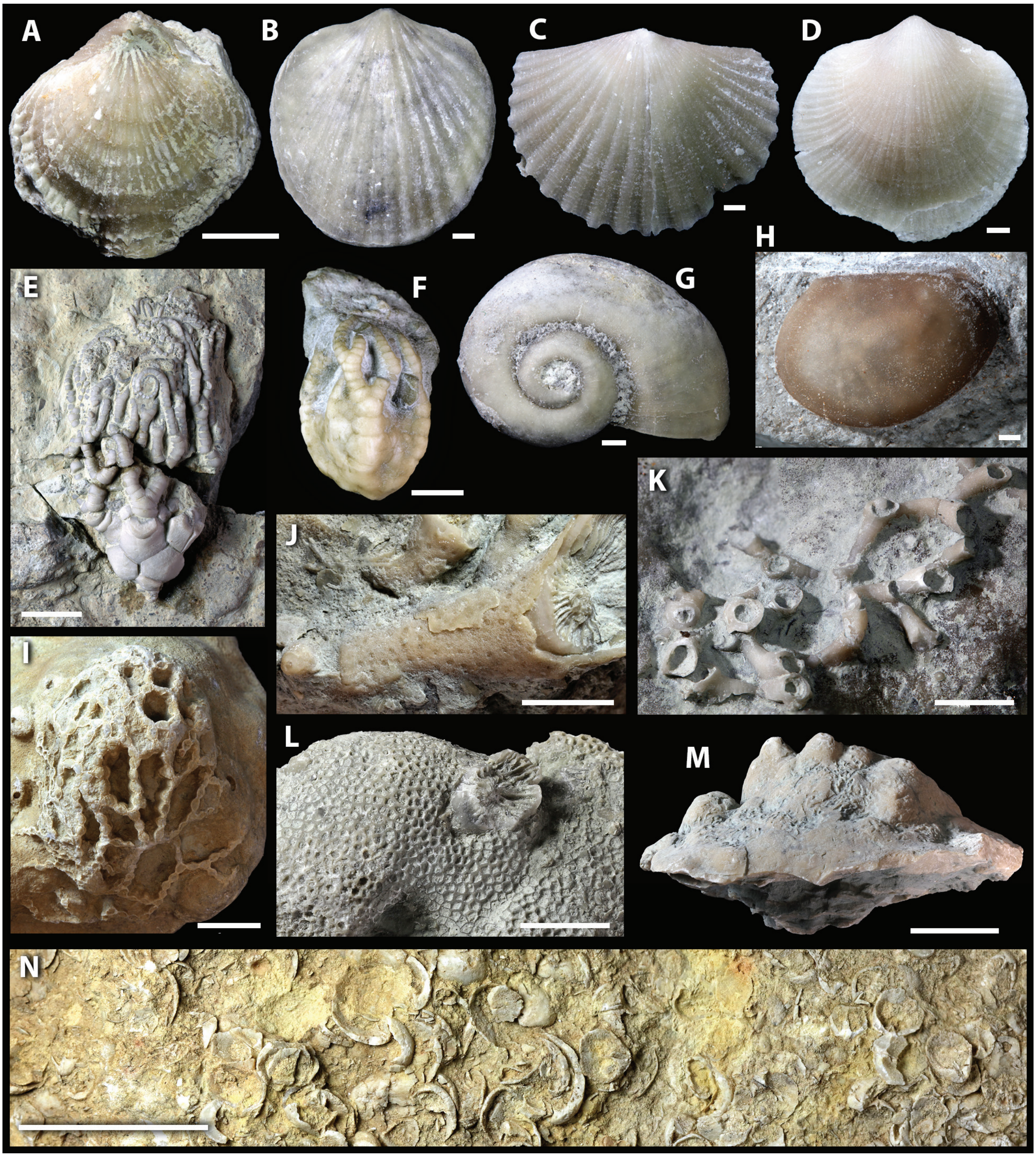

Fig. 8.6. Selected fossils from the Reinu quarry of the Varbola and Tamsalu formations (Rhuddanian). Scale bars: M, N – 5 cm; E, I, L – 1 cm; A, F, J, K – 5 mm; B–D, G, H – 1 mm. **A–D** – brachiopods from the Varbola Formation; **A** – *Sypharatrypa hillistensis*, GIT 554-2500; **B** – *Zygospiraella*, GIT 835-1781; **C** – *Hesperorthis hillistensis*, GIT 855-848; **D** – *Onniella trigona*, GIT 554-2501. **E–F** – crinoids from the Varbola Formation; **E** – *Euspirocrinus hintsae*, GIT 405-256; **F** – *Paerticrinus arvosus*, GIT 405-255. **G** – gastropod from the Varbola Formation, *Naticonema*, GIT 535-161. **H** – leperditicopid from the Varbola Formation, GIT 368-329. **I–L** – corals from the Varbola Formation; **I** – halysitid encrusting stromatoporoid, GIT 666-49-1; **J** – heliolitid encrusting rugose coral *Streptelasma*, GIT 393-75; **K** – auloporid encrusting stromatoporoid, **L** – endobiotic rugose coral *Streptelasma* in *Paleofavosites balticus*, GIT 666-20. **M** – stromatoporoid with bioeroded surface, Varbola Formation, GIT 362-505. **N** – *Borealis borealis borealis* coquina, Tamsalu Formation, GIT 623-1095.

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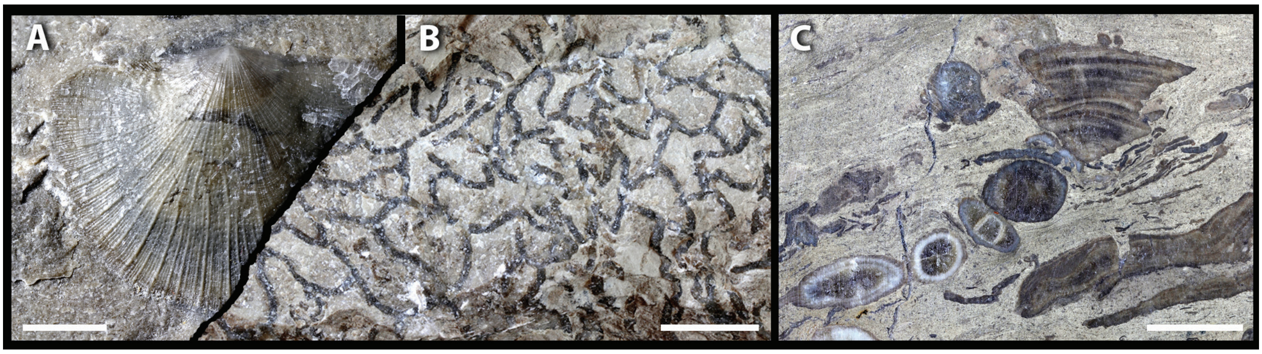

Fig. 8.7. Selected fossils from the Reinu quarry, Ärina Formation (Hirnantian, Ordovician). Scale bars: B, C – 1 cm; A – 5 mm. **A** – brachiopod *Eostropheodonta* GIT 674-698. **B** – tabulate coral *Catenipora*, GIT 734-239. **C** – stromatoporoids and rugose corals, GIT 748-25.

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Excursion Day 3

Stop 9: Põhja-Kiviõli II open-pit mine

Heikki Bauert and Olle Hints

Location: Latitude 59.365394°N, longitude 26.842046°E; Ida-Viru County, NE Estonia.
Stratigraphy: Sandbian, Kukruse Regional Stage, Viivikonna Formation.
Status: Active open-pit mine; please follow safety regulations; sampling and fossil collecting are welcome.
More information: https://geoloogia.info/en/locality/23669

Kukersite oil shale has been Estonia's most important mineral resource for over a century, with the first test mining site opened in NE Estonia in 1916. Oil shale has been used primarily for energy production in power plants and producing shale oil and other chemicals. Oil shale production peaked in the 1970-1980s, with over 30 million metric tonnes excavated in Estonia annually. As of 2022, the annual production slightly exceeded 10 million tonnes. However, due to the high environmental impact of oil shale mining and utilisation, the production is expected to decrease gradually, even though carbon capture, utilisation and storage technologies (CCUS) could make its impact on climate much smaller.

The Põhja-Kiviõli II open-pit mine (Fig. 9.2, 9.4) is owned and operated by Kiviõli Keemiatööstus (KKT, https://www.keemiatoostus.ee/en). It is located in NE Estonia, along the northern edge of the central part of the main oil shale deposit (Fig. 9.1).

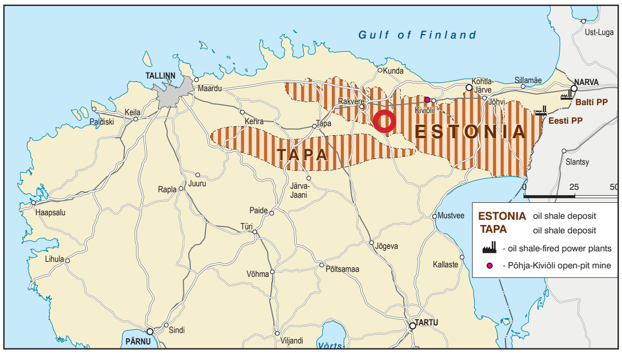

Fig. 9.1. Locality map showing the oil shale deposits in Estonia (from Bauert & Nõlvak 2014).

Characteristics of the kukersite oil shale

Oil shale is commonly defined as a fine-grained sedimentary rock containing organic matter (OM) that yields substantial amounts of oil and combustible gas upon destructive distillation. The kukersite OM deposited in argillaceous marine limestones and as many as 50 beds of kukersite and kerogen-rich limestone, alternating with biomicritic limestones (wackestones), have formed during the main phase of kukersite OM deposition in northeastern Estonia during the latest Mid to earliest Late Ordovician time span (Fig. 9.8).

Fig. 9.2. Oil shale succession in the Põhja-Kiviõli II open-pit mine. Photo: Gennadi Baranov, 2019.

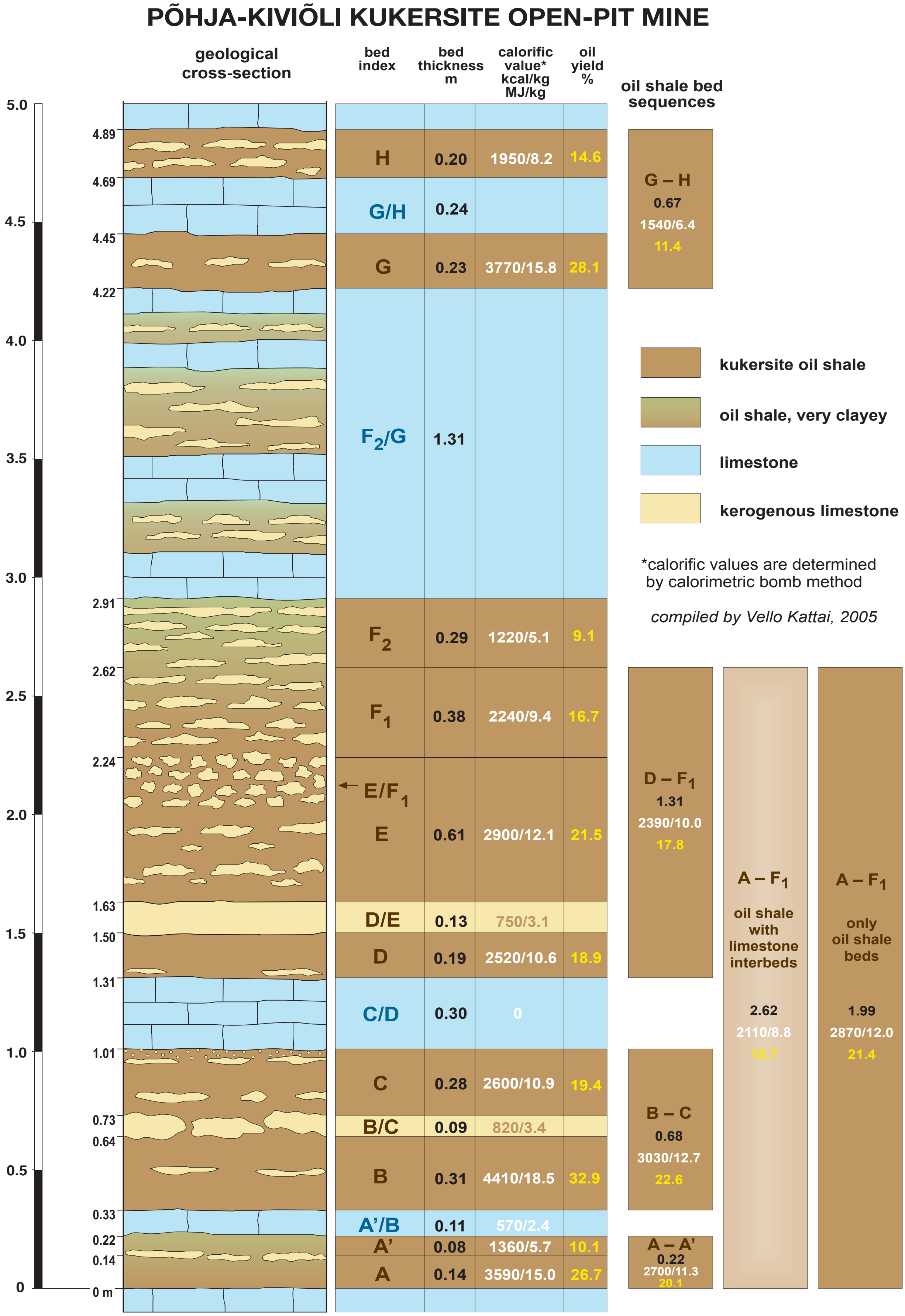

Fig. 9.3. Succession and properties of the oil shale seams in the Põhja-Kiviõli opencast mine (from Bauert & Nõlvak 2014).

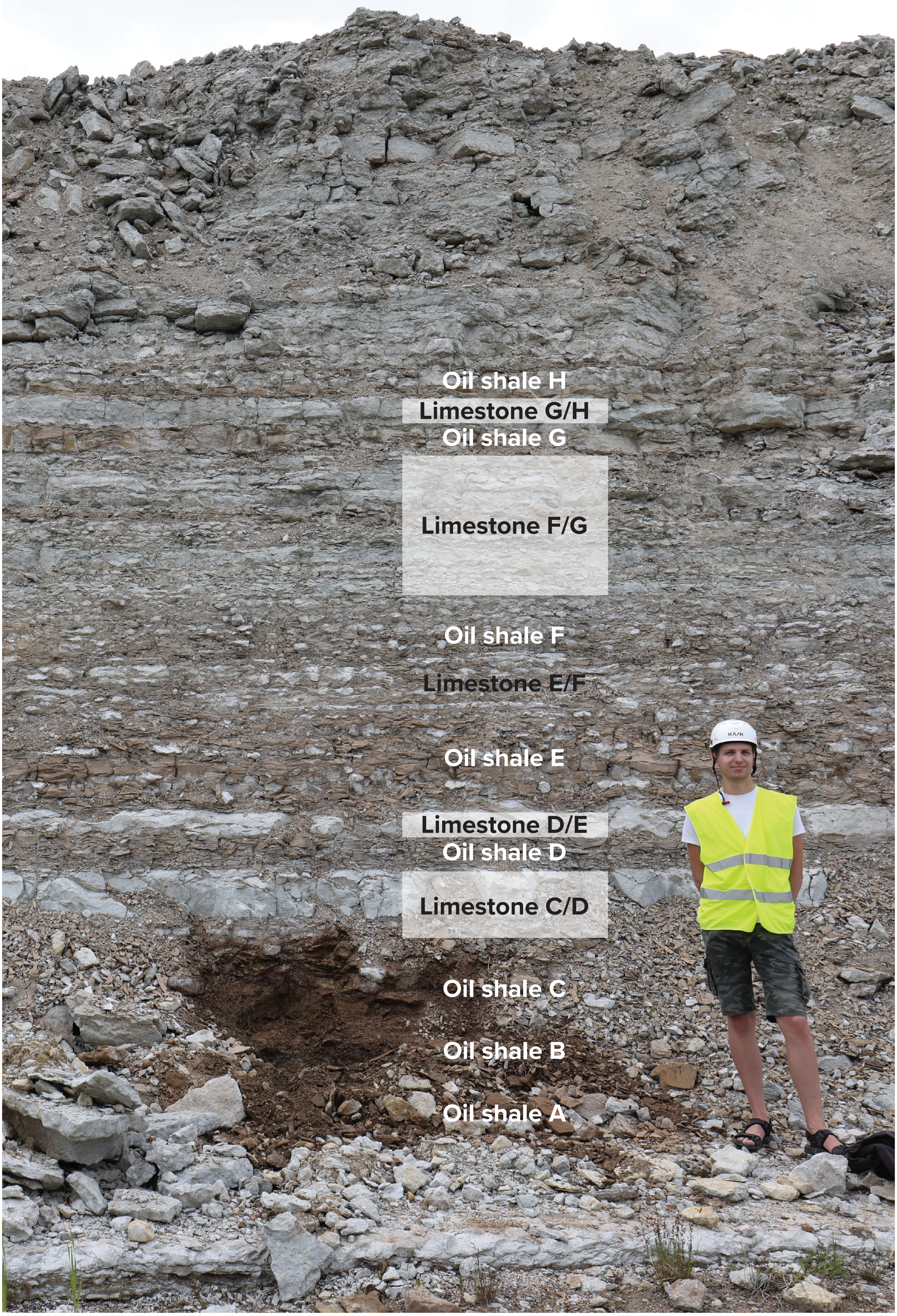

Fig. 9.4. Succession of the oil shale seams in the Põhja-Kiviõli II opencast mine. The lowermost beds are covered by debris, their appriximate position is indicated. The subdivition of beds E to F is complicated on weathered walls. Photo: Olle Hints, 2023.

The kukersite oil shale beds (seams) form an up to 20–30 m thick succession. However, individual kukersite beds of chocolate-brownish colour are commonly 10–40 cm thick and may reach as much as 2.4 m (bed III in the Kerguta-565 drill core; Põldvere 2006) in thickness. The beds designated from “A” to “F2” are feasible for mining and are currently mined in three open-pit mines (Narva, Põhja-Kiviõli, Ubja) and two underground mines (Estonia, Ojamaa).

The main characteristics of individual kukersite beds in the Põhja-Kiviõli mine are shown in Fig. 9.3. The OM content of kukersite oil shale beds varies considerably, reaching as high as 50% TOC in beds B and E in the central area of the Estonia deposit (Foster et al. 1989). Rock-Eval pyrolysis analyses (Dyni et al. 1989; Foster et al. 1989) indicate that kukersite oil shales have a significant hydrocarbon potential [S1 & S2 = 300–350; S1 – kg of hydrocarbons (extractable) per tonne rock; S2 – kg of hydrocarbons kerogen pyrolysate) per tonne rock] and are characterised by a high hydrogen index [HI = 675–960; mg hydrocarbons (S2) per gram of total organic carbon]. These data suggest the prevalence of Type I kerogen in kukersite OM. The elemental composition of kukersite kerogen is as follows: C – 67%, H – 8.3%, O – 12.8%, N – 2.2%, S – 3.5%, H/C – 1.48, O/C – 0.14, S/C – 0.02 (Derenne et al. 1989).

The matrix minerals in Estonian kukersite oil shale beds and interbedded more or less argillaceous limestones

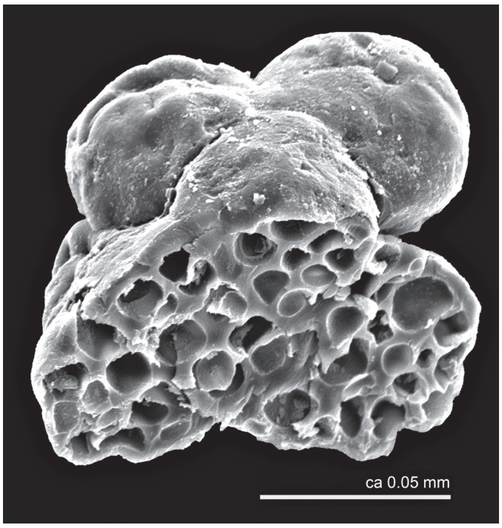

Fig. 9.5. *Gloeocapsomorpha* prisca SEM image (photo: Jaak Nõlvak).

(Bauert & Kattai 1997) include mainly low-Mg calcite (usually >50%, but less in kukersite beds), dolomite (generally less than 15%) and siliciclastic minerals. The XRD analyses and thin section studies have revealed that the siliciclastic component mainly comprises silt-sized quartz and illite, while feldspars and chlorite occur in subordinate amounts. Besides, kukersite oil shale contains authigenic pyrite.

The origin of kukersite

Major kukersite-type OM accumulations have been recorded in the late Uhaku to Kukruse age rocks (Kõrgekallas and Viivikonna formations). However, a few thin kukersite beds or kukersite OM-enriched marlstone beds are known to occur at several other stratigraphic levels in the Ordovician succession (Kõrts 1992): in the Kunda Stage (lower Darriwilian) as well as in the Keila and Nabala stages (uppermost Sandbian to Katian). Based on the dominant OM type, the kukersite is classified as a *Gloeocapsomorpha*-related telalginite (Cook & Sherwood 1991; telalginite refers to the presence of lensoidal, flattened spheroidal or fan-shaped algal remains in OM).

The algal structure of the kukersite was recognised by a Russian botanist M. Zalessky in 1917. He described oval bodies in kukersite kerogen and interpreted them as the remains of an extinct microorganism. Due to morphological similarity with the extant cyanobacterium *Gloeocapsa quaternata* Kützing, he named the colonial cellular bodies in kukersite as *Gloeocapsomorpha prisca*. Viewed under the light microscope, the microfossils are bright yellow. The individual colonies are spherical to oval in outline and range in size from 10 to 40 µm (Fig. 9.5). The external surface is smooth and unbroken, with no pitting (Burns 1982). A thorough revision of *Gloeocapsomorpha prisca* by Foster et al. (1989) showed that based on morphological and biochemical characteristics, *G. prisca* has a close similarity with the extant, mat-forming and stromatolite-forming marine cyanobacterium *Entophysalis major*.

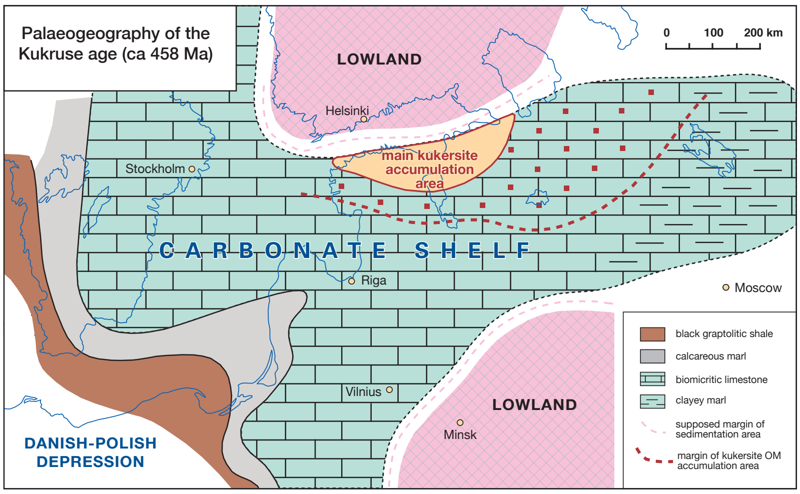

Fig. 9.6. Palaeogeography of the Baltoscandian basin during the Kukruse time, earliest Late Ordovician, when the majority of kukersite oil shale accumulated. Scheme from Bauert & Nõlvak (2014).

Depositional environment of kukersite

The depositional environment of the kukersite is still vaguely known. The few points so far established are as follows:

1. A major kukersite deposition occurred during a regression of the Kukruse sea southwards. The regression is suggested by detailed bed-by-bed lithostratigraphic studies, which have revealed a hiatus in sedimentation for beds of the Peetri Member of the Viivikonna Formation in northern Estonia and the appearance of younger kukersite beds (beds III – IX) on north-south transect in a distance of 80 km. At the same time, most kukersite beds are traceable for over 250 km in the west-east direction (Bauert & Kattai 1997).

2. The kukersite OM deposited along the northern margin of the shallow carbonate shelf, bordering the Finnish lowland in the north (Fig. 9.6).

3. Many hardgrounds, either with thin pyritic impregnation veneer or without impregnation, have been recorded in the Uhaku – Kukruse succession. Most represent synsedimentarily lithified carbonate seafloors (Wilson & Palmer 1992), but a few resemble modern coastal microkarst forms. The surfaces attributed to microkarst have developed narrow, subvertical cavities with highly irregular walls that may extend down to 25 cm from the hardground level (Bauert 1989). One such surface is observed on top of kukersite bed III and is traceable over several hundred square kilometres.

4. Based on the premise that *G. prisca* was an intertidal mat-forming cyanobacterium (similar, but not identical to extant *E. major*), Foster et al. (1990; Fig. 9.6) proposed a model that *G. prisca* grew on broad intertidal mats that may have been subaerially exposed. Tidal movements and offshore winds were suggested as agents for transporting algal mat fragments to deeper-water accumulation areas. Another plausible alternative for kukersite deposition could be a sink-down of relatively inert cyanobacterial OM directly from algal blooms.

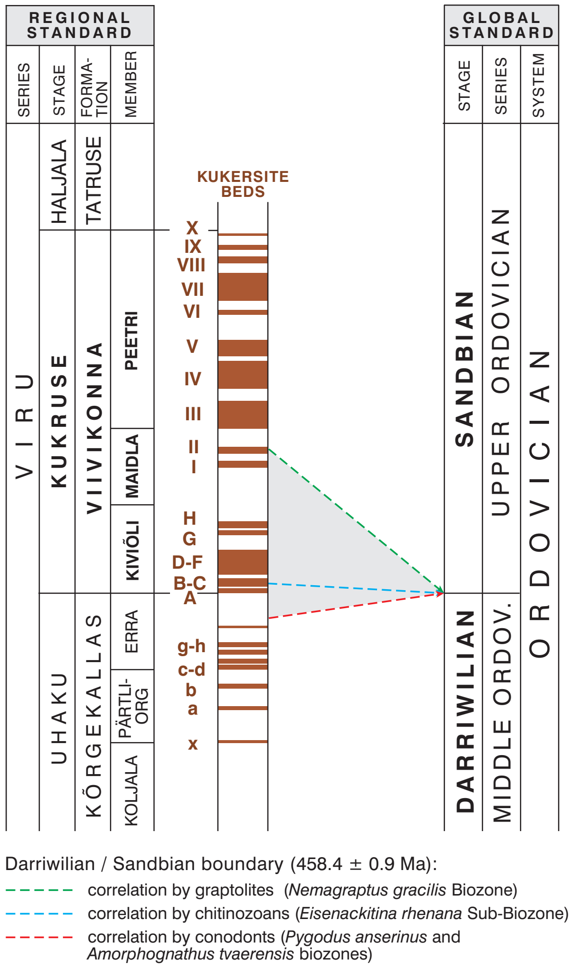

Fig. 9.7. Stratigraphic chart of the Kukruse Stage, showing levels of main indexed kukersite seams and possible correlation between global and regional time scales (redrawn from Hints et al. 2007).

Faunas of the Kukruse Stage

Abundant marine fossils, with more than 250 species listed (Bekker 1921; Rõõmusoks 1970), have been collected from both argillaceous limestones and kukersite oil shale beds during the past two centuries (Fig. 9.8 to 9.10). The most common fossils encountered are trilobites, brachiopods and bryozoans, whereas, in some kukersite beds, even delicate feathery structures of bryozoans may be well preserved (Fig. 9.9). It should be pointed out that contrary to most other organic-rich rocks, no anoxia is recorded during the accumulation of kukersite, as indicated by flourishing bottom life, the abundance of trace fossils and the relative scarcity of authigenic pyrite.

Kukruse Regional Stage and the base of the Upper Ordovician

The Fågelsång section in Scania, southern Sweden, has been chosen as the GSSP for the global Upper Ordovician Series as it represents the level of the first appearance of *Nemagraptus gracilis* Hall (Bergström et al. 2000). An overview of the present knowledge for correlating the base of the global Sandbian Stage with Baltoscandian stages by means of graptoloids, chitinozoans and conodonts was given by Hints et al. (2007).

Graptoloids are rare and only occasionally found in shallow shelf carbonate successions, the first reliable finds of *N. gracilis* come from the middle part of the Kukruse Stage in some central Estonian sections (Nõlvak & Goldman 2007). No *N. gracilis* has been recorded from the

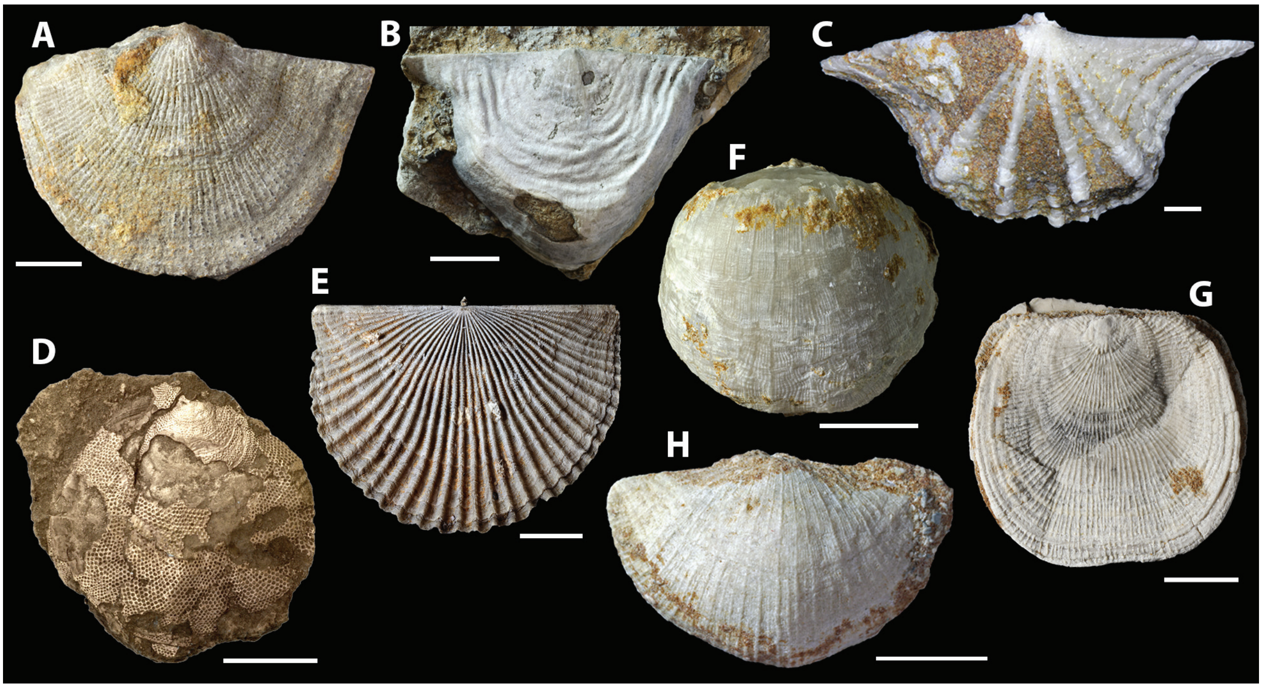

Fig. 9.8. Selected brachiopods from the Viivikonna Formation, Kukruse Stage (Sandbian). Scale bars: B, C, D – 1 cm; A, E–H – 5 mm. **A** – *Estlandia marginata*, Humala, GIT 543-1305. **B** – *Kiaeromena* (*Kiaeromena*) *estonensis,* Küttejõu, GIT 677-4. **C** – *Kullervo lacunata*, Kiviõli, GIT 543-433. **D** – *Foveola ivari*, Küttejõu, TUG 1003-307. **E** – *Cyrtonotella kuckersiana kuckersiana*, Kukruse, GIT 400-124. **F** – *Bekkerina dorsata*, Kohtla, GIT 251-179. **G** – *Orthisocrania planissima*, Küttejõu, GIT 772-125. **H** – *Sowerbyella* (*Sowerbyella*) *liliifera,* Kohtla-Järve, GIT 675-590.

outcrop area of the Kukruse Regional Stage in northern Estonia (Fig. 9.7).

A study on conodonts from the Kiviõli Member of the Kukruse Stage in the Kohtla section (ca 15 km east of the Põhja-Kiviõli open-pit mine) was conducted by V. Viira and co-authors in 2006. They recorded the FAD of *Amorphognathus tvaerensis* within the limestone interbed A/B, just above the base of the Kukruse Stage. It should be noted that in the Fågelsång section in Scania, *A. tvaerensis* was recorded above the *N. gracilis* find (Bergström et al. 2000), which means that in Estonian sections, the base of the Upper Ordovician lies either at the boundary of the Uhaku/Kukruse stages or somewhat lower.

Some chitinozoan species, particularly *Eisenackitina rhenana* and *Conochitina savalaensis* (Nõlvak & Bauert 2015), have proven to be reliable indicators for correlating the base of the Kukruse Stage throughout Estonia. Both chitinozoans appear close to the kukersite bed A in the Viru underground mine and Savala drill core sections. Estonian researchers have found these chitinozoans also in Latvia, Lithuania and NE Poland; T. Vandenbroucke (2004) identified *E. rhenana* in the Fågelsång section.

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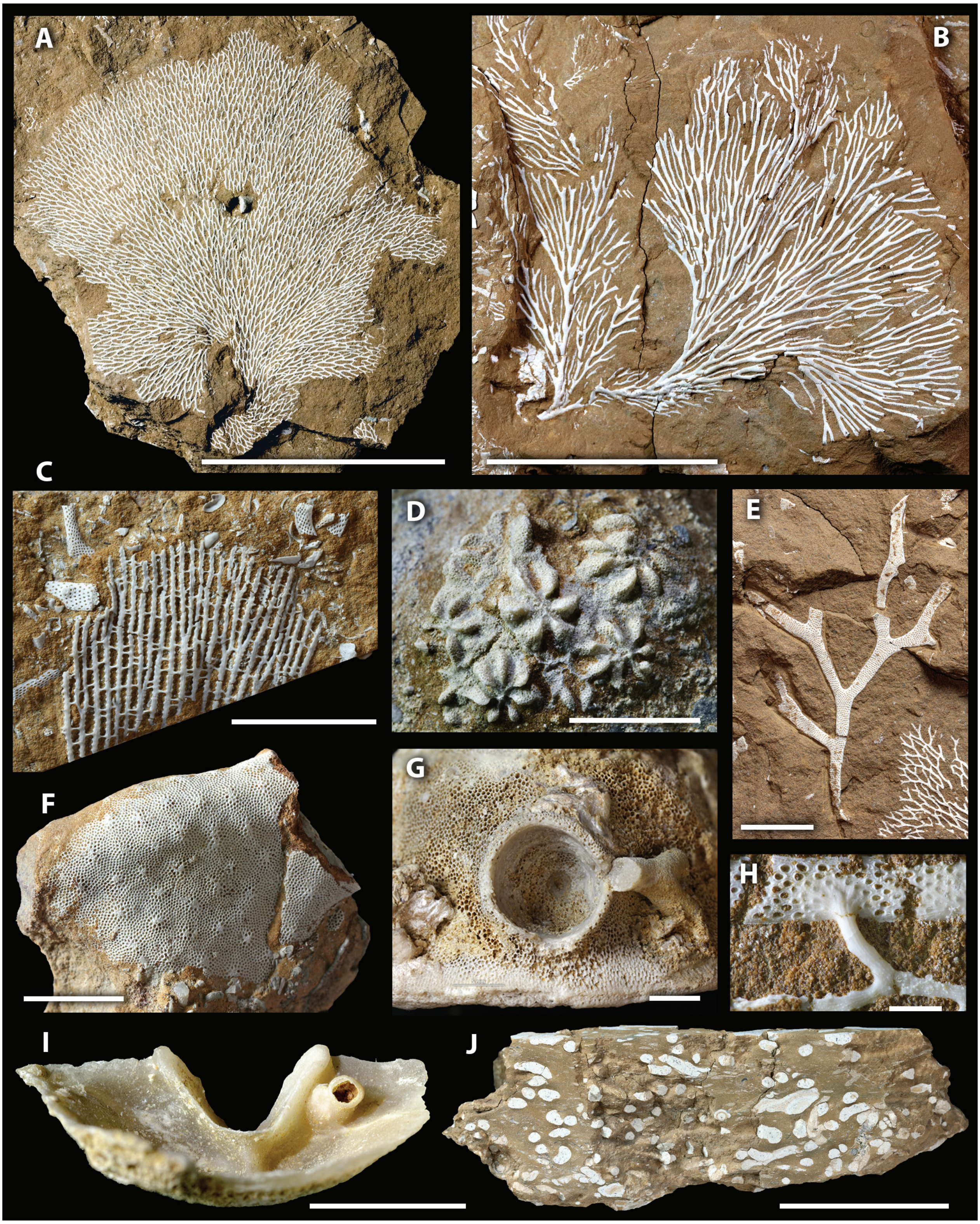

Fig. 9.9. Selected fossils from the Viivikonna Formation, Kukruse Stage (Sandbian). Scale bars: A, B, J – 5 cm; C–F – 1 cm, G, I – 5 mm; H – 1 mm. **A**–**F**, **H** – bryozoans; **A** – *Chasmatopora furcata*, North Estonia, GIT 398-995; **B** – *Pseudohornera bifida*, North Estonia, GIT 369-315; **C** – *Esthonioporina quadrata*, Küttejõu, GIT 537-2501; **D** – *Revalopora revalensis*, Põhja-Kiviõli, GIT 343-168; **E** – *Pachydictya kuckersensis*, Kohtla, GIT 537-1602; **F** – *Hemiphragma panderi*, Kohtla-Järve, GIT 537-3664; **H** – *Graptodictya bonnemai,* Kohtla, GIT 537-1606-2. **G**, **I**, **J** – trace fossils; **G** – *Kuckerichnus kirsimae* in *Diplotrypa*, Kohtla-Järve, TUG 72-826-2; **I** – *Burrinjuckia clitambonitofilia* in the ventral valve of *Clitambonites squamatus*, North Estonia, GIT 343-236-1; **J** – *Tisoa siphonalis*, North Estonia, GIT 362-612.

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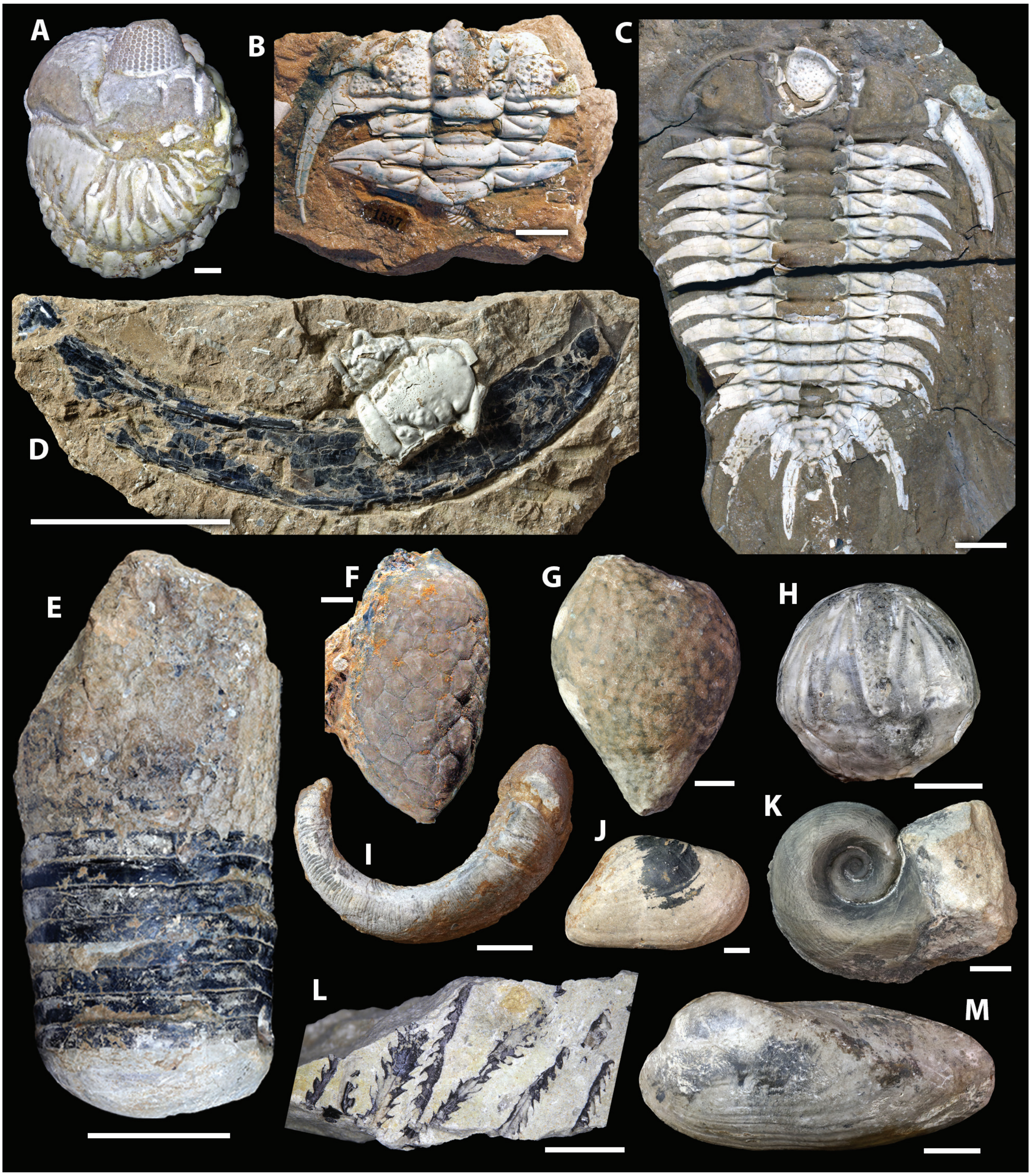

Fig. 9.10. Selected fossils from the Viivikonna Formation, Kukruse Stage (Sandbian). Scale bars: D, E – 5 cm; B–C, G - I, M – 1 cm; F, J, I – 5 mm; A – 1 mm. **A**–**C** – trilobites; **A** – *Estoniops exilis*, Kohtla, GIT 459-165; **B**, **C** – *Paraceraurus aculeatus*, **B** – Kukruse, TUG 1085-79, **C** – Kohtla-Järve, TUG 1672-52. **D** – cnidarian *Sphenothallus kukersianus* (together with a trilobite fragment), Kohtla, TUG 1087-32-1. **E** – cephalopod *Ormoceras*, North Estonia, GIT 695-51. **F** – eocrinoid *Heckerocrinus laevis*, Ubja, TUG 1589-137. **G**, **H** – blastozoans; G – *Echinosphaerites pirum*, Kiviõli, GIT 631-81; **H** – *Cystoblastus kokeni*, Kohtla-Järve, TUG 1727-548. **I**, **K** – gastropods; **I** – *Ecculiomphalus*, Küttejõu, GIT 343-89; **K** – *Bucania czekanowskii,* Küttejõu, TUG 666-37. **J**, **M** – bivalves; **J** – *Dystactella aedilis*, North Estonia, GIT 398-200; **M** – *Goniophora*, North Estonia, GIT 398-207. **L** – graptolite *Oepikograptus bekkeri*, Kohtla, GIT 343-613-1.

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Stop 10: Valaste waterfall and Baltic Klint

Oive Tinn

Location: Latitude 59.44411°N, longitude 27.33510°E; Ida-Viru County, NE Estonia.
Stratigraphy: Cambrian Series 2 to Darriwilian.
Status: Geological sightseeing spot of the Baltic Klint.
More information: https://geoloogia.info/en/locality/13283

The Baltic Klint is one of the most extensive outcrops of Lower Palaeozoic rocks in the world. The total length of the Baltic Klint is nearly 1200 km; the height reaches 56 meters (Fig. 10.1; Suuroja 2006). The Klint emerges at the western side of the Öland Island in Sweden, follows along the southern coast of the Gulf of Finland and reaches up to the Ladoga Lake in Northwest Russia. The nearly 300 km long North Estonian Klint is part of this large structure. Geologists value the Baltic Klint mostly because of the extraordinary preservation of the Lower Palaeozoic rocks that have not been subject to metamorphism and folding.

The section between Valaste and Saka is the highest and most spectacular, offering impressive views to the outcrop, as well as an uninterrupted panoramic view to the Baltic sea. The artificial Valaste waterfall, falling from the 54 m high North Estonian Klint, is the highest waterfall in Estonia. Its height is usually between 26 and 28 m, but after exceptionally heavy rainfalls the strong flow may erode a deep pit in the sandstone on the foot of the Klint, and the total height of the waterfall can be up to 30 meters. Downwards, the waterfall continues as a 10–15 m high rapid, flowing into the sea. In fact, the waterfall at Valaste is man-made. Due to the slight southward dip (3–4 m per 1 km) of the limestone layers and the absence of water outlet, the fields in the Klint area were suffering from excessive water during rainy seasons. At the beginning of the 19th century, a 7 km long and up to 2 m deep drain was made to aid water run off the manor's fields nearby. As a result, the water flow has cleaned and eroded the cliff face, exposing the Lower Cambrian to the Middle Ordovician sedimentary sequence. A platform has been constructed in front of the waterfall in order to make observing the site safer and more attractive.

The section (Fig. 10.2, 10.3) is stratigraphically similar to the Ontika Klint, 3 km west of Valaste (Mägi, 1990).

At its lowermost part, near the sea level, a shallow bank exposes the **Cambrian** "Blue Clay" of the Terreneuvian age (Lontova Formation). This formation contains pyritic trace fossils, occasional shells *Aldanella kunda* which belong to the purported small shelly fossils, and shells of *Platysolenites* (Hints 2014). It is noteworthy that regardless of the age, this lower Cambrian sediment has still

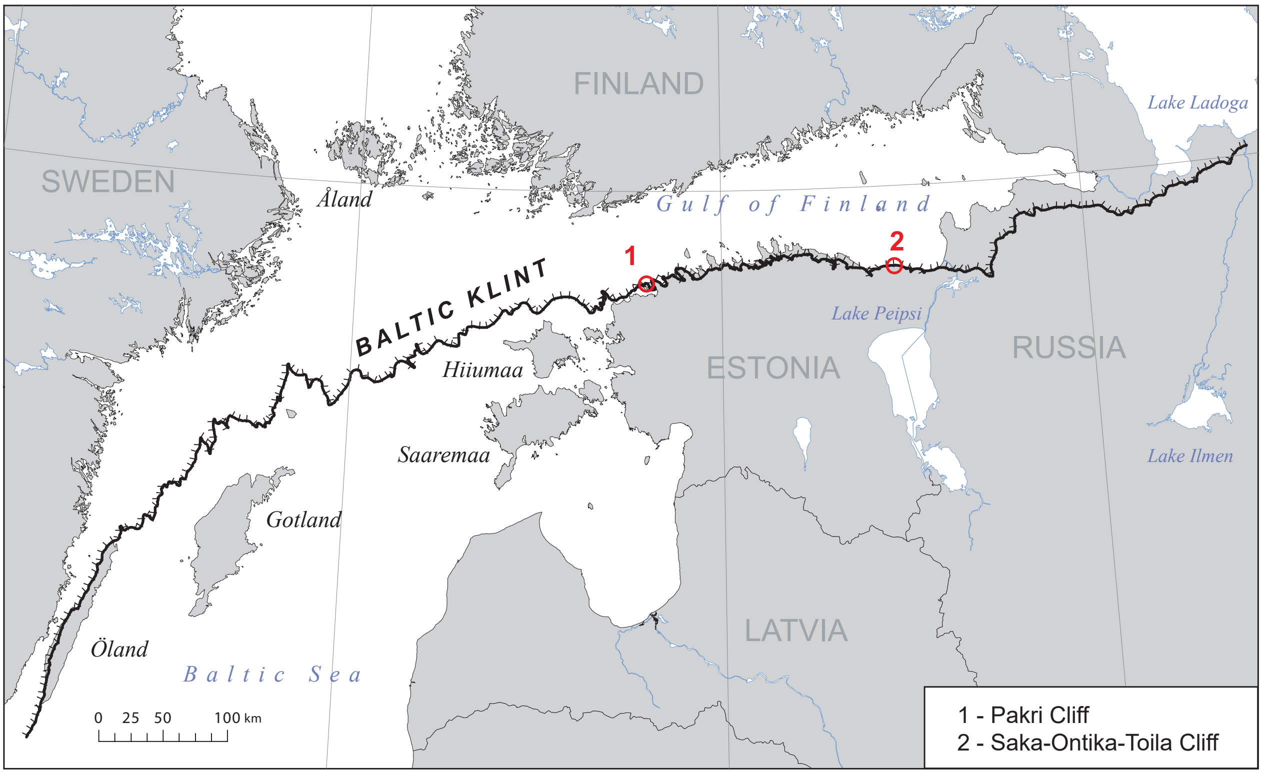

Fig. 10.1. Map showing the extent of the Baltic Klint - a 1200-km-long escarpment exposing Cambrian and Ordovician rocks.

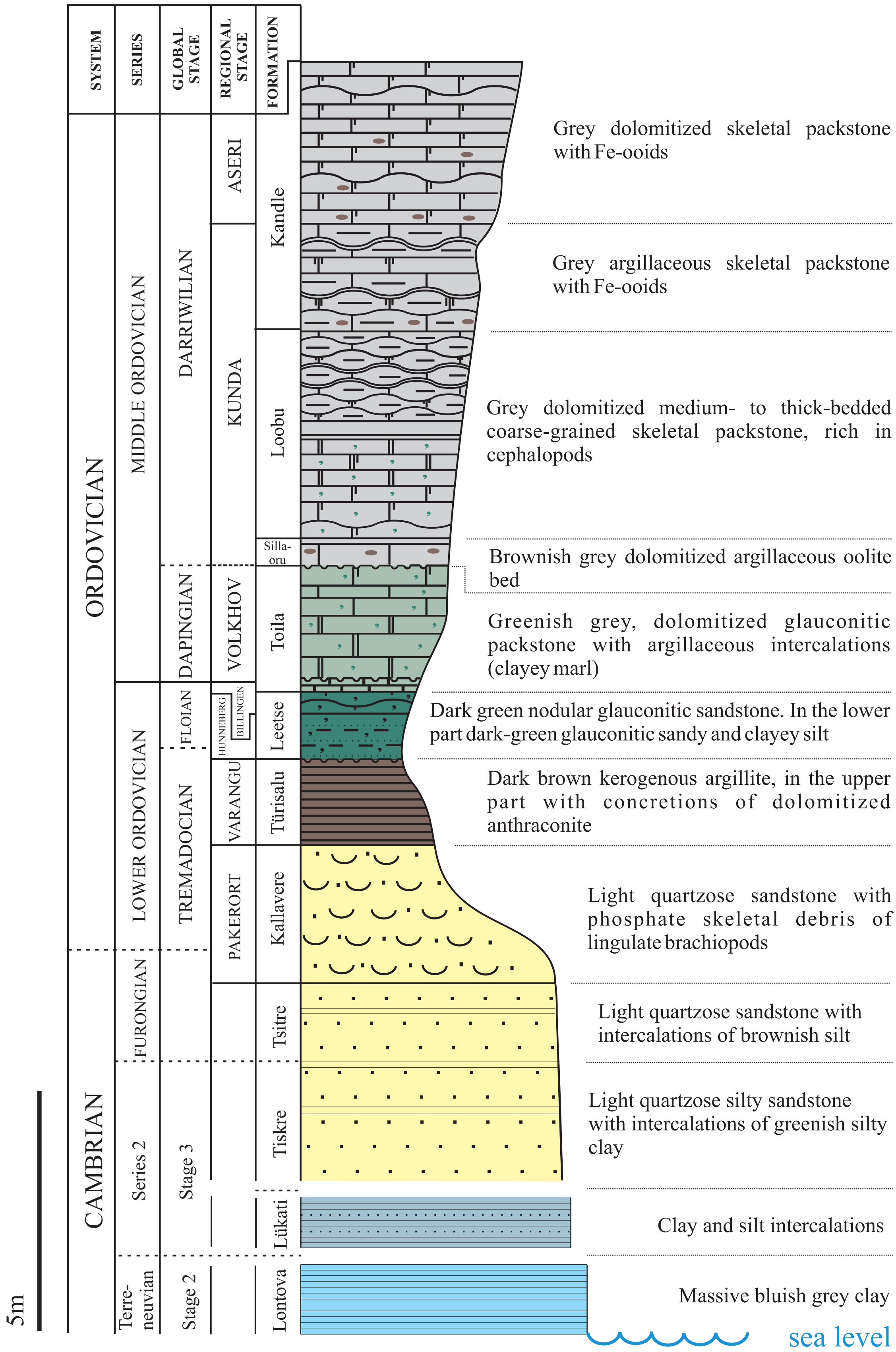

Fig. 10.2. Valaste waterfall section after Tinn 2004.

Fig. 10.3. Baltic Klint at Valaste, showing the succession of Cambrian Series 2 siliciclastics to Middle Ordovician carbonate rocks. Photo: Olle Hints.

retained its plasticity, which is explainable with the low burial depth and lack of thermal overprinting (Hints 2014). On the slope upwards, occasional partly buried banks of intercalated clay and silt of the Lükati Formation (Cambrian Series 2) can be spotted. A more continuous section starts with the light-coloured sandstones of the Tiskre, Tsitre and Kallavere formations. The latter of these yields lingulate shell fragments, as well as conodont *Cordylodus lindstroemi* (Heinsalu et al. 1991), which marks the Cambrian–Ordovician boundary within the lower part of the Kallavere Formation.

The Lower Ordovician is represented by the dark brown argillite of the Türisalu Formation (Tremadocian). At Valaste, this formation, and also the overlying dark green glauconitic sandstone of the Leetse Formation, are considerably thinner than in the western part of the North Estonian Klint on the Pakri Peninsula. However, the data on conodonts (Viira et al., 2006) indicate that stratigraphically the Valaste section is more complete than similar sections in the western part of the Klint escarpment. The Tremadocian–Floian boundary lies within the Leetse Formation.

The Middle Ordovician is represented by greenish-grey limestones of the Toila Formation (Volkhov Stage, Dapingian) and variable Darriwilian limestones of the Sillaoru, Loobu, Napa (Kunda Stage) and Kandle (Aseri Stage) formations. The base of the Darriwilian is tentatively drawn between the Volkhov and Kunda regional stages. The Darriwilian limestones are rich in fossils, including cephalopods, trilobites, brachiopods etc (Fig. 10.4).

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Fig. 10.4. Cephalopod limestone of the Kunda Regional Stage, lower Darriwilian is a typical rock type of the Baltic Klint successions. Sample from the Päite Cliff, NE Estonia. Photo: Avo Miidel, 2002.

Stop 11: Aru-Lõuna (Kunda-Aru) quarry

Leho Ainsaar

Location: Latitude 59.44406°N, longitude 26.47941°E; Lääne-Viru County, NE Estonia.
Stratigraphy: Darriwilian, Kunda to Uhaku regional stages.
Status: Active quarry; please follow safety instructions. Hammering and fossil collecting are welcome!
More information: https://geoloogia.info/en/locality/10007

The large, ca 3.5 km^2 in area, active Aru-Lõuna (Aru-South) limestone quarry is located south of the small town of Kunda and is operated by the company Heidelberg Materials Kunda AS. The limestone is used for the manufacture of cement and crushed limestone aggregate. Cement production in Kunda has a 130-year history.

The Aru-Lõuna quarry walls expose an excellent over 18 m thick succession of Middle Ordovician carbonates (Fig. 11.1, 11.4). The lower part of the Darriwilian Stage (Kunda and Aseri regional stages) is exposed by the smaller escarpments (ca 3 m) on the quarry floor (stop A; Fig. 11.2) or trenches. The main wall section (stop B; Fig. 11.3) spans the succession of the middle to the upper part of the Lasnamägi and lower to the middle part of the Uhaku regional stages, being coeval with the upper part of the Darriwilian Stage.

The boundary between the Kunda and Aseri regional stages is marked by a pyritised discontinuity surface with deep (8–15 cm) burrows (pockets; Einasto & Hints 2004). It is underlain by thick-bedded skeletal fine-detrital packstone with small glauconite grains of the Loobu Formation. The Kandle Formation of the Aseri Regional Stage is represented by oolitic limestone, medium-bedded brownish-grey skeletal packstone to grainstone with some sharp goethitic discontinuity surfaces. The thickness of the Kandle Formation is 1.3–1.5 m. The Aseri Stage represents the peak of the Middle Darriwilian Carbon Isotope Excursion on the δ^{13}C curves. It has been recognised in the Kandle Formation of the Aru-Lõuna quarry section, reaching the δ^{13}C of +1‰ on a background of +0.3‰ (Ainsaar et al. 2020).

Two main limestone units, the Väo and Kõrgekallas formations, are exposed in the southeastern quarry wall. The lower unit, Väo Formation (Lasnamägi and lower Uhaku regional stages), represents the main building limestone in the coastal areas in northern Estonia, including Tallinn. It is composed of light grey wackestone-packstone with a large number of distinct discontinuity surfaces and burrows. Thin interbeds (0.2–4 cm) of wavy microlaminated marlstone intercalate with limestone beds of 10–30 cm in thickness. The reddish-brown pattern of burrows is a characteristic feature of the Lasnamägi building stone. The total thickness of the Väo Formation is about 11 m, and it is subdivided into the Rebala, Pae, and Kostivere members.

The upper unit, Kõrgekallas Formation, is represented by wavy-bedded to seminodular argillaceous limestone (wackestone) with interbeds (8–20 cm) of pure skeletal packstone. The total thickness of the formation is about 10 m. The lowermost and middle members of the formation, the Koljala and Pärtliorg members, are exposed in the upper part of the main quarry wall and on the uppermost terrace in a thickness of 7 m.

For centuries, the Lasnamägi building limestone was quarried manually and used widely in the Tallinn area. Except for the formal lithostratigraphic units, the individual limestone beds have been referred to by names and numbers introduced during the long tradition of quarrying. In total, 70 individual limestone beds have been distinguished in the Väo and Kõrgekallas formations, each

Fig. 11.1. Overview of the Aru-Lõuna quarry. Photo: Leho Ainsaar, 2023.

represented by a sedimentary cycle of marlstone-limestone (Einasto & Hints 2004). Considering the depositional time for the whole interval ca 2.5–3 myr (Goldman et al. 2020) it gives an average time for the cycle 36–42 kyr, fitting well with the Milankovitch 41K obliquity cyclicity.

Fig. 11.2. Stop A in the Aru-Lõuna quarry. Photo: Leho Ainsaar, 2023.

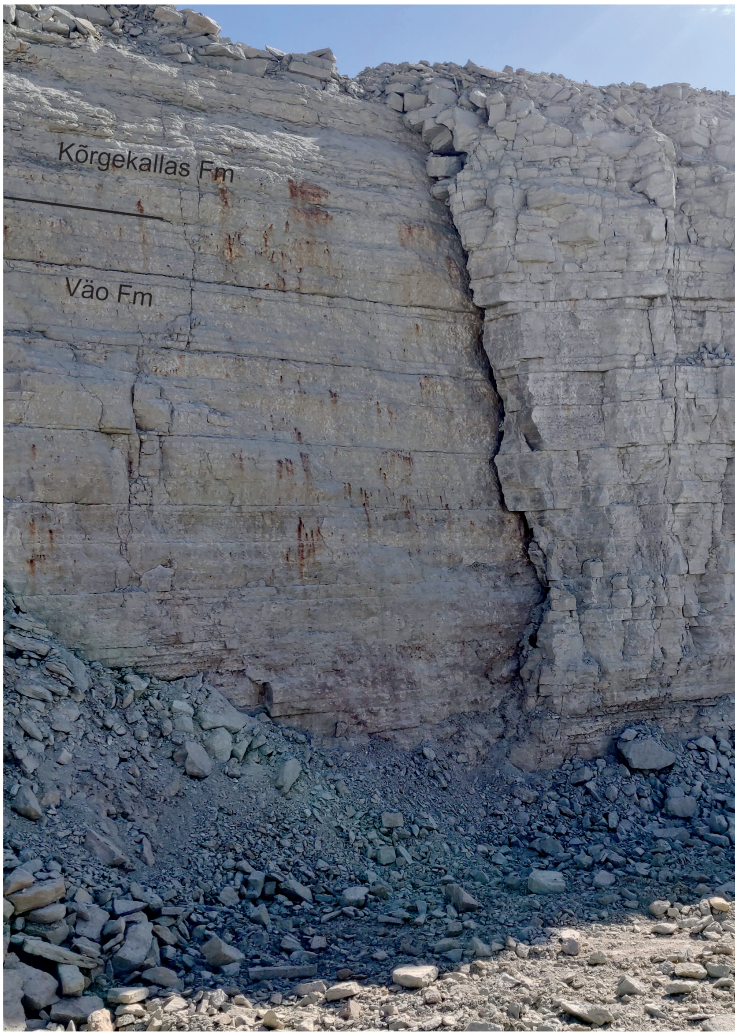

Fig. 11.3. Stop B in the Aru-Lõuna quarry. Photo: Leho Ainsaar, 2023.

The Aru-Lõuna quarry is rich in fossils, especially in the lower part of the succession (Fig. 11.5).

Description of the outcrop (modified from Einasto and Hints 2004)

Lasnamägi–Uhaku stages, Väo Formation

(a) The Rebala Member forms the lower part of the Väo Formation. The lowermost Rebala Member (2.8 m thick) is represented by thin-to thick-bedded argillaceous limestone, very seldom used as building stone. The thick-bedded lower part (0.75 m) is considered a good building stone, but excavating it below the argillaceous limestones is complicated. In the quarry, the Rebala Member is exposed only partly.

(b) The Pae Member is 0.8 m thick in the Aru quarry. The rocks of this member are commonly secondarily dolomitised and well visible as a more brownish belt in the sections. The dolomitisation is very weakly developed, and the member does not differentiate very clearly in the quarry walls. The Pae Member consists of medium- to thick-bedded, slightly argillaceous limestone with interbeds of calcareous marlstone (up to 10 cm thick in the upper part).

(c) The Kostivere Member, 7.5 m in thickness, is represented by light grey thick- to medium-bedded pure skeletal packstone with numerous distinct discontinuity surfaces, interbeds of marlstone, and some interbed of skeletal packstone marks the basal part of microcyclites. The member represents the best quality building stone in northern Estonia. By the bed-by-bed correlation of the stratotype Lasnamägi and Kunda sections using the distinctive beds named given by quarry workers, the boundary between the Lasnamägi and Uhaku stages is situated about 1.2 m higher from the base of the Kostivere Member.

Uhaku Stage, Kõrgekallas Formation

(a) The Koljala Member is 2.7 m thick and consists of relatively pure skeletal packstone and argillaceous limestone (wackestone) with marlstone interlayers. On the upper surfaces of less argillaceous limestone, there occur discontinuities with pockets, similar to those in the Lasnamägi Stage. They mark the boundaries of microcyclites. The kukersite kerogene grains appear in the marlstone interlayer in the upper part of the member (0.85 m). The upper bound-

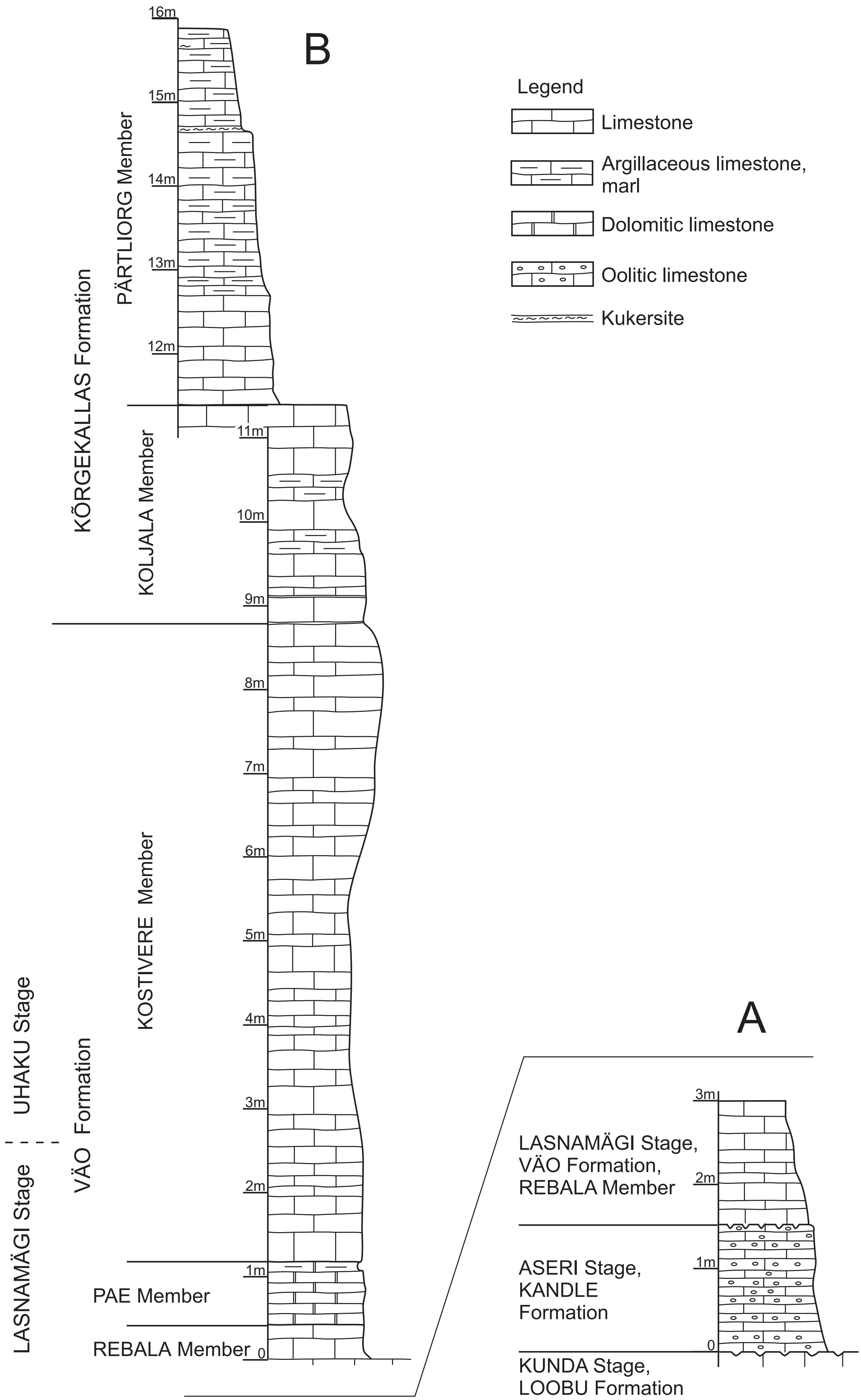

Fig. 11.4. Aru-Lõuna succession.

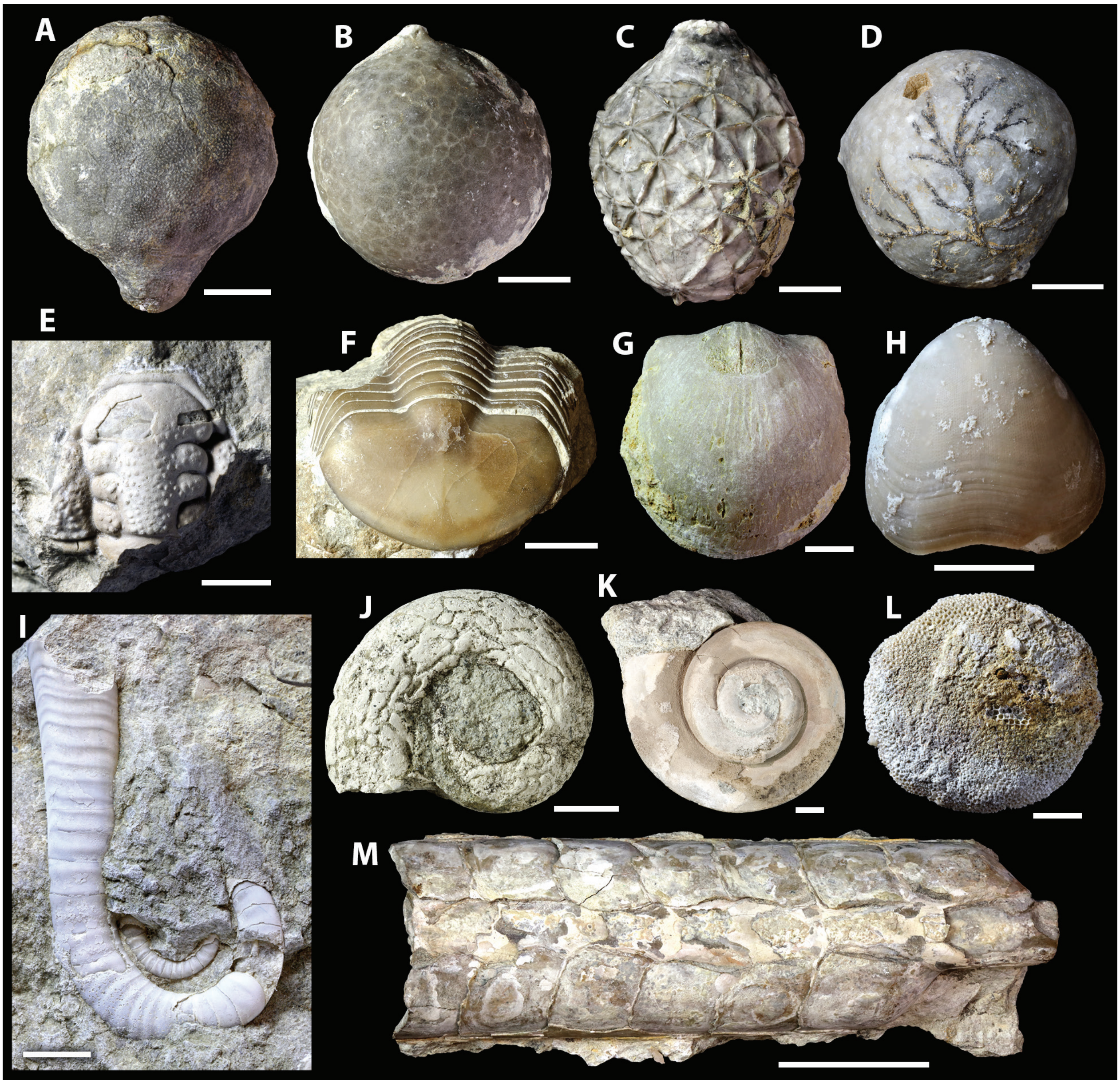

Fig. 11.5. Selected Darriwilian fossils from the Kunda-Aru quarry. Scale bars: M – 5 cm; A–F, H–J – 1 cm; G, K, L – 5 mm. **A–B** – blastozoans from the Kõrgekallas Formation; **A** – *Sphaeronites*, GIT 337-470; **B** – *Echinosphaerites aurantium*, GIT 398-348; **C** – *Heliocrinites*, GIT 398-357. **D** – graptolite *Hormograptus sphaericola*, attached to the cystoid *Echinosphaerites aurantium*, GIT 602-21. **E–F** –trilobites; **E** – *Paraceraurus*, Väo Formation, GIT 337-365; **F** – *Illaenus*, Kunda Regional Stage, GIT 437-73. **G–H** – brachiopods from the Kõrgekallas Formation; **G** – *Tallinnites imbrexoidea*, GIT 337-978; **H** – *Porambonites* (*Equirostra*) *aequirostris*, GIT 337-1303. **I**, **M** – cephalopods; **I** – *Lituites lituus*?, Väo Formation, GIT 337-366; **M** – fragment of large *Endoceras incognitum*, Kunda Regional Stage, GIT 225-1030. **J**, **K** – gastropods from the Kunda Regional Stage; **J** – trace fossil *Arachnostega gastrochaenae* on the gastropod *Lesueurilla helix* steinkern; **K** – *Pararaphistoma qualteriata*, GIT 337-960. **L** – bryozoan *Orbipora distincta*, Kõrgekallas Formation, GIT 337-1304.

ary is marked by the last distinct discontinuity surface with burrows (pockets).

(b) The Pärtliorg Member is exposed in thickness of 4.5 m, consisting of semi-nodular argillaceous wackestone with rare pure limestone (packstone) and marlstone interbeds with occasional kukersite enrichment and a 10 cm thick kukersite bed in the uppermost part.

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Excursion Day 4

Arbavere core repository and research centre

Tavo Ani

Location: Latitude 59.436332°N, longitude 25.983257°E; Lääne-Viru County, northern Estonia.
More information: https://egt.ee/maapouealane-teave/arbavere-uurimiskeskus/arbavere-uurimiskeskusest

The Arbavere drill core warehouse is a facility that stores and displays drill cores from various geological formations and mineral deposits in Estonia. It is part of the Arbavere drill core research centre, which was established by the Geological Survey of Estonia in 2018.

The first geological station and drillcore storage in the Arbavere area was established in the early 1970s (Suuroja 2020). Its purpose was storing and studying basement drill cores. The place was chosen because of its vicinity to the areas of basement geological mapping and phosphorite exploration and otherwise suitable geographic position. During the 1970s, about 40 km of cores were drilled per year. They were used in geological mapping, hydrogeological research and exploration of mineral resources. In 1975, the initial field station moved into an old farm named "Palkoja" across the Loobu river. In the early years, an old farmhouse offered accommodation for geologists, but soon drill core warehouses were built, and the old farmhouse was replaced by a newer facility. Geologists were working in the field station the whole year. Subsequently, additional warehouses and other facilities were built. These were completed in 1978, and the next decade constituted a golden age for geology due to active drilling in NE Estonia for 1:50000 geological mapping, exploration of phosphorite and identifying the mineral potential of basement rocks. By the 1990s, Arbavere was hosting approximately 10 thousand core boxes from Estonia.

The Arbavere research centre has always been used also for field practice and studies for researchers and students from Tallinn and Tartu. Between 1993 and 2017, the field station suffered from the reorganisation and uncertain status of the Geological Survey as well as lack of proper funding.

In 2018, the Geological Survey of Estonia was re-established as a state institution under the Ministry of Economic Affairs and since then the Arbavere Centre has seen major improvement of drill core storage and study facilities and supporting infrastructure. It has been decided that Arbavere will become the central state core repository in Estonia. By 2023, six new warehouses have been built, accompanied with research rooms and technical possibilities. In June 2023, a new research building was opened and the developments continue in upcoming years.

At present the warehouses host more than 120 kilometres of drill cores (EGT 2023), and the amount is constantly expanding with new additions from ongoing exploration and research projects. The field station also provides services for drill core description, sampling and in-situ analyses. The latest investment has been a drillcore log-

Estonian Geological Survey's Arbavere drill core repository and research center. Photo: Sirli Sipp-Kulli, 2023.

ger, which combines XRF, photospectrometer, high-resolution camera and magnetic susceptibility detector and other sensors. It is a valuable tool for applied geologists as well as for researchers and students who study the geology and mineral resources of Estonia.

During the ISOS-14 conference, three reference drillcores covering the entire Ordovician succession in different parts of Estonia will be demonstrated: Männamaa (Põldvere 2008), Kolu (Nezdoli et al. 2022) and Ruhnu (Põldvere 2003).

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Stop 12: Männamaa drill core, western Estonia

Marko Kabel

Location: Latitude 58.83816°N, longitude 22.62839°E; Hiiumaa Island, western Estonia.
Stratigraphy: Complete Ordovician succession from the Tremadocian to Hirnantian.
Status: Reference section, drilled for geological mapping in 1988.
More information: https://geoloogia.info/en/locality/498

The Männamaa (F-367) borehole was drilled in the central part of Hiiumaa Island, western Estonia, with the aim of 1:200000 deep geological mapping (Põldvere 2008). The borehole is 358.3 m deep. The Ordovician strata in the Männamaa core are covered by the 29 m thick Quaternary cover and ca 17 m of Silurian limestones. Ordovician strata start from a depth of 46 m and continue until 183 m. Being near to the Kärdla impact crater (Sandbian in age), the succession is weakly influenced by its ejecta in the Tatruse Formation, Haljala Regional Stage. During different periods, the core has been sampled for microfossils (chitinozoans, acritarchs, ostracods etc), geophysics and geochemistry (e.g., Grahn et al. 1996; Hints et al. 2010; Kiipli et al. 2008; Meidla and Ainsaar 2008; Meidla and Tinn 2008; Nõlvak 2008; Põldvere et al. 2008; Shogenova and Shogenov 2008; Truuver et al. 2021; Suuroja et al. 2008; Uutela 2008).

Fig. 12.1. Männamaa F-367 core box No 34, showing a series of Sandbian K-bentonites with the Kahula Formation, including the infamous Kinnekulle Bed, which marks the base of the Keila Regional Stage. Photo from the Estonian Land Board database.

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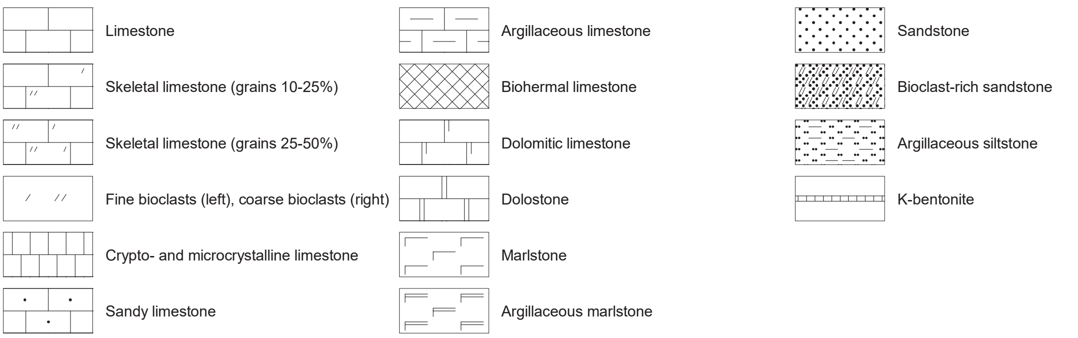
Lithological log legend:



Männamaa (F-367) core interval 37-190 m

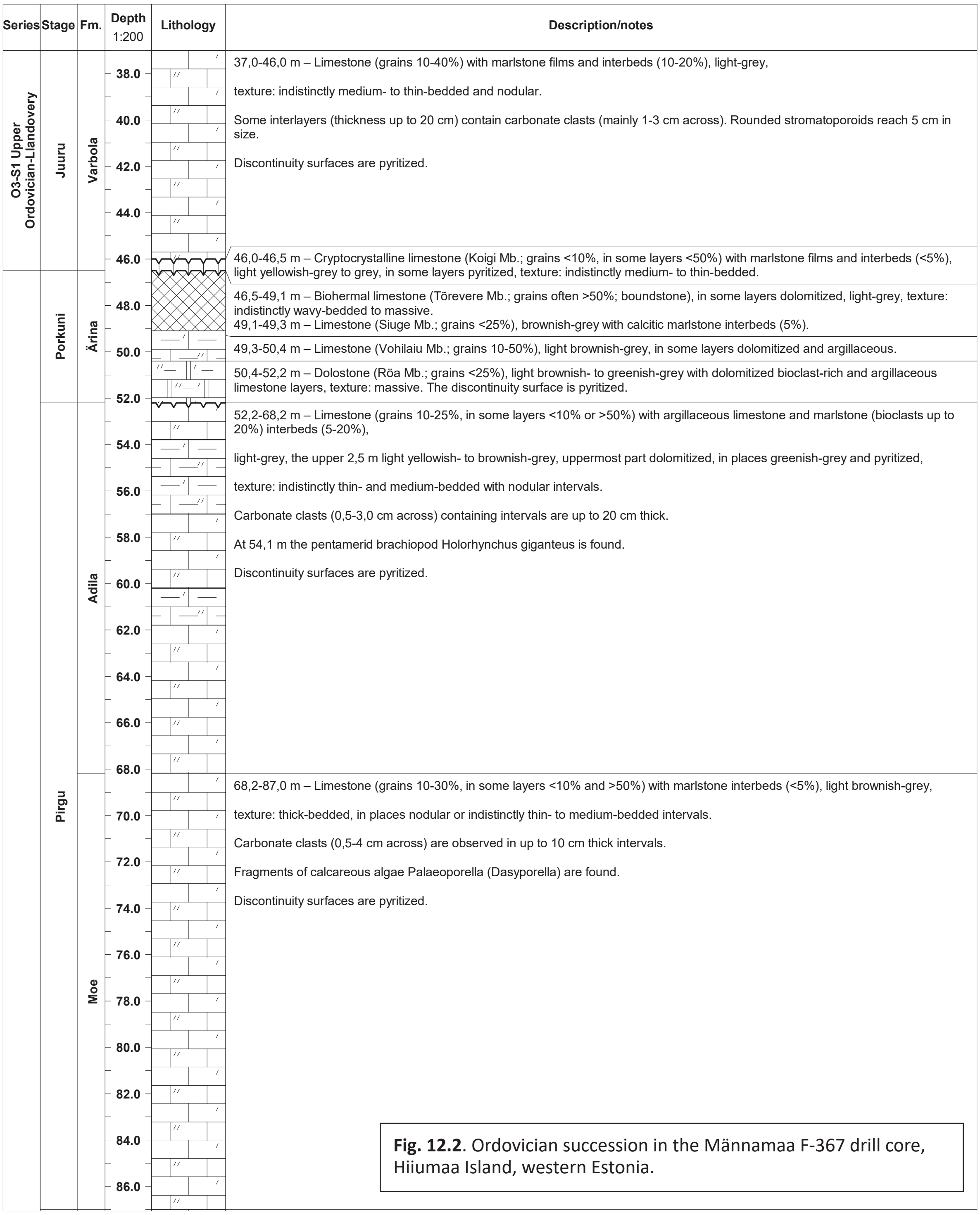
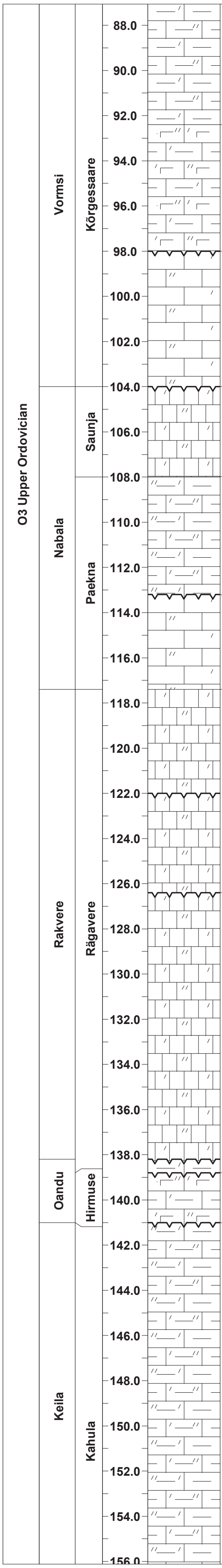


Fig. 12.2. Ordovician succession in the Männamaa F-367 drill core, Hiiumaa Island, western Estonia.



87,0-92,4 m – Limestone (grains 10-30%), light grey, slightly argillaceous with interbeds of highly argillaceous limestone and marlstone (bioclasts up to 30%),

texture: thin- and medium-bedded, rarely thick-bedded and nodular.

The discontinuity surface is pyritized.

92,4-98,0 m – Calcareous marlstone (bioclasts in some layers up to 50%), dark greenish-grey, intercalation with greenish-grey, medium to highly argillaceous limestone (grains 10-25%),

texture: thin- and medium-bedded, in places nodular.

Phosphatized discontinuity surfaces lie on the lower boundary.

98,0-104,0 m – Limestone (grains 10-25%, in some layers <10%, often pyritized), light grey and yellowish-grey, with marlstone (bioclasts up to 30%) interbeds (5-10%),

texture: thin- and medium bedded, in places nodular.

A phosphatized and pyritized discontinuity surface lies on the lower boundary.

104,0-108,0 m – Limestone (grains <10%, in some layers <25%), beigish light-grey, with rare calcitic marlstone interbeds (1-2%),

texture: indistinctly thin- and medium-bedded.

Calcite-filled primary and secondary veins are found.

108,0-113,2 m – Limestone (grains 25-50%), light greenish-grey, slightly argillaceous with marlstone (bioclasts up to 50%) interbeds (5-20%),

texture: thin- and medium-bedded, rarely indistinctly nodular.

At 108,5-109,1 m lies a beigish-grey, burrowed micro- to cryptocrystalline limestone interbed.

Discontinuity surfaces are pyritized.

113,2-117,4 m – Limestone (grains 10-25%), light-grey, with marlstone (bioclasts up to 10%) interbeds (<5%),

texture: indistinctly thin- and medium-bedded.

Discontinuity surfaces are pyritized.

117,4-126,4 m – Limestone (Tudu Mb.; grains 10-25%), light beigish-grey, with rare marlstone interbeds (<5%),

texture: thin- and medium-bedded, very rarely thick-bedded.

The uppermost 0,5 m contains kerogenous interlayers, at 117,45 and 117,7 m lie dark brown distinct kukersite oil shale interbeds (thickness 1 cm and 5 cm, respectively).

Discontinuity surfaces are pyritized.

126,4-138,2 m – Limestone (Piilse Mb.; grains <10%, in some layers 30%), light-grey, with rare marlstone interbeds (<5%),

with small pyrite mottles (especially at 128,0-133,0 m), in places with beige shade,

texture: thin- and medium-bedded.

Calcite-filled veins occur.

138,2-138,8 m – Limestone (Tõrremäe Mb., grains 10-25%, rarely <40%), light grey, slightly argillaceous with rare marlstone interbeds (5%), texture: indistinctly medium- and thin-bedded.

Discontinuity surfaces are pyritized.

138,8-141,0 m – Calcareous marlstone (bioclasts in some layers up to 40%), dark greenish-grey, intercalation with light greenish-grey, in some layers dolomitized, slightly to highly argillaceous limestone (grains 10-30%). Clay content increases downwards.

141,0-157,3 m – Argillaceous limestone with calcareous marlstone intercalations.

Limestone (grains 25-60%) is light grey or greenish-grey, mainly medium to highly argillaceous. Grain content increses upwards, in some layers bioclasts are accumulated in up to 5 cm high conic bodies with distinct edges. At 144,0-146,0; 148,0-148,8 and 154,0-155,0 m interlayers of slightly argillaceous, often microcrystalline limestone are common.

Marlstone (bioclasts in some layers up to 40%) prevails in the intervals 141,0-142,6; 146,2-147,4; 149,0-152,6 and 155,0-156,9 m, where calcite and clay content changes in thin layers and patches.

Texture: indistinctly nodular or thick- to medium-bedded, with micro- to thin-bedded intervals (thickness up tp 10 cm).

Fig. 12.2 (continued). Ordovician succession in the Männamaa F-367 drill core, Hiiumaa Island, western Estonia.

At 156,44 m and on the stage boundary lie greenish-grey K-bentonite beds (thickness 1 cm and 40 cm (Kinnekulle), respectively).

157,3-158,6 m limestone (Jõhvi Substage; grains 25-50%), light greenish-grey, with rare marlstone interbeds (<5%), texture: medium- and thick-bedded. At 157,7 m lies 2 cm K-bentonite bed.

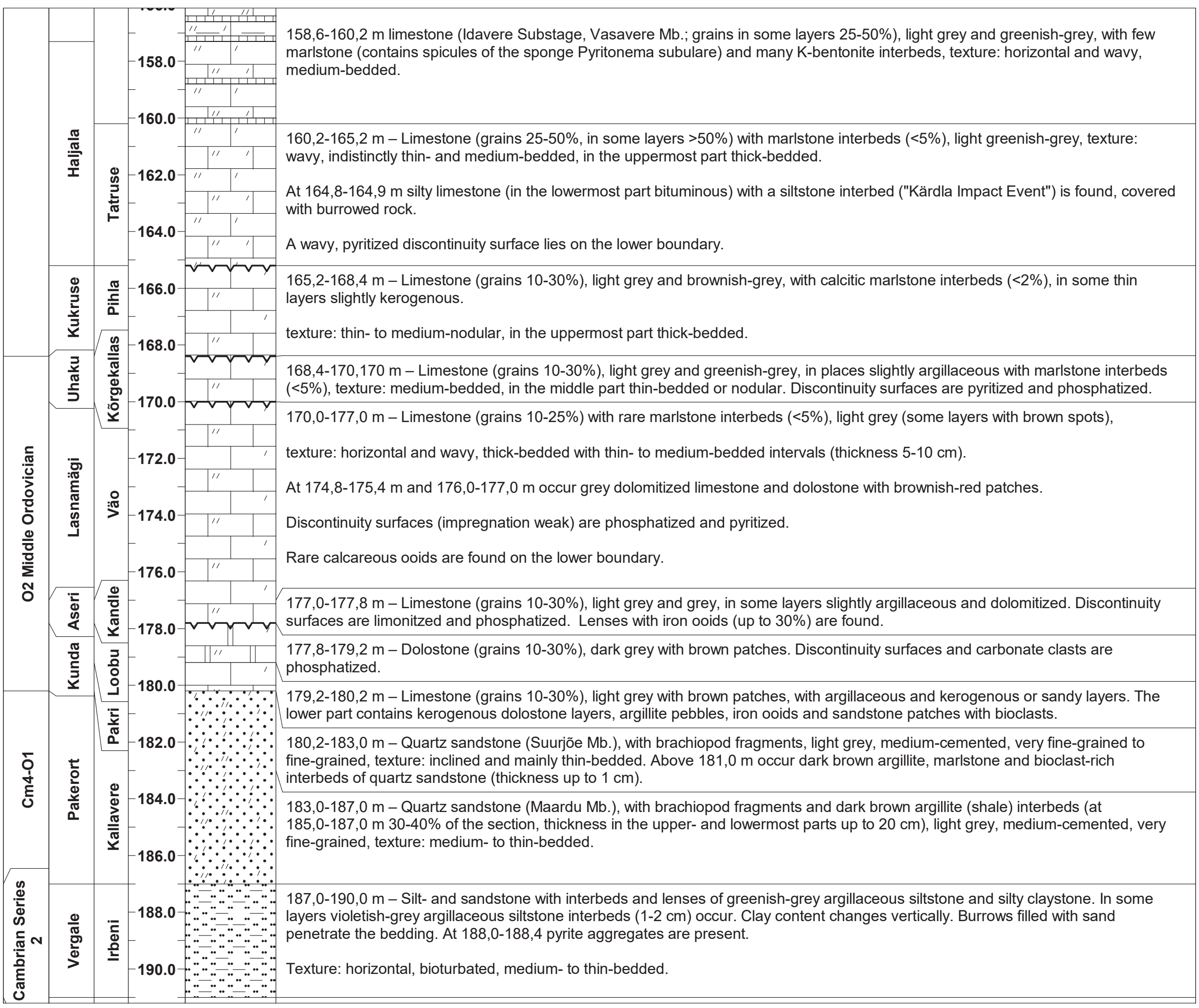


Fig. 12.2 (continued). Ordovician succession in the Männamaa F-367 drill core, Hiiumaa Island, western Estonia.

Stop 13: Kolu drill core, Central Estonia

Marko Kabel

Location: Latitude 58.81051°N, longitude 25.24221°E; Järva County, central Estonia.
Stratigraphy: Complete Ordovician succession from the Tremadocian to Hirnantian.
Status: Reference section, drilled for geological mapping in 2021.
More information: https://geoloogia.info/en/locality/24828

The Kolu EGT0016, drilled in 2021 in central Estonia, is one of the newest deep cores that reaches basement rocks in Estonia (Nezdoli et al. 2022). It has dip 80.9°, elevation of 56 m asl, and its depth is 550.60 m. The Quaternary cover is 9.2 m thick, followed by Llandovery Rumba Formation. The Ordovician–Silurian boundary is probably between 100–104 m depth, within the Varbola Formation, Juuru Regional Stage. The lower boundary resides within the Kallavere Formation, probably near the depth of 271–272 m. In addition to coring, the Kolu borehole was logged using gamma log, cavernometry, temperature, electric resistivity, density and optical camera.

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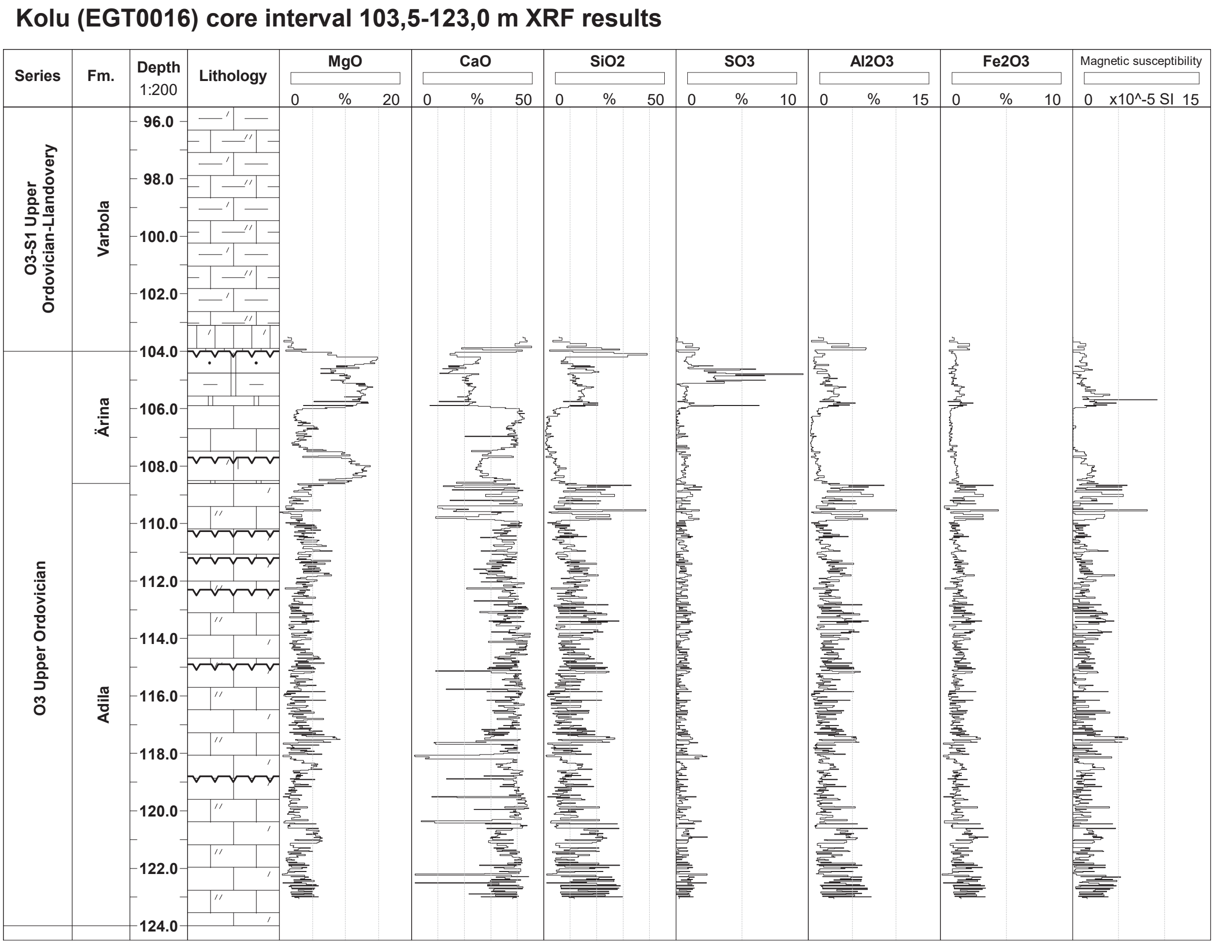


Fig. 13.1. Example results of XRF scanning of main elements across the Hirnantian (Porkuni Regional Stage) in the Kolu drill core. Geotek MSCL-XYZ Core Workstation scanner at the Arbavere Center was used. Note the cyclic patterns of several elements in the Adila Formation.

Kolu (EGT0016) core interval 95,5-280 m

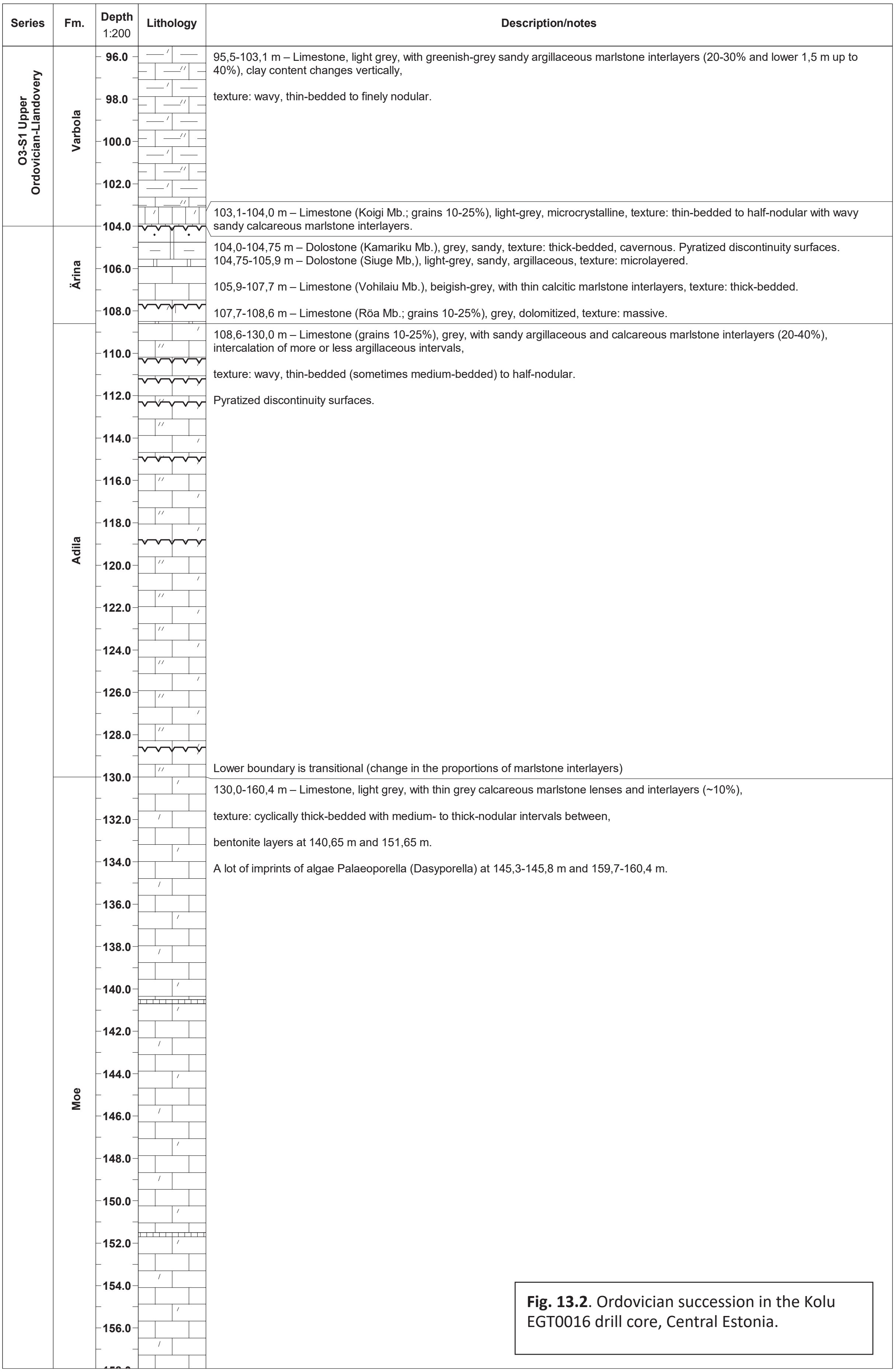
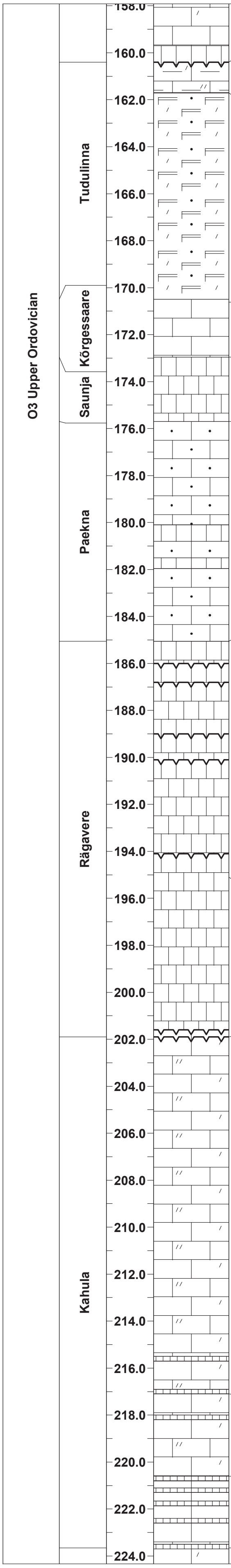


Fig. 13.2. Ordovician succession in the Kolu EGT0016 drill core, Central Estonia.



159,7-160,4 m – Limestone, microcrystalline, beigish-grey, cavernous (dissolved fragments of calcareous algae Palaeoporella (Dasyporella). On the lower boundary pyritized discontinuity surface.

160,4-161,7 m – Limestone (grains 10-25%), grey, slightly argillaceous, with thin marlstone interlayers and films, texture: thin- to medium-bedded or half-nodular. Lower boundary is transitional.

161,7-170,5 m – Marlstone (bioclasts 10-25%), dark-greenish grey, argillaceous, sandy, dolomitic, with little purple patches and slightly argillaceous grey limestone nodules (20-50%),

texture: thin- to thick-bedded.

Lower boundary is transitional.

170,5-172,95 m – Limestone, grey, with thin greenish-grey calcareous marl interlayers and films (~10%), texture: wavy, medium-bedded to half-nodular. Pyratized discontinuity surfaces.

172,95-175,7 m – Limestone, cryptocrystalline, beigish-grey, with brownish-grey marlstone films, texture: wavy, medium-bedded.

Contains rare blueish pyritic patches.

175,7-185,05 m – Limestone, grey, sandy, slightly argillaceous with greenish-grey calcareous marlstone interlayers and films (30-40%),

texture: wavy, medium-bedded to half-nodular (183,3-185,05 m medium- to thick-bedded).

Cryptocrystalline limestone at 180,1-180,8 m and 181,5-181,95 m.

185,05-195,1 m – Limestone (Tudu Mb.), cryptocrystalline, light-grey to beigish-grey, with thin dark-grey calcareous marlstone interlayers and films,

texture: wavy, medium-bedded.

Kukersitic marlstone interlayers: 187,1 m (1 cm); 188,0 m (5 cm); 188,45 m (2 cm); 189,9 m (3 cm); 190,2 m (3 cm).

Lower boundary is transitional.

195,1-201,6 m – Limestone (Piilse Mb.), cryptocrystalline, light-grey to beigish-grey, with thin grey calcareous marlstone interlayers,

texture: wavy, medium-bedded.

Contains rare blueish pyritic patches.

201,6-201,9 m Limestone (Tõrremäe Mb.), grey, with few grey marlstone interlayers and blueish-grey pyritic patches, texture: wavy, medium- to thick-bedded. On the lower boundary broken pyritic discontinuity surface.

201,9-217,1 m – Limestone (grains 10-25%), greenish-grey, in intervals argillaceous, with greenish-grey marlstone interlayers.

texture: irregularly half-nodular (a few medium-bedded layers).

Upper 10 cm (probably destoyed during drilling) limestone with pyritic discontinuity surfaces (Hirmuse Fm.).

K-bentonite layers: 215,6 m (5 cm) and on the lower boundary at 217,1 m (10 cm; Kinnekulle).

217,1-220,6 m – Limestone (grains 10-25%), grey, slightly argillaceous, texture: wavy, indistinctly thin- tho medium-bedded (upper 1 m half-nodular). K-bentonite 218,15 m (5 cm).

220,6-223,65 m – Limestone (Vasavere Mb.), light grey, with greenish-grey calcareous marlstone (thickness 2-10 cm) interlayers, texture: medium-bedded. Marlstone interlayers contain white Pyritonema spicules.

K-Bentonite layers: 220,7 m (1 cm); 221,15 m (5 cm); 221,75 m (5 cm); 222,5 m (2 cm); 223,6 m (5 cm).

Fig. 13.2 (continued). Ordovician succession in the Kolu EGT0016 drill core, Central Estonia.

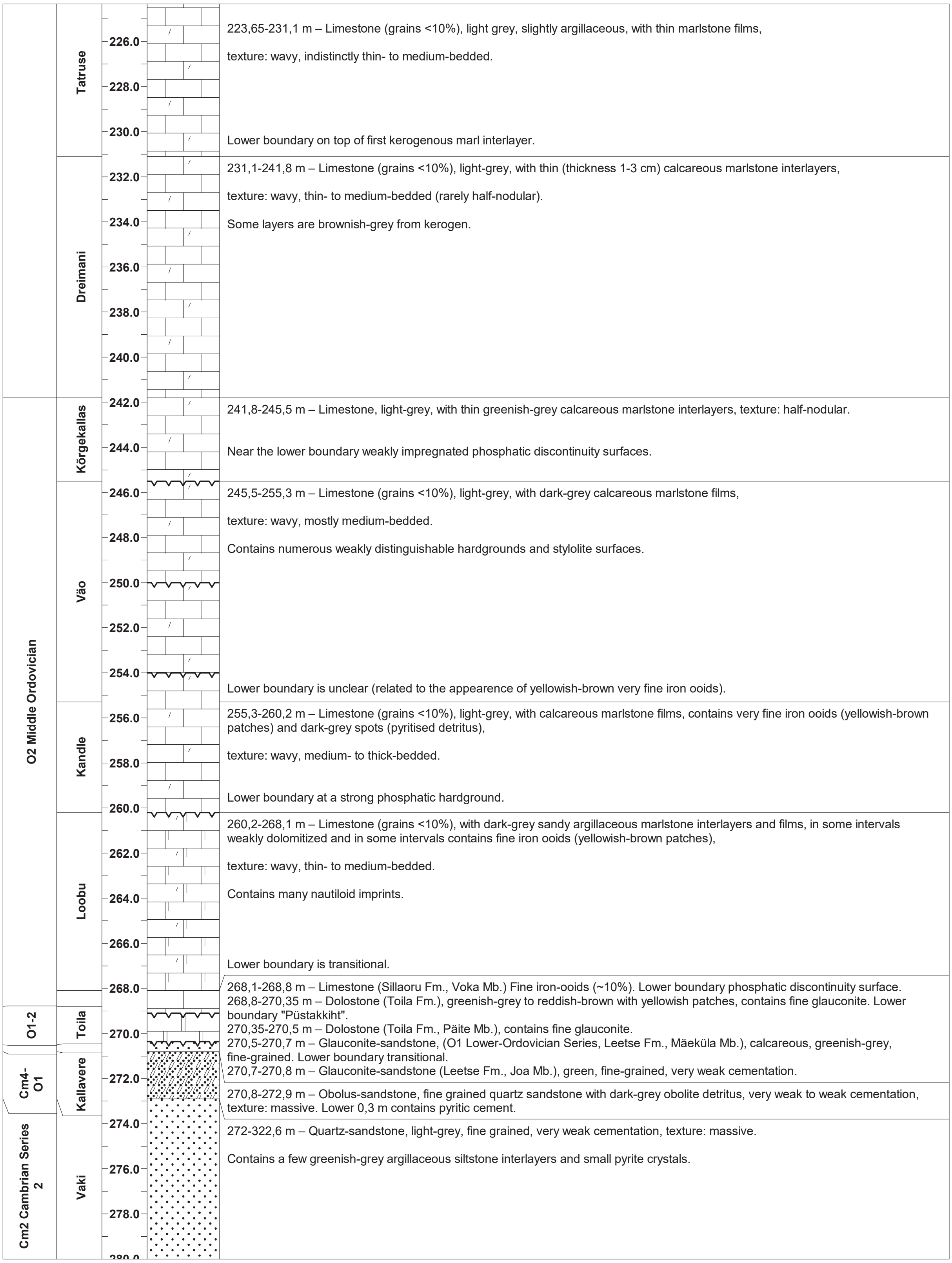


Fig. 13.2 (continued). Ordovician succession in the Kolu EGT0016 drill core, Central Estonia.

Stop 14: Ruhnu drill core, SW Estonia

Marko Kabel

Location: Latitude 57.80316°N, longitude 23.24135°E; Ruhnu Island, SW Estonia.
Stratigraphy: Complete Ordovician succession from the Tremadocian to Hirnantian.
Status: Reference section, drilled for oil and gas prospecting in 1972.
More information: https://geoloogia.info/en/locality/972

The Ruhnu (500) core was drilled in 1972 on Ruhnu Island (Põldvere 2003). It is one of the deepest boreholes in Estonia, with a total length of 787.4 m. The primary purpose of the drilling was prospecting for oil and natural gas. This attempt failed, and only Cl-Ca-Na type mineral groundwater (salinity 17 g/l) was found in the lower and middle Cambrian sediments. The Quaternary cover in the area is about 8 m. Below that, the Eifelian Narva Formation occurs. The thickness of the Devonian is 138.3 m, and the Silurian strata are about 454.9 m thick, reaching a depth of 601 m. The boundary between the Ordovician and Silurian systems most likely correlates with a level within the Õhne Formation. Thus, the Ordovician succession is ca 106 m thick. The Ordovician succession in this area corresponds to the relatively deeper-water environments, which are characteristic of South Estonia, Latvia and Sweden.

The Ordovician succession in Ruhnu drillcore has been heavily sampled and analysed for palaeontology, geochemistry and geophysics. Many tens of research papers have been published using the data from the Ruhnu core and making it one of the key Ordovician–Silurian sections in Baltoscandia.

The section is well characterised palaeontologically, and numerous brachiopods, conodonts, chitinozoans, graptolites, agnathan and fish microremains, ostracods and other fossils have been collected.

References

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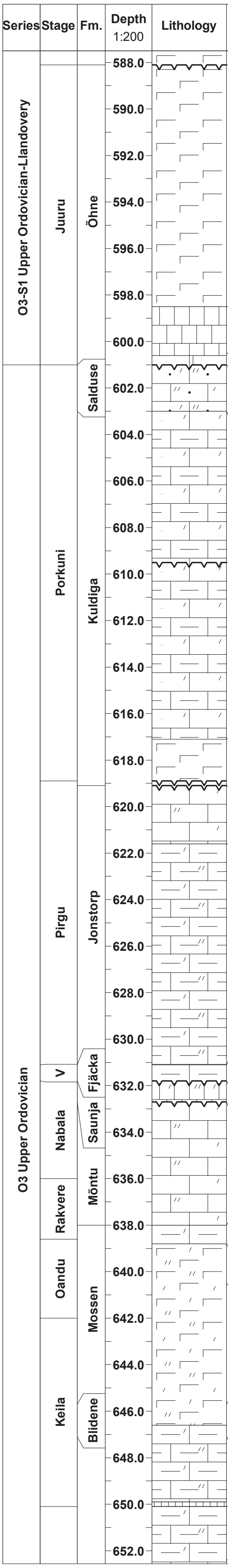
Ruhnu (500) core interval 588-720 m



Description/notes

588,1-598,5 m – Calcareous marlstone, greyish-green and violetish-brown, with interbeds and nodules of slightly argillaceous limestone (grains <10%),

texture: wavy, irregularly medium- to thin-bedded and medium- to thin-nodular.

598,5-600,6 m – Cryptocrystalline limestone (grains <10%), light grey, slightly argillaceous with calcareous marlstone interbeds (20-40%), texture: wavy, irregularly nodular.

600,6-601,0 m – Limestone, greyish-green, slightly to highly argillaceous, dolomitized. The wavy discontinuity surface is pyritized.

601,0-603,0 m – Limestone (grains 10-50%, in some layers >50%), light grey, containing ooids, sandy, texture: cross- and micro- to thin-bedded. Content and diameter (mostly up to 1 mm) of carbonate ooids increases upwards. Well rounded quartz sand interbeds (thickness 0,5-2 cm) are present.

603,0-609,5 m – Limestone (grains 10-25%), dark greenish-grey, with calcitic marlstone interbeds, clay content changes vertically,

texture: wavy, medium- to thin-bedded or thick- to thin-nodular.

In the upper part, irregular, up to 5 cm, bluish-grey limestone interbeds (more numerous in the upper part) contain carbonate clasts or pellets and quartz sand.

The discontinuity surface on the lower boundary is pyritized.

609,5-617,1 m – Limestone (grains 10-25%), greenish-grey, slightly argillaceous, interbedded with calcareous marlstone (bioclasts <10%) containing skeletal fragments,

texture: wavy, irregularly thin- to thick-bedded.

The clay content increases upwards.

617,1-618,9 m – Calcareous marlstone, light greenish-grey, with nodules and clasts of highly argillaceous limestone (grains 10-25% and in some layers 25-50%), texture: massive, sometimes nodular. In the lower part skeletal fragments concentrate in layers. Burrows are filled with brown marlstone and rust-coloured iron compound.

619,1-621,6 m – Limestone (grains 10-25%), brownish-red, at some levels dark yellow, with calcitic marlstone interbeds (10-20%). The marl content changes vertically. Crinoids are dominating. Discontinuity surfaces are goethitized or not impregnated.

621,6-631,1 m – Limestone (grains 10-25%), argillaceous, brownish-red, with calcitic marlstone (bioclasts 10-25%) interbeds (40-50%, upper part 20%),

texture: wavy, thin-nodular, lower 0,6 m medium-bedded or medium-nodular.

The clay content decreses upwards.

Flat iron ooids occur on the lower boundary.

631,1-631,8 m – Limestone (grains <10%), greenish-grey and light-grey with limonitized spots, argillaceous, with shale-like marlstone interlayers (35%).

631,8-632,7 m – Limestone (grains 10-25% and 25-50%), in some layers cryptocrystalline, yellowish-grey.

632,7-638,0 m – Limestone (grains 10-25%, in the lower part 25-50%), light greenish-grey (upper 0,5 m violet spots), with calcareous marlstone interbeds (5-7%),

texture: irregularly thin- to medium-bedded, some layers are thick-bedded.

Discontinuity surfaces are rust-coloured (limonitized?)

638,0-638,8 m – Limestone (grains <10% or 10-25%), light grey to greenish-grey, with calcitic marlstone (40%; bioclasts 10-25%) interbeds, texture: irregularly nodular. Discontinuity surfaces are pyritized.

638,8-640,50 m – Calcareous marlstone (bioclasts 10-25%), greenish-grey, with rare nodules of argillaceous limestone (20-30%; grains <10%), texture: massive and in some layers nodular.

640,5-645,7 m – Calcareous marlstone (bioclasts 10-25%), dark greenish-grey, dolomitized, in the lower part argillaceous,

texture: wavy, indistinctly bedded, in some layers thin-nodular.

Contains angular fine quartz grains.

645,7-647,1 m – Calcareous marlstone (bioclasts 10-25%), dark greenish-grey, dolomitized, with rare limestone nodules, texture: wavy, indisctinctly bedded or nodular.
Basal 0,5 m is greenish-grey, highly argillaceous limestone with calcareous marlstone interbeds.

647,1-650,1 m – Limestone (unsorted grains 10-25%, in some layers >50%), light grey and greenish-grey, argillaceous, with calcareous marlstone interbeds (30%) and greenish-yellow to light grey microbedded K-bentonite claystone (20 cm) on the lower boundary. Texture: wavy, thin- to medium-bedded or irregularly nodular.

650,1-652,4 m – Limestone (grains 10-25%), light greenish-grey, argillaceous, in some layers microcrystalline with interbeds of calcareous marlstone (30-40%), texture: wavy, thin- to medium-bedded or irregularly nodular.
Iron ooids are found.

Fig. 14.1. Ordovician succession in the Ruhnu 500 drill core, SW Estonia.

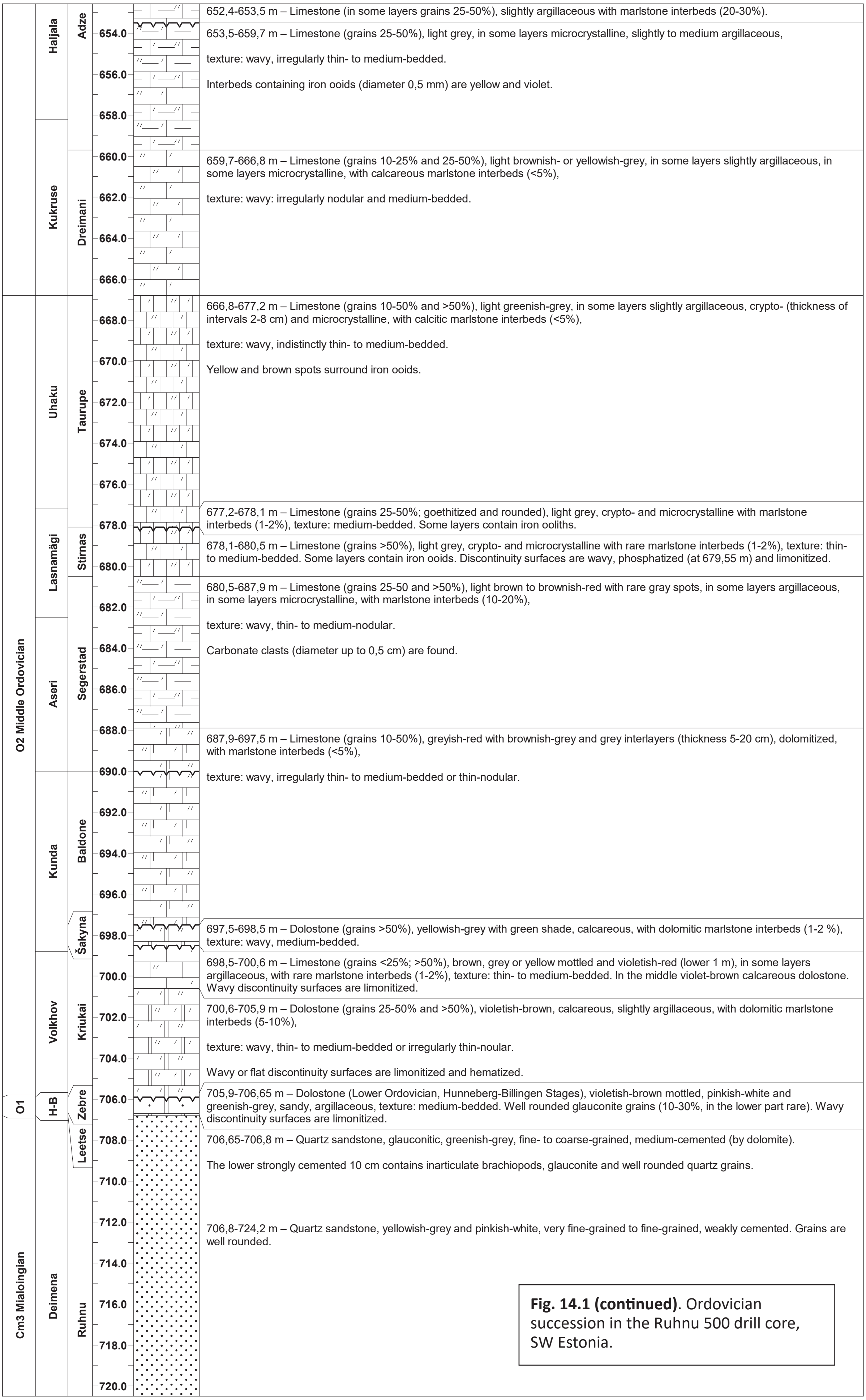


Fig. 14.1 (continued). Ordovician succession in the Ruhnu 500 drill core, SW Estonia.

Stop 15: Nõmmeveski waterfall and canyon

Oive Tinn

Location: Latitude 59.50937°N, longitude 25.79010°E; Harju County, North Estonia.
Stratigraphy: Tremadocian to Darriwilian, from the Pakerort to Aseri regional stages.
Status: The outcrop is under nature protection – no hammering.
More information: https://geoloogia.info/en/locality/12189

The Nõmmeveski waterfall and canyon are located in the Lahemaa National Park, a scenic area in North Estonia about 50 km east of Tallinn, rich in forests, flora and fauna. At Nõmmeveski, the Valgejõgi River has eroded a canyon typical for many rivers in northern Estonia. The canyon was cut at the place where the water was spilled over the edge of the Baltic Klint (Fig. 15.1). The canyon and the 1.2 meter-high waterfall on its bottom mark the location of the klint at Nõmmeveski and its surroundings. The steep-sloped canyon-like valley is 15–20 meters deep, 60–70 meters wide and 450–470 meters long. It is assumed that initially, the waterfall was situated at the beginning of the canyon, and its height could have reached 10–15 meters (Miidel 2003). In the walls of the canyon, Lower and Middle Ordovician and partly upper Cambrian rocks are cropping out.

Historically, in 1927, in order to make use of the rapid water, a small hydroelectric power station that provided electricity to the Joaveski sawmill factory was built in Nõmmeveski Canyon, in the place of an even older watermill. In 1964, the buildings perished in a fire, and only the ruins mark the former power station today.

Stratigraphically, the Nõmmeveski section is similar to other North Estonian sections. According to Miidel (2003), the Nõmmeveski canyon walls expose the following strata (from top to bottom):

4.9 m – Kunda Stage, Loobu Formation: grey hard thick-bedded limestone with rare glauconite grains and thin-bedded clayey limestone;

0.4 m – Kunda Stage, Sillaoru Formation: brownish-grey limestone with brown Fe-ooids;

2.5 m – Volkhov Stage, Toila Formation: light grey glauconitic limestone, the middle part is clayey, the lower part dolomitised and hard;

0.2 m – Billingen Stage: dolomitised glauconitic limestone;

0.7 m – Hunneberg Stage, Leetse Formation: green quartz-glauconitic sandstone and clayey glauconitic sand;

2.8 m – Pakerort Stage, Türisalu Formation: dark brown kerogenous black shale, middle part consists of grey or yellowish siltstone with shale interbeds;

6.3+ m – Pakerort Stage, Kallavere Formation: yellowish and grey medium to fine-grained quartzose sandstone, in the uppermost part cross-bedded with shells and skeletal debris of brachiopods, in the lower part siltstone with interbeds of dark shale.

Fig. 15.1. Upper part of the succession in Nõmmeveski Canyon, showing the limestones of the Volkhov and Kunda regional stages, Dapingian to Darriwilian. Photo: Olle Hints, 2018.

The strata exposed in the Nõmmeveski Canyon are rich in fossils (Fig. 15.2). The canyon walls have yielded brachiopods from genera *Clitambonites*, *Antigonambonites*, *Porambonites*, *Iru*, *Raunites*, *Paurorthis*, *Ranorthis*, *Productorthis*, *Nicolella*, *Orthambonites*, *Lycophoria;* echinoderm *Echinoencrinites*; *cephalopod Discoceras*; bryozoan *Dianulites*. Microfossil samples taken from

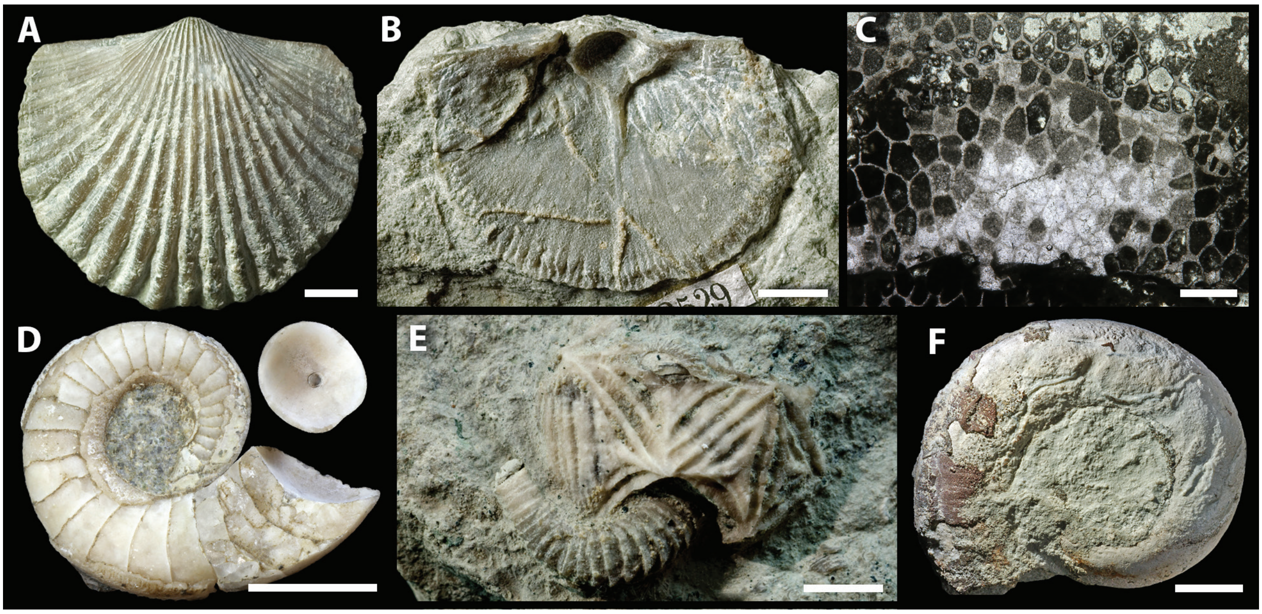


Fig. 15.2. Selected fossils collected from the Nõmmeveski Canyon. The abbreviations and numbers refer to specimen numbers in the Estonian geocollections database (https://geocollections.info). Scale bars: A, B, D, E – 5 mm; C – 1 mm; F – 1 cm. **A** – *Orthambonites majuscula* GIT 125-83, Kunda Stage; **B** – *Gonambonites parallelus* GIT 129-25, Kunda Stage; **C** – *Dianulites petropolitanus* GIT 537-2160, Kunda Stage; **D** – *Discoceras* sp. GIT 426-291, Volkhov Stage; **E** – *Echinoencrinites* sp. GIT 640-49, Kunda Stage; **F** – *Pararaphistoma vaginati* GIT 404-226, Kunda Stage.

the walls of the canyon for processing ostracods also yielded diverse and well-preserved fauna from Billingen, Volkhov and Kunda stages – among these are paleocopid ostracods *Tvaerenella*, *Rigidella*, *Ogmoopsis*, *Brezelina*, *Protallinella*, *Glossomorphites* and eridostracans *Conchoprimitia* and *Incisua* (Tinn et al. 2006).

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Stop 16: Jägala waterfall

Oive Tinn

Location: Latitude 59.45006°N, longitude 25.17861°E; Harju County, North Estonia.
Stratigraphy: Tremadocian to Darriwilian, from the Pakerort to Aseri regional stages.
Status: Outcrop is under nature protection – no hammering.
More information: https://geoloogia.info/en/locality/10087

The Jägala waterfall (Fig. 16.1, 16.2) is located at the lower reaches of the Jägala River, about 25 km east of Tallinn. The ca 50 m wide and 8 m high Jägala waterfall is the highest natural waterfall in Estonia. (The Valaste waterfall at the North Estonian Klint with its up to 30 m is higher, but that is an artificial waterfall that was formed thanks to the drainage trench directed to the Klint escarpment.) The upstream receding waterfall has created an about 300 m long and 10–14 m high shadowy canyon. It has been estimated (Miidel 1997) that, on average, the klint edge retreats about 16–17 cm per year, and thus the age of the waterfall may be around 3000 years. However, the retreat of the waterfall is not uniform but depends on the strength and crumbling of the topmost limestone unit (Meidla 2008).

The outcrop behind and next to the waterfall exposes the Lower and Middle Ordovician sequence (Fig. 16.1). The base of the outcrop consists of organic-rich black shale (graptolite argillite) of the Türisalu Formation (Tremadocian). Although a large part of this formation lies below the water line, shale pieces broken open by the falling water are abundant in the river canyon and around the waterfall. The Türisalu Formation is covered by the grey glauconitic mudstone of the Varangu Formation (according to Nõlvak et al. 2019, it may be the lower part of the Leetse Formation and Hunneberg Regional Stage). On top of this unit lies the glauconitic sandstones of the Leetse Formation (Tremadocian/Floian; Fig. 16.3). These are overlain by variably dolomitised glauconitic limestones of the Toila Formation (Dapingian, Volkhov Regional Stage). The boundary interval of the Volkhov and Kunda regional stages is marked by a distinctive thin brownish-grey unit of argillaceous limestone with Fe-ooids, the Sillaoru Formation. On top of the Sillaoru Formation lies an about 10 cm thick bed of the Pakri Formation (Darriwilian), which consists of yellowish-grey dolomitised limestone with quartz grains. The uppermost part of the outcrop comprises hard nautiloid-rich limestone beds of the Loobu Formation (Darriwilian, Kunda Regional Stage). In the canyon wall, the Loobu Formation is topped by about 0.6 m thick bed of marly limestones of the Aseri Regional Stage (Darriwilian; Orviku 1940), although this part of the section is mainly covered by vegetation.

The outcrop of the Jägala waterfall is the stratotype of the Jägala Member (Kunda Stage, Pakri Formation), which is represented by quartz-rich limestone. Besides, the Jägala outcrop also comprises the stratotype of the

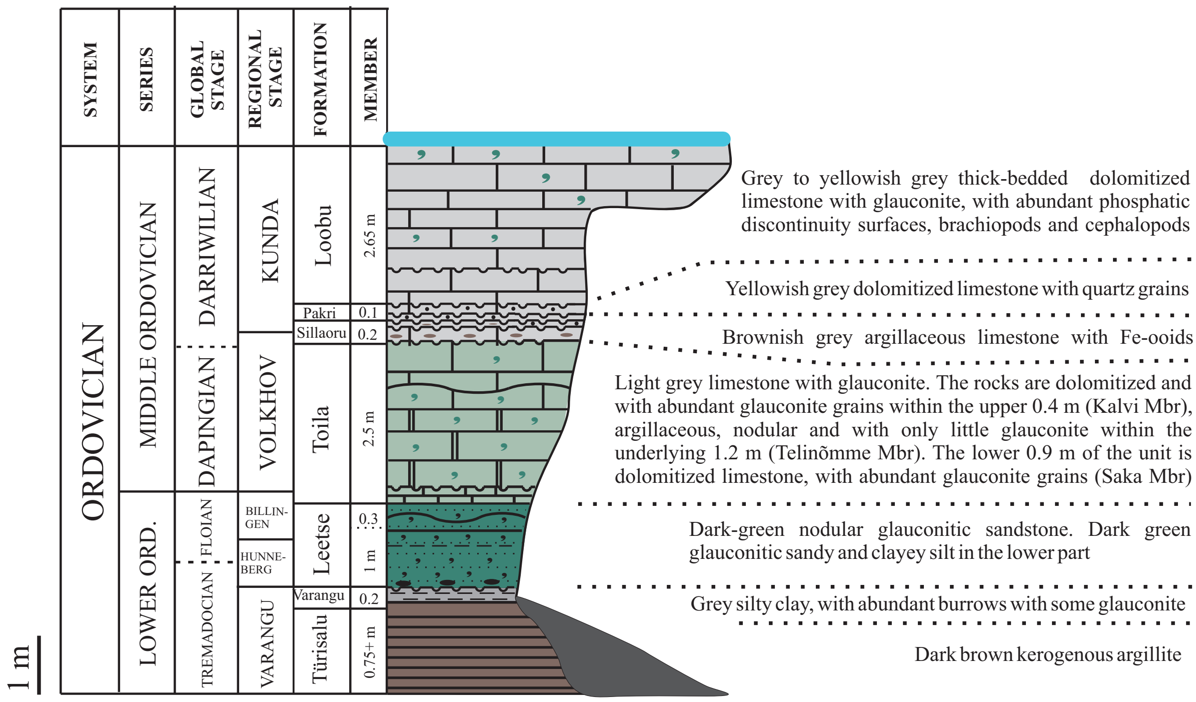

Fig. 16.1. Jägala waterfall section (modified after Meidla 2008 and https://sisu.ut.ee/stratotuup/o-jägala-joaastang).

Fig. 16.2. Jägala waterfall, where Tremadocian to Darriwilian succession in exposed. Photo: Gennadi Baranov, 2022.

Joa Member (Leetse Formation, Tremadocian, Floian).

The Jägala waterfall and canyon sections are rich in fossils (Fig. 16.4). Among these are trilobites from the Kunda Regional Stage (*Asaphus expansus*, *Illaenus wahlenbergi, Metopolichas verrucosus, Pseudoasaphus globifrons*); cephalopods *Proterovaginoceras, Estonioceras, Tragoceras, Ormoceras, Eichwaldoceras*; brachiopods from genera *Gonambonites*, *Orthambonites*, *Lycophoria* from the Kunda Stage*; Antigonambonites, Raunites, Porambonites, Nothorthis, Productorthis* from

Fig. 16.3. Lower part of the Jägala waterfall section, showing the glauconitic sandstone of the Leetse Formation, Tremadocian-Floian. Hammer points to the boundary between the Varangu and Leetse formations (according to an alternative interpretation by Nõlvak et al. (2019), the Varangu Formation is missing in the section. Photo: Olle Hints, 2012.

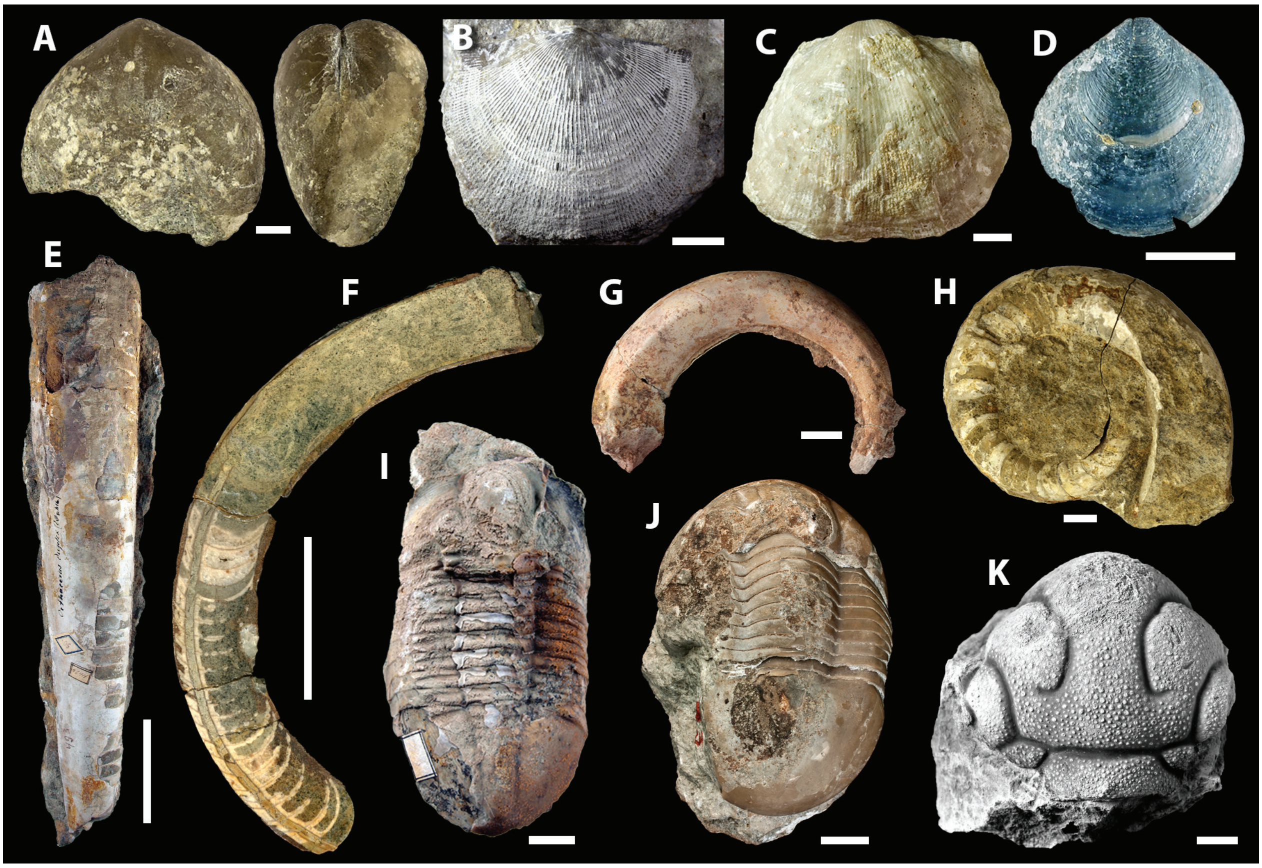

Fig. 16.4. Selected fossils collected from the Jägala Waterfall and nearby sections. Scale bars: E, F – 5 cm; H, I, J – 1cm; A, B, C, D, G, K – 5 mm. Institutional abbreviations: GIT – Department of Geology, Tallinn University of Technology; TAM – Estonian Museum of Natural History; TUG – Natural History Museum, University of Tartu. **A** – pentamerid brachiopod *Eoporambonites latus* TUG 2-869, Volkhov Stage; **B** – billingsellid brachiopod *Clitambonites adscendens* GIT 543- 357, Aseri Stage; **C** – billingsellid brachiopod *Gonambonites inflexus* GIT 129-10, Kunda Stage; **D** – lingulid brachiopod *Ungula ingrica* TUG 1619-161, Tremadocian; **E** – endoceratid cephalopod *Proterovaginoceras incognitum* TUG 860-1651, Kunda Stage; **F** – tarphyceratid cephalopod *Tragoceras falcatus* GIT 426-126, Kunda Stage; **G** – eogastropod *Ecculiomphalus* TAM G433:1118; **H** – tarphyceratid cephalopod *Estonioceras perforatum* TUG 2-128, Kunda Stage; **I** – asaphid trilobite *Pseudoasaphinus tecticaudatus* TUG 860-1281, Aseri Stage; **J** – illaenid trilobite *Illaenus wahlenbergi* TAM G439:1254, Kunda Stage; **K** – lichid trilobite *Metopolichas verrucocus* TUG 1085-51, Kunda Stage.

the Volkhov Stage and *Panderina, Ingria, Siphonotreta* from the Billingen Stage. Also, gastropods *Lesueurilla, Pararaphistoma and Ecculiomphalus* are common in the Kunda Stage.

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Notes

14th International Symposium on the Ordovician System

ISOS-14 Field Guide

The Ordovician of Estonia