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Conodont biostratigraphy across the lower boundary of the Haljala Stage in northwestern Estonia

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Lower boundary of Haljala Stage, based on conodont distribution in NW Estonia

The Peetri section exposes the lower boundary of the Haljala Stage, which was traditionally drawn at the top of a thick kukersite-rich interval attributed to the Kukruse Stage. The new results indicate that the boundary is at a lower level in the section and upper part of the kukersite-rich interval exposed belongs to the Haljala Stage. This shows that the stratigraphy in the Kukruse-Haljala interval is still problematic and should be re-addressed. The presence of a complete succession of conodont zones in this interval in the Peetri section indicates that the hiatus at the base of the Haljala Stage in NW Estonia is probably smaller than considered earlier.

Haljala Stage, conodont, NW Estonia

P450, Stratigraphy

Haljala lademe alumine piir Loode-Eestis konodontide leviku alusel

Peetri kõvikul paljanduvad Kukruse ja Haljala Haljala lademete piirikihid. Traditsiooniliselt on piiriks loetud kukersiiti sisaldavast intervallist kõrgemale jääv tugevaim püriidistunud katkestuspind. Uued andmed näitavad, et nimetatud lademete piir läbilõikes asub allapool ja et ülemine kukersiidirikas intervall vastab Haljala lademe basaalsele osale. Ka ilmnes, et Haljala Lademe alumisele osale vastav Idavere alamlade on läbilõikes esindatud ja lünk lademete piiril on ilmselt mahult väiksem, kui seni arvatud. On ilmne, et Kukruse-Haljala lademe piiriintervalli stratigraafia Loode-Eestis vajab täiendavat uurimist.

Haljala lade, konodondid, Loode-Eesti

P450, Stratigraafia

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Introduction

The first documentation of the strata that were later attributed to the Ordovician comes from 18 century in Estonia. The systematic studies were initiated at the beginning of 19 century. The basic version of the stratigraphic correlation of the Ordovician System in Estonia was proposed by Schmidt in 1858 (Schmidt, 1858) and in his subsequent monographic papers (Schmidt, 1879, 1881). Later papers by Raymond (1916), Bekker (1922, 1925), Orviku (1940), Jaanusson (1944, 1995 and many others) and Männil & Meidla (1994) have contributed to the development of the scheme (see Meidla et al., 2014 for a summary).

The global Ordovician stages are defined based on graptolites or conodonts (Harper, 2011). In Estonia, zonal graptolites have been found only in two intervals (Pakerort-Varangu and Uhaku-Kukruse), making conodont biozones essential for correlating the regional stages to the global units (Meidla et al., 2014). Conodonts have great practical importance in geological studies. Their widespread distribution, high rates of evolutionary change, abundance in the fossil record, and fairly robust mineralogy allow to use them for high-resolution biostratigraphy of the Palaeozoic rocks. The Ordovician conodont research has more than 50 years of history in Estonia (Männik & Viira, 1990) and resolution of biozones is fairly high in the Lower and Middle Ordovician.

Systematic studies of conodonts in Estonia started in 1960ies (Viira, 1967), and the first regional conodont zonation was published shortly afterwards (Viira, 1974). Later, conodont faunas and stratigraphy in the interval from the upper Cambrian up to the upper Silurian were studied in detail (Viira 1982, 1983; Viira et al., 1987, 2001; Kaljo et al., 1988; Männik 1992). However, only a limited quantity of the Upper Ordovician conodont data from outcrops in Estonia are published (Männik & Viira, 2012).

The Peetri Outcrop in NW Estonia exposes the Upper Ordovician succession across the boundary between the Kukruse anda Haljala stages. The outcrop has been a place of interest for more than 90 years, mainly due to the kukersine-containing interlayers, referring to its relationships to the oil shale deposit. In drillcores, the lower boundary of the Haljala Stage is mostly drawn by lithological features. The brownish organic-containing rocks are generally considered characteristic of the Viivikonna Formation (Kukruse Stage) and the lower boundary of the Haljala Stage is usually drawn above the uppermost kukersine-rich bed. Because there are occasional findings of kukersite also in the Haljala Stage, (Rõõmusoks, 1983; Ainsaar, 1990), the latter practice should be used with caution. In the outcrop area, probable lower boundary of the Haljala Stage is marked by a discontinuity surface and represents a gap in the succession (Hints, 1997a). The hiatus is well seen in the successions of ostracods (Põlma et al., 1988, fig. 7, 9-11) and chitinozoans (Hints et al., 1994). Although the faunal change is apparent, more than one discontinuity surface can be recognized in this interval (Nõlvak & Hints, 1996) and, in such cases, the boundary is hard to establish without detailed biostratigraphic information.

The papers addressing the distribution of fossils in the Peetri section are mostly dealing with the boundary between the substages of the Haljala Stage or describing the Haljala or Kukruse stages separately (Jaanusson, 1976; Rõõmusoks, 1970; Põlma et al., 1988; Öpik, 1930; Hints & Nõlvak, 1990; Nõlvak & Hints, 1991, 1996). The boundary between the Haljala and Kukruse stages in the Peetri outcrop is less commonly addressed and continuous succession across this boundary hasn't been published before. Papers addressing the Idavere Substage of the Haljala Stage have pointed out reduced thickness or absence of this unit in NW Estonia (Jaanusson, 1945), based on the fact that the Idavere Substage lacks diagnostic species in the Peetri section (Hints & Nõlvak, 1990; Nõlvak & Hints, 1996) or is absent in this area (Nõlvak & Hints, 1991).

This thesis summarizes a biostratigraphical study of the Peetri section based on conodonts. The aim of the study is to clarify the stratigraphy of the Kukruse-Haljala boundary interval in NW Estonia. The Peetri section is one of the few sections to address this topic as it allows to take large samples that is essential for conodont studies.

General geological setting and stratigraphy

Estonia is situated on the southern slope of Fennoscandian Shield. The crystalline basement of Proterozoic age is overlain by a bedrock succession of the Ediacaran to Devonian age, with thickness of the sedimentary rocks increasing southward (Meidla, 2014). Continuity of the geological studies for about two centuries is due to large exposure of Paleozoic rocks with exceptionally rich and well-preserved fossil fauna (Raukas & Teedumäe, 1997). Almost horizontal strata, with minor dipping to the south, are nearly untectonised and unmetamorphosed (Rõõmusoks et al., 1997), making Estonia a key area for the Palaeozoic research. The very high number of drillcores obtained in course of large- and medium-scale geological mapping have provided a huge amount of geological information of global significance (Raukas & Teedumäe, 1997).

The Ordovician world was dominated by thalassocratic conditions, with wide distribution of epicontinental seas and relatively flat seabottom topography. The latter made carbonate sediments dominant over siliciclastics (Harper, 2011). Although plate movement caused magmatic and tectonic activities, the Ordovician period is characterized by wider distribution of carbonate sediments than any other period (Nõlvak, 1997). The Ordovician world was divided into different continents that were biogeographically distinct. The period is also characterized by one of the most important life radiations in the Earth history, the Great Ordovician Biodiversification Event (GOBE), an episode of rapid expansion of species, genera and families of marine organisms (Hints et al., 2010). The GOBE is arguably the most important biodiversity rise of marine life in the Earth history (Webby, 2004), when skeletal organisms (like bryozoans, conodonts, corals, ostracods, brachiopods) are considered to went through the most important diversification (Harper, 2006).

The Ordovician strata in Estonia are mainly characterized by different carbonate rocks with variable content of siliciclastics. The Lower Ordovician is known for its terrigenous, noncarbonate rocks (silty sandstone, siltstone, argillite, glauconitic sandstone - Rõõmusoks, 1983). Thickness of the Ordovician rocks varies from 70-180 m in Estonia, being the largest in the central and eastern mainland area and noticeably decreasing toward the outcrop belt in north, and southwestern areas (Meidla et al., 2014). The Middle and Upper Ordovician limestones with marl interlayers are locally dolomitized and contain occasional bentonite interlayers in the Upper Ordovician. Characteristic of NE Estonia is the occurrence kukersite oil-shale in the basal Upper Ordovician (Meidla et al., 2014). Variations are due to the continental drift of Baltica from southern high latitudes to tropical realm (Cocks & Torsvik, 2005).

The Baltoscandian Ordovician Paleobasin can be subdivided into different facies zones based on their distinctive lithological features and fauna. The marginal area of the Ordovician Palaeobasin (North-Estonian and Lithuanian shelves by Harris et al., 2004) is mostly chartacterized by shallow water carbonate sediments with numerous discontinuity surfaces whilst more clayey sediments are characteristic of the deeper part of palaeobasin (Scandinavian and Livonian basins by Harris et al., 2004)(fig. 1). The Estonian part of the Ordovician paleobasin shows a distinct pattern of facies zones, each of them with very distinctive features. The correlation across the facies belts is creating difficulties in macro- and micropalaeontological studies (Meidla et al., 2014).

Basin development in the Middle Ordovician Period ended with a transgression in Estonia and the beginning of Upper Ordovician is characterized as the unification stage of development (Nestor & Einasto, 1997). Tectonically stable period with mostly bioclastic argillaceous-calcareous muds accumulated. Other half of period is known for volcanic ash fallouts, due to volcanic activity in closing of Iapetus ocean near-by. During the Haljala to Keila age a complete eustatic macrocycle took place with transgression in beginning, stable period in the middle, and rapid regression in the end of it. Purer bioclastic calcareous sediments accumulated in the beginning (Tatruse formation) and in the end (Pääsküla and Saue members of the Kahula Formation) of the eustatic cycle, bioclastic muds with various clay content (Vasavere and Kahula formation) deposited in the middle of it.

The differences in rock composition are associated with micropaleontological and macrofaunal differences indicating to highly variable environmental conditions in the basin (Meidla et al., 2014). Separation of Ordovician regional stages are based on rich faunas (trilobites, ostracods, conodonts, citinozoans and other fossils) and on lithological characteristics of the units. Earlier studies were based on numerous outcrops in northern Estonia, the later contribution (from the second half of previous century) rely on the results of comprehensive geological mapping and high number of drill cores (Rõõmusoks, 1983). The extensive information from the drilling program revealed problems of correlation of the strata in the outcrop area with those in the subsurface in southern Estonia, arising from paleogeography of the Ordovician paleobasin. The results of almost two centuries' work have a high regional importance: the Estonian stratigraphic nomenclature is adopted as a standard for the western-northwestern parts of the East European Craton (Männil & Meidla, 1994).

In the regional biostratigraphic correlation of the Ordovician strata also bentonites can be used. The bentonites, evidence of volcanic ash falls, are useful regional event-stratigraphic horizons (Siir et al., 2015, Bergström et al., 1995). These layers can be identified according to their geochemical features but, as these features vary in the same bed and different beds can be quite similar geochemically, biostratigraphic control during correlations is essential. The regional bentonite correlation was started by Jaanusson & Männil (1941) and is still important in the Upper Ordovician of Estonia. Another tool among non-biostratigraphic methods is carbon isotope chemostratigraphy that can be used for both regional and global correlations but also a biostratigraphic control is required (Ainsaar et al., 2010).

The modern concept of global Ordovician series and stages is relatively young. Previously each region adopted the systems and their subunits that were heavily influenced by the peculiarities of the regional geology, gaps in the succession etc. Common practice was to link the regional subdivisions with the British series and/or stages. The standardized global Ordovician stratigraphic scheme with three series and seven stages was finalized in 2007 (Chen et al., 2009) and several systems of subunits have been proposed as well (e.g. time slices – Webby et al., 2004; stage slices – Bergström et al., 2009).

The present paper addresses the boundary interval of the Kukruse and Haljala stages. The Kukruse Stage (Schmidt 1879) is known by its oil shale bearing sediments and the richest Ordovician fauna in Estonia. High diversity of faunas, with more than 330 species and subspecies, (Rõõmusoks 1970, table 10) suggests optimal life conditions. The stage is equivalent to the Viivikonna and Pihla formations in North Estonia (Table 1). The Viivikonna formation is known for its argillaceous bioclastic limestones with various marl and kukersite content. Based on the amount of organic compound in the rocks, it is divided into three members (Kiviõli, Maidla, Peetri). The Peetri (upper) and Maidla members are exposed in the Peetri section (Nõlvak & Hints, 1996). The Viivikonna formation grades westwards into bioclastic limestones of the Pihla Formation and into argillaceous limestone with dark pyritized skeletal detritus of the Dreimani Formation southwards. Thickness of the stage varies between 3 m in West Estonia and 20 m in East Estonia (Hints, 1997b).

The Haljala Stage is a relatively new unit, being introduced by Jaanusson only in 1995. The Haljala Stage replaced the former Idavere and Jõhvi stages that are now treated as substages of the Haljala Stage (Jaanusson, 1995). This change was explained by difficulties of distinguishing the Idavere and Jõhvi stage outside the North Estonia shelf. The Haljala stage is known for bearing most of the Estonian Ordovician bentonite layers. It comprises the Tatruse Formation and the lower parts of the Kahula and Adze formations (Table 1), the latter occurring only in south of Estonia as argillaceous limestone with thin bentonite layers and in some parts with phosphate ooids (Hints, 1997a). The Lower part of the stage is represented by the Tatruse Formation, regularly bedded hard bioclastic limestone with distinctive fauna (Põlma et al., 1988). The Tatruse formation can be found all over northern Estonia, the area between Keila and Raasiku being a possible exception (Rõõmusoks, 1983). The upper part of Haljala Stage is represented by the Kahula Formatsion. Lower part of the formatsion comprises the Vasavere Member (usually attributed to the lower substage of the Haljala Stage), argillaceous limestones with marl and bentonite interlayers (Hints, 1997a). The Vasavere Member typically contains two bentonite beds but the number of bentonite beds may reach up to 18 in the Island of Hiiuma, western Estonia (Hints, 1997a). The number of bentonite layers increases further towards Sweden where they are attributed to the Grefsen Bentonite Group (Bergström et al., 1995). In western mainland Estonia, where usually only two layers can be recognized, the upper one, known as the ’b’ layer (Jürgenson 1958), represents the boundary between Idavere and Jõhvi substages of the Haljala Stage (Männil 1963). More eastwards the bentonite layers are getting scarce (Põlma et al., 1988, fig. 7, Bergström et al., 1995, Fig. 12) and the boundary bentonite is harder to recognized (Hints, 1997a). Number of the bentonite layers increases in the west and the ‘b’ layer becomes difficult to identify. The Grefsen and Sinsen groupe bentonites are hard to differentiate from one another, not only lithologically but also geochemically

(Bergström et al., 1995; Kiipli et al., 2014). This suggests that bentonites as stratigraphic boundaries within the Haljala Stage should be used with precaution (Nõlvak & Hints, 1996). The boundary between the substages of the Haljala Stage is difficult to find without the 'bentonite criteria' as there is no other distinctive lithological feature or significant faunal change at this level (Öpik, 1930; Männil, 1963; Rõõmusoks, 1970; Jaanusson, 1976; Põlma et al., 1988; Hints & Nõlvak, 1990; Hints et al., 1999). Some papers state that the Idavere Substage is not present (Nõlvak & Hints, 1991) or lacks diagnostic species (Nõlvak & Hints, 1996) in the Peetri section. Lower boundary of the Haljala Stage in North Estonia is usually drawn at a double pyritized discontinuity surface characterised by distinctive cavities, some 5 cm or more in diameter and sometimes extending close to 40 cm downwards (Põlma et al., 1988). In boreholes this boundary is mostly defined by lithological characteristic (lack of kukersite above the Viivikonna Formation - Rõõmusoks, 1983). Thickness of the stage in Estonia reaches 10-20 m (Hints, 1997a).

In North Estonia there is a signifficant faunal change at the boundary between the Kukruse and Haljala stages (Rõõmusoks, 1970, fig. 12; Põlma et al., 1988, fig. 18). The high-resolution biostratigraphy of the Kukruse-Haljala boundary interval is based on chitinozoans (Nõlvak & Grahn, 1993). The last comprehensive overview of Estonian geology is about twenty years old (Raukas & Teedumäe, 1997) and outdated in some parts. Since that paper was published parts of the stratigraphic scheme have been revised (e.g. the Vasavere Formation is considered now as lowermost member of the Kahula Formation). It is evident that the Ordovician biostratigraphy in Estonia needs to be re-addressed. As the stratigraphically important graptolites are very rare and occur only sporadically in the Estonian succession (Meidla et al., 2014), chitinozoan, ostracods and conodonts are the most useful biostratigraphic tools in the region (Nõlvak & Grahn, 1993, Meidla & Sarv, 1990).

Table 1. Upper Ordovician stratigraphy in Estonia (after Meidla et al., 2014 and Männik & Viira, 2012).

System	Series	Stage	Graptolite zones	Condont zones	Conodont subzones	Reg. stage	Correlation of the formations: NW Estonia	Correlation of the formations: N&NE Estonia
Ordovician	Upper	Katian	*Dicranograptus clingani*	‘Uppermost *Baltoniodus* range’		Keila	Vasalemma	
		Sandbian	*Diplograptus foliaceus*	‘Uppermost *alobatus* range’		Haljala	Kahula	Kahula
				Amorphognathus tvaerensis	*Baltoniodus alobatus*			
					Baltoniodus gerdae		Tatruse	Tatruse
			Nemagraptus gracilis		*Baltoniodus variabilis*	Kukruse		
				Pygodus anserinus			Pihla	Viivikonna

Conodonts

Conodonts, phosphate microfossils, range from the Upper Cambrian into the topmost Triassic (Sweet, 1988). Christian Heinrich Pander discovered conodonts while looking for fish remains in the Lower Ordovician rocks in St. Petersburg region, in the Silurian rocks from Estonia and in the Carboniferous rock near Moscow. The conodonts were first described as teeth and jaws belonging to species of fish that are now extinct (Pander 1858).

The conodonts were first studied by examining surfaces of rock slabs until Ellison and Graves in 1941 demonstrated that specimens can be isolated from carbonates by dissolving them in 10 to 15 percent formic or acetic acid (Sweet, 1988). After discovering this method, data about conodonts started to increase rapidly, they were reported from the Cambrian to Triassic interval all over the world.

The detailed conodont record from the upper Cambrian up to the Přidoli in Estonia allows to analyze diversity and evolutionary trends of conodonts (Männik & Viira, 2012). Several extinction events have been also recognised (Jeppsson & Männik 1993; Männik, 2006).

Nature and use of conodonts

Conodonts are widely used in geological studies, mainly in stratigraphy, but their nature remained problematic for a long time. Based on their morphology, they were considered to belong to molluscs or annelid worms (Sweet, 1988). Finally, in 1983 (Briggs et al., 1983), the first well-preserved conodont animal fossil was found. It revealed that conodonts were small slender vermiform animals with ray-supported fin at one or both sides of the posterior part of the body. They had big eyes and bilaterally symmetrical jaw apparatus consisting of various elements (Sweet, 1988; Sweet & Donoghue, 2001). Based on the morphology and construction of the body fossils, but also on geochemical studies of conodont elements (Ellison, 1944), it's been concluded that conodonts were primitive chordates, probably the oldest known ancestors of vertebrates. However, not all paleontologists agree with this (Turner et al., 2010).

Conodonts were marine organisms adapted to life in various environments. Some of them were evidently nekto-benthic living in shallow-water shelf areas, others likely pelagic, living in deep shelf and basinal environments. Cosmopolitan taxa are common in the latter group. Main factors affecting the distribution and composition of conodont faunas were water temperatures, salinity, turbidity, oxygen concentration, light conditions, etc. Marine environments are characterized by stable water temperatures, salinity and limited turbidity in offshore regions and by more varied water temperature, salinity and turbidity conditions in nearshore areas (Sweet, 1988). A good example is Ordovician genus *Amorphognathus* who occupied different water depth in different latitudes. Species that occur in low-latitude deepwater sediments can also be found in rocks that formed in high-latitude cool, shallow waters where temperatures may have been closely the same as in low-latitudes deeper waters. Two main realms, (North) Atlantic Province with cooler water and normal salinity and (North American) Midcontinent Province characterized by warmer with high salinity water, existed in Ordovician (Pyle & Barnes, 2002). Faunas in these two realms are quite different. The Baltoscandian Ordovician conodont fauna belongs to the cool-water North Atlantic Realm (Viira & Männik, 1997).

Since the end of 1980s, conodonts are widely used in petroleum exploration (Sweet, 1988). This was due to the studies by Epstein et al. (1977) describing the thermal alteration of conodonts. The specimens display successive changes in colour, from pale yellow to brown, black, white and finally crystal clear (transparent) with increase of temperature. The relationship between temperatures affecting the specimens and the colour are experimentally proven. The Conodont Colour Alteration Index (CAI), a scale allowing measuring degree of heating of rocks was worked out. Knowledge of this index is useful for assessing the occurrence possibility of oil and/or gas in rocks. The conodont colour alteration index (CAI) is 1 in the Estonian material (Viira & Männik, 1997).

In recent years conodonts are used in climate studies. The stable oxygen isotopic ratio in apatite ($\delta^{18}O_{apatite}$) from conodont elements demostrates high precision and accuracy in oxygen isotope analysis (Trotter et al. 2008).

Conodont elements

Well-preserved conodont elements consist of crown and basal filling, but in most cases, due to its fragility, the basal filling is missing. All conodont elements, although morphologically highly variable, have similar internal laminated structure. Thermally unaltered crowns are pale yellow in colour, translucent (*hyaline*), and usually possessing fuzzy-edged masses that are opaque (*albid*) or whitish by appearance (*white matter*) in their upper parts (Sweet, 1988).

Based on the internal structure of elements, on the arrangement of tissue layers and the peculiarities of growth process inferred from the layering, Bengtson (1976) recognized three different evolutionary stages of conodonts and named these as protoconodonts, paraconodonts and euconodonts. Protoconodonts are believed to evolve into paraconodonts and those into euconodonts that are also known as the "real conodonts" (Sweet & Donoghue, 2001).

The conodonts occur mainly as separated elements in rock samples. Morphologically different elements were originally attributed to different genera and species. However, finds and study of natural bedding-plane assemblages and fused clusters suggested that a conodont animal possessed an apparatus consisting of morphologically different elements. Another indication that conodont animal had an apparatus consisting of different elements was the co-occurrence of certain elements in samples. Walliser (1964) proposed reconstructions of some conodont apparatuses. The first version of a multielement classification of conodonts was presented by Lindström in 1970 (Sweet, 1988). Afterwards, the multielement taxonomy became generally accepted. In modern systematics, the Class Conodonta is considered to be a part of the subphylum Vertebrata (Briggs, 1992) and the phylum Chordata (Donoghue et al., 2000).

Peetri outcrop

The Peetri Outcrop is located in the Saue Parish, Harju County, 8 km west of Tallinn, near the Tallinn-Keila Highway (fig. 1). It consists of two outcrops: an inclined shaft and a deep trench (fig. 2). The section in the Peetri inclined shaft is designated as the stratotype section for the Peetri Member of the Viivikonna Formation (Männil, 1984). The first reference to the Peetri Outcrop in the paper by Pogrebov (1920, 'Прибалтийские горючие сланцы' - 'Oil shale of the Baltic Region') addresses the 9 m thick kukersine-rich part of the section in the inclined shaft. The same information is referred to by Bekker (1921) in his paper about the Kukruse Stage. One of the first full descriptions of the Peetri composite section was given by Rõõmusoks (1970). The description and references to macrofauna (Rõõmusoks, 1970) are still extensively used today (Hints & Nõlvak, 1990; Nõlvak & Hints, 1991, 1996; Kiipli, 2008). The so-called upper Peetri Outcrop (deep trench) exposes the lower and middle parts of the Kahula Formation, with the Vasavere Member in rather limited thickness at its base (0.5-0.6 m; Rõõmusoks, 1983). The basal part of the succession contains two bentonites of the Grefsen Complex (Bergström et al., 1995; Kiipli, 2008).

Figure 1. A: Post-Tremadocian Ordovician facies zonation (after Meidla et al., 2014) and location of the area shown in B; B: location of the Peetri outcrops (red circle). Estonian Land Board, 2016.

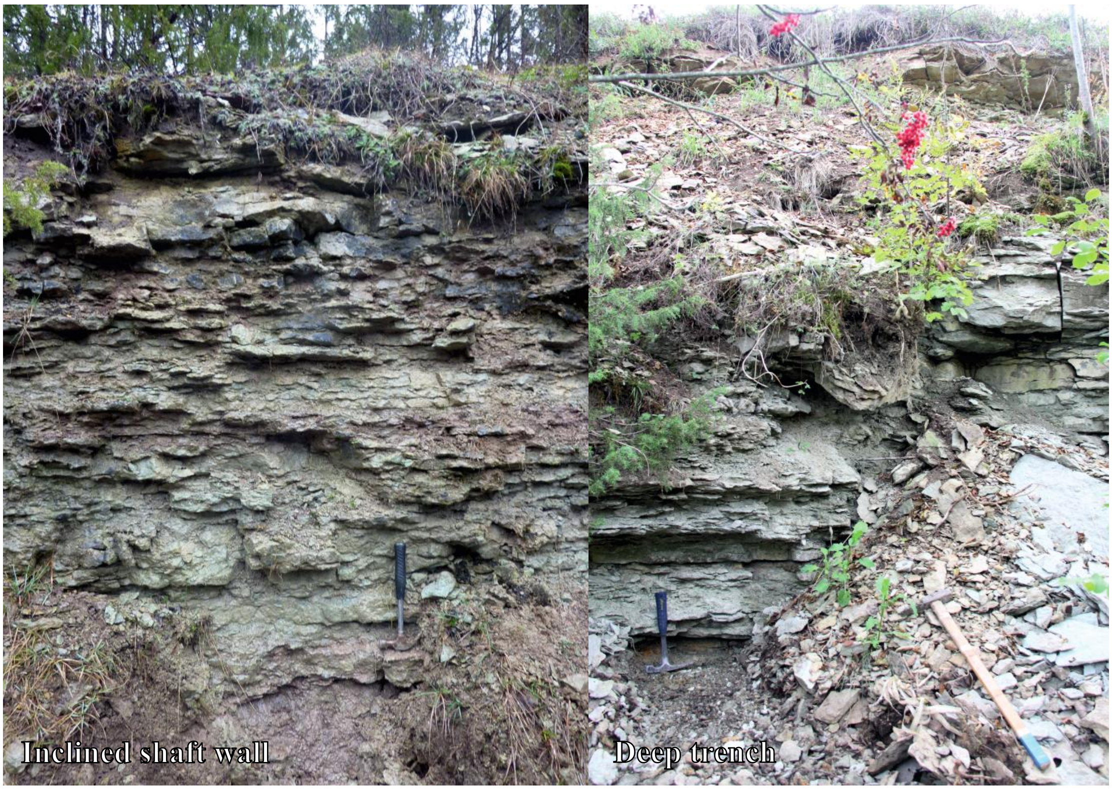

Figure 2. The Peetri sections, inclined shaft wall on the left and deep trench on the right.

Previous studies of the section

Pogrebov (1920) describes the succession in the Peetri inclined shaft, 9 m in thickness (fig. 3). Only the upper part of succession is described in detail as this description is overlapping the interval dealt with in this thesis.

Description by Pogrebov (Pogrebov, 1920, p. 27-28), from the top:

1. 0,40 m (0,0-0,4 m) – Soil, with pieces of limestone.
2. 0,18 m (0,4-0,58 m) – Argillaceous limestone, marl.
3. 0,06 m (0,58-0,64 m) – Thick-bedded limestone.
4. 0,10 m (0,64-0,74 m) – Argillaceous limestone, marl.
5. 0,16 m (0,74-0,9 m) – Thick-bedded grey limestone.
6. 0,01 m (0,9-0,91 m) – Greenish to yellowish clay.
7. 0,02 m (0,91-0,93 m) – Fine-grained argillaceous sandstone, with pyritized concretions in the basal part.
8. 0,06 m (0,93-0,99 m) – Thick-bedded limestone.
9. 0,12 m (0,99-1,11 m) - Argillaceous limestone, marl.

10. 0,10 m (1,11-1,21 m) - Thick-bedded limestone.

11. 0,08 m (1,21-1,29 m) - Fine-grained argillaceous greenish to pinkish sandstone, with greenish burrows filled with clay.

12. 0,26 m (1,29-1,55 m) – Thick-bedded greenish-grey limestone.

13. 0,15 m (1,55-1,70 m) – Limestone, with kukersite spots.

14. 0,40 m (1,7-2,10 m) – Thick-bedded limestone, with abundant burrows filled with kukersite.

15. 0,12 m (2,1-2,22 m) - Limestone, with kukersite spots.

16. 0,62 m (2,22-2,84 m) - Greenish-grey limestone, with kukersite in the lower part.

17. 0,13 m (2,84-2,97 m) – Greenish-brown limestone, with abundant kukersite spots.

18. 0,19 m (2,97-3,16 m) – Bituminous limestone, with thin kukersite interlayers.

19. 0,22 m (3,16-3,38 m) – Irregularely bedded limestone, with nodular limestone.

20. 0,18 m (3,38-3,56 m) – Thick-bedded greenish-grey limestone.

The Pogrebov's beds 21-34 (interval 3,56-10,71 m, 7,15 m in thickness) contain various limestones.

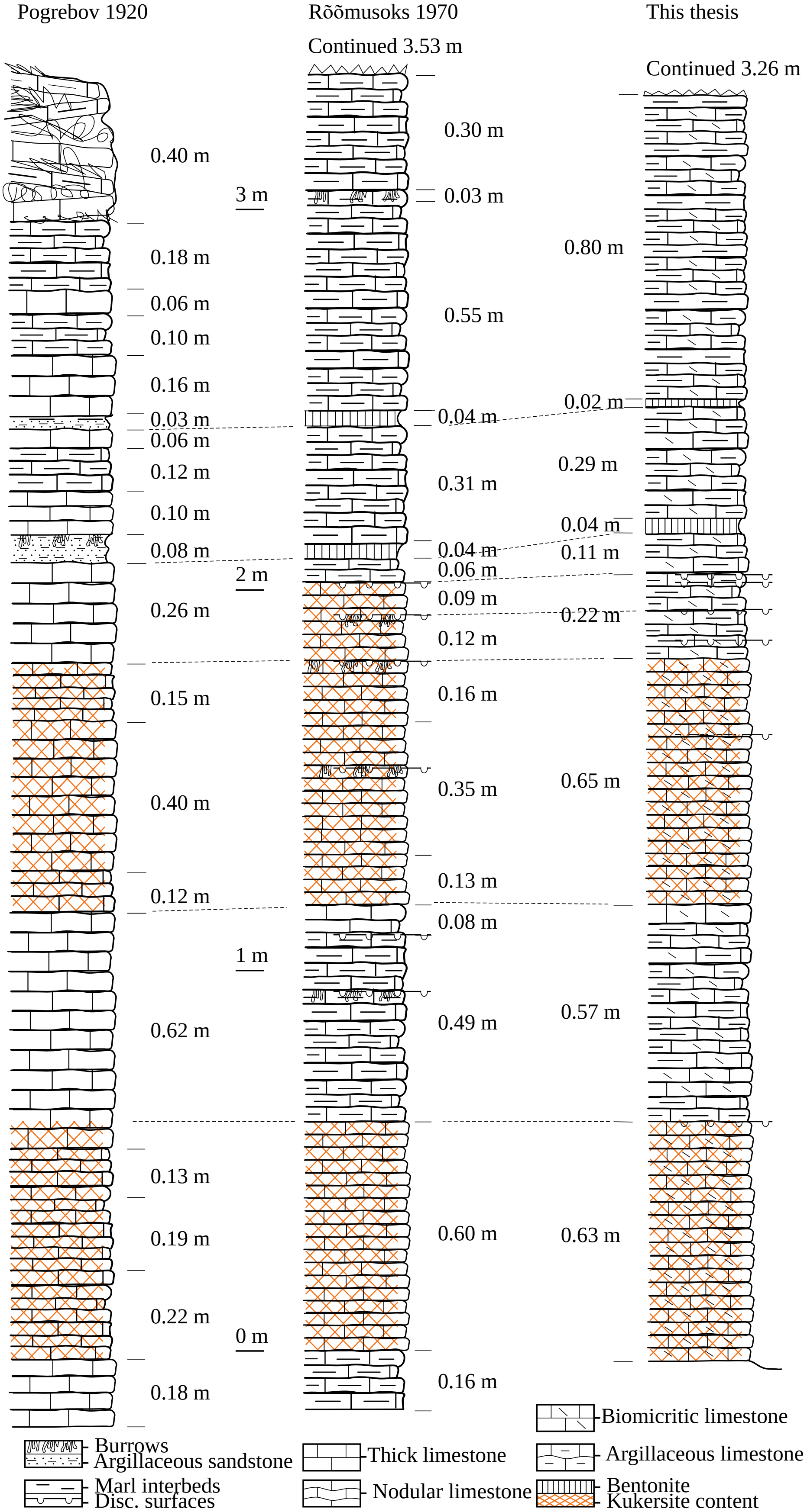

Figure 3. From left to right Peetri section according to the descriptions by Pogrebov (1920), Rõõmusoks (1970) and this thesis.

Rõõmusoks (1970) describes both sections (inclined shaft; deep trench), indicating the total thickness of the the Jõhvi (4.41 m) and Idavere (0.45 m) substages of the Haljala Stage and Kukruse Stage (8.23 m) (fig. 3). Only upper part of the Kukruse Stage is described in detailed and this description is partly overlapping the interval dealt with in this thesis. Description by Rõõmusoks (1970), from the top:

Haljala Stage, Jõhvi Substage (Rõõmusoks, 1970, p. 226):

1. 0,23 m (0,0-0,23 m) – Blueish-grey argillaceous limestone.
2. 0,29 m (0,23-0,52 m) – Blueish-grey limestone, lower part more argillaceous
3. 0,21 m (0,52-0,73 m) – Blueish-grey argillaceous limestone.
4. 0,12 m (0,73-0,85 m) – Limestone, more thick-bedded and less argillaceous.
5. 0,36 m (0,85-1,21 m) – Blueish-grey argillaceous limestone, with marl interlayers.
6. 0,23 m (1,21-1,44 m) – Limestone, more thick-bedded and less argillaceous.
7. 0,28 m (1,44-1,72 m) – Blueish-grey argillaceous limestone.
8. 0,43 m (1,72-2,15 m) – Blueish-grey limestone, lower part more argillaceous.
9. 0,01 m (2,15-2,16 m) – Marl interlayer.
10. 1,67 m (2,16-3,83 m) – Blueish-grey argillaceous limestone, with rare marl interlayers.
11. 0,03 m (3,83-3,86 m) – Limestone, upper part more argillaceous, thin-bedded, with burrows, organic matter observed in lower part.
12. 0,55 m (3,86-4,41 m) – Blueish-grey argillaceous limestone, with rare marl interlayers.

Haljala Stage, Idavere Substage (Rõõmusoks, 1970, p. 188):

1. 0,02 m (0,00-0,02 m) – Bentonite.
2. 0,35 m (0,02-0,37 m) – Argillaceous limestone.
3. 0,02 m (0,37-0,39 m) – Bentonite.
4. 0,06 m (0,39-0,45 m) – Argillaceous limestone with pyritized discontinuity surface at the base.

Kukruse Stage (Rõõmusoks, 1970, p. 132-135):

1. 0,09 m (0,00-0,09 m) – Blueish-grey limestone, with brownish shade, thick-bedded. Upper boundary marked by uneven double pyritized discontinuity surface with burrows. Lower boundary marked by slightly pyritized discontinuity surface with burrows.

2. 0,12 m (0,09-0,21 m) – Blueish-grey nodular limestone, brownish in some places, with small pyritized pebbles. Lower boundary marked by uneven pyritized discontinuity surface with burrows.

3. 0,16 m (0,21-0,37 m) – Brownish nodular limestone, with thin kukersite interlayers, contains pyritized skeletal fragments.

4. 0,35 m (0,37-0,72 m) – Blueish-grey nodular limestone, with burrows filled with kukersite clay. Contains disperse pyrite. 0.12 m below the top uneven pyritized discontinuity surface with burrows.

5. 0,13 m (0,72-0,85 m) – Brownish-grey nodular limestone, with thin kukersite interlayers, contains small pyritized skeletal fragments.

6. 0,08 m (0,85-0,93 m) – Greenish-grey nodular limestone, with burrows filled with kukersite. Lower boundary is marked by pyritized discontinuity surface with burrows.

7. 0,49 m (0,93-1,42 m) – Limestone, resembles the unit described above but is more argillaceous. 0,15 m below the top hard pyritized discontinuity surface with shallow burrows.

8. 0,60 m (1,42-2,02 m) – Brownish-grey nodular limestone, with thin (1-3 cm) kukersite interlayer containing burrows filled with kukersite.

9. 0,16 m (2,02-2,18 m) – Greenish-grey limestone, in the lower part more argillaceous, burrows are filled with kukersite.

The Rõõmusoks's beds 10-36 (interval 2,18-8,23 m, 6,05 m in thickness) contain various limestones.

Hints & Nõlvak (1990) and Nõlvak & Hints (1991, 1996) provided a description of the Peetri outcrop that is based on Rõõmusoks (1970). Their section in the trench contains the Haljala Stage (4,85 m) and topmost part of the Kukruse Stage (~0,30 m), while the inclined shaft contains the lowermost part of the Haljala Stage (~0,20 m) and the Kukruse stage (8,23 m).

Description of the section (Nõlvak & Hints, 1996, p. 85-56), from the top:

Haljala Stage, Jõhvi Substage, Kahula Formation, Aluvere Member.

1. 2,95 m (0,00-2,95 m) – Light-grey to greenish-grey, fine-grained, medium-bedded (up to 10 cm), argillaceous biomicritic limestones with distinct intercalations of marl. Skeletal particles are sometimes pyritized.

2. 1,45 m (2,95-4,40 m) – Liht-grey, fine-grained, medium to highly argillaceous, biomicritic limestones with rare intercalations of marl. At a depth of 3,85 m, a discontinuity surface is observed. The lower boundary is marked by a K-bentonite layer (3-5 cm) of Grefsen bentonite complex.

Haljala Stage, Idavere Substage, Vasavere Formation.

3. 0,45 m (4,40-4,85 m) – Light-grey, fine-grained, argillaceous biomicritic limestone. In the lower part the limestone is slightly kerogenous. At a depth of 4,80 m a K-bentonite layer (3-5 cm) is observed. The lower boundary is marked by a pyritized discontinuity surface.

Kukruse Stage, Viivikonna Formation, Peetri Member

4. 1,42 m (4,85-6,27 m) – Light-grey to buff-grey, thin to medium-bedded, pure to argillaceous bioturbated limestone with thin (2-3 cm) kukersite layers and lenses. The texture is wavy-bedded, rarely seminodular. The upper boundary is marked by a complex of at least 6 pyritized discontinuity surfaces.

5. 2,87 m (6,25-9,12 m) – Intercalation of light-grey, fine-grained, thin to medium-bedded biomicritic limestone and buff-grey, seminodular, pure to argillaceous kerogenus limestone with thin (2-3 cm) layers of kukersite.

Kukruse Stage, Viivikonna Formation, Maidla Member

This interval corresponds to The Nõlvak & Hints's beds 6-7 (9,12-13,08 m, 3,96 m in thickness) and consists of various limestones.

Material and methods

Sampling

Altogether nine samples were collected from the Peetri section on 19.09.2014 and 03.02.2016, six from the inclined shaft wall and three from the trench (Fig. 4). An extra sample was taken in 2016, after processing the samples collected earlier. The outcrops were described and measured (fig. 4). The basic fieldwork tools (hammer and chisel) were used for cleaning the outcrop and taking the samples. The sampling was aimed at covering the transition from the Kukruse Stage up to Haljala Stage, considering the published information (Rõõmusoks, 1970, Nõlvak & Hints, 1996). Tabel 2 contains a list of samples with the depths and descriptions.

Tabel 2. Gathered samples position in the outcrops.

Sample	Depth (cm from the top of outcrop)	Description
Inclined shaft wall		
TC14 - 1	180-190	Kukersite-rich limestone, 13-23 cm below the lowermost observed pyritized discontinuity surface.
TC16- 1	153-160	Thicker bed in lower part of the argillaceous limestone, 7-14 cm above from lowermost observed pyritized discontinuity surface.
TC14 - 2	110-114	Thicker bed in the middle of argillaceous limestone, below the brownish kukersite bearing limestone interval.
TC14 - 3	65-68	Limestone below the pyritized discontinuity surface, 65 cm below the top of the section.
TC14 - 4	12-16	Limestone below the bentonite and 5-9 cm above the topmost observed pyritized discontinuity surface.
TC14 - 5	0-10	Limestone above the bentonite layer.
Trench		
TC14 - 6	408-418	Limestone, 10 cm thick layer below the upper bentonite.
TC14 - 7	366-376	Limestone, 10 cm thick layer, 30 cm above the upper bentonite.
TC14 - 8	261-266	Limestone, 130-145 cm above the upper bentonite.

The description of the section at Peetri in this chapter (fig. 4) is based on observation made in September 2014 and February 2016.

Description of the section, from the top:

Trench (Upper outcrop)

Haljala Stage, Kahula Formation, Aluvere member

1. 4,06 (0,00-4,06 m) – Bluish-grey, medium-bedded (up to 10 cm), argillaceous biomicritic limestone, with marl intercalations.

Haljala Stage, Kahula Formation, Vasavere Member

2. 0,35 m (4,06-4,41 m) – Bluish-grey, thin-bedded (1-3 cm), argillaceous biomicritic limestone. Bentonite layers are observed in the top (thickness 2 cm) and bottom (6 cm) of the interval.

Inclined shaft wall

Haljala Stage, Kahula Formation, Vasavere Member

3. 0,10 m (0,00-0,10 m) – Bluish-grey, argillaceous biomicritic limestone. Equivalent to the lower part of the interval 2 in the trench section.

4. 0,02 m (0,10-0,12 m) – Bentonite, equivalent to the basal bentonite of the interval 2 in the trench section.

5. 0,11 m (0,12-0,23 m) – Bluish-grey, argillaceous biomicritic limestone.

6. 0,22 m (0,23-0,45 m) – Bluish-grey, argillaceous biomicritic limestone. Pyritized discontinuity surfaces observed at the depths 0,23 m (with burrows), 0,25 m, 0,32 m, 0,40 m.

7. 0,65 m (0,45-1,10 m) – Semi-nodular brownish-grey kukersine bearing biomicritic limestone. Kukersine occurs in marl intercalations, in variable amounts. The first noticeable kukersite seam in the section occurs in the top of this interval. Pyritized discontinuity surface occurs 0,2 m below the top of this interval.

8. 0,57 m (1,10-1,67 m) – Bluish-grey, argillaceous biomicritic limestone. Two thicker limestone layers observed at depths 1,10-1,14 m and 1,53-1,60 m.

Kukruse Stage. Viivikonna Formation, Peetri Member

9. 0,63 m (1,67-2,30 m) – Nodular brownish-grey kukersite-bearing biomicritic limestone. Kukersite content is higher than in the previous intervals. Pyritized discontinuity surface with deep burrows observed at the top of the interval. At depth 2,20+ m the kukersine content increases in limestone.

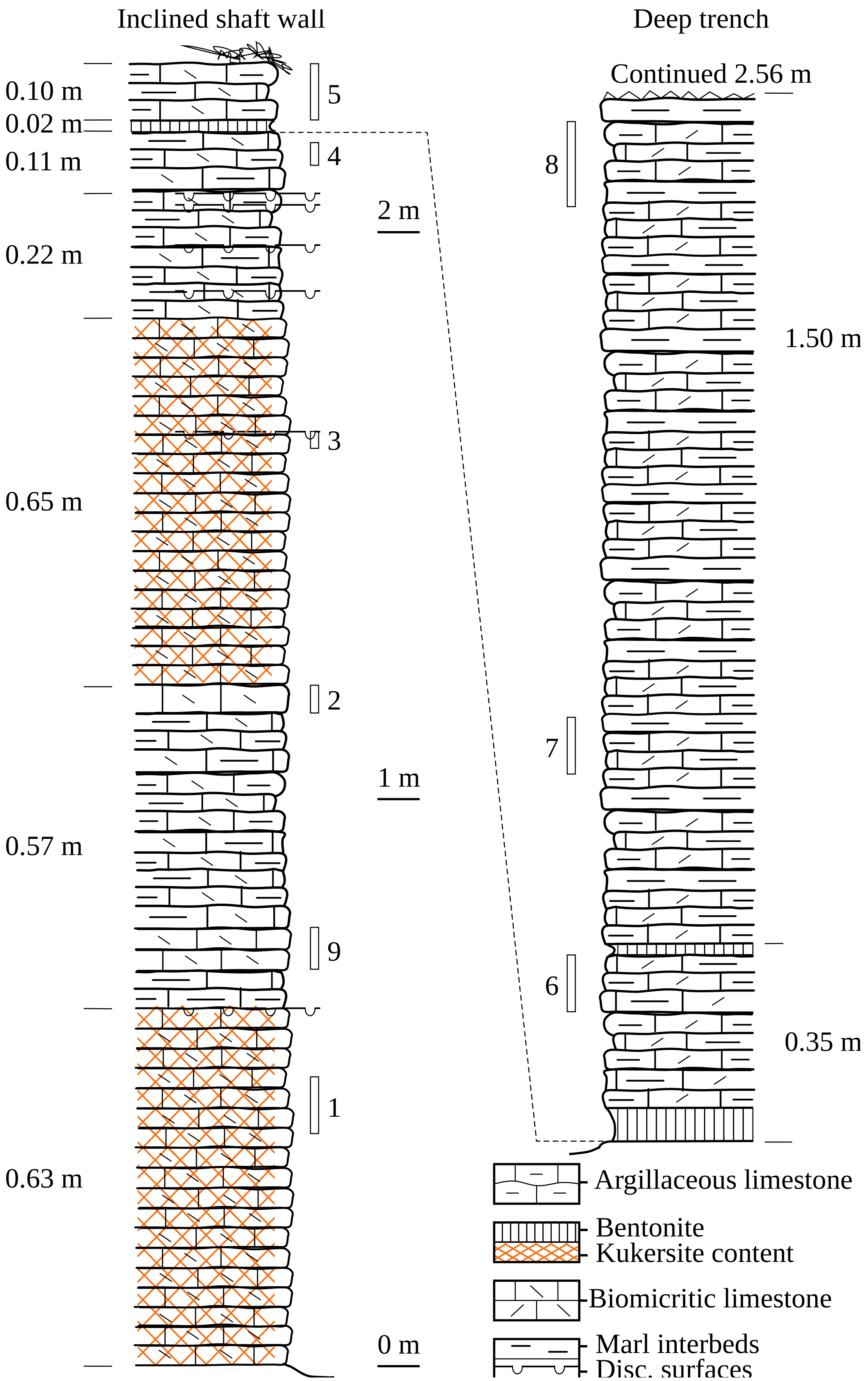

Figure 4. The Peetri section and the position of samples (boxes with numbers next to the column).

Sample preparation

The sample preparation was carried out in the Department of Geology of the University of Tartu, with exception of one sample (TC16-1) (treated in spring 2016) and fractionation in heavy liquid for all samples was carried out in the Institute of Geology at Tallinn University of Technology. The laboratory preparation lasted from autumn 2014 till autumn 2015 and was aimed at releasing the conodonts elements from the rock by means of diluted acetic acid. The conodont elements were picked under the binocular microscope at a magnification x16-25.

The samples were washed with water and liquid soap. Each sample was broken down to sizeable pieces (diameter up to 10 cm) for further processing. The weighed samples were soaked in acetic acid, to dissolve the limestone. The approach was based on Jeppson et al. (1999): 7-8% solution of acetic acid was replaced in every 2 weeks, after most of the acid had already reacted with limestone. Simple washing with water was used to dispose the clay component after the complete dissolution. This was carried out by means of running water that turns the residue in a suspension, whereas heavier parts were sinking faster than the clay component that could be removed together with excess water. The washed residue was further treated with formic acid, to get rid of dolomite, and with hydrogen peroxide, to get rid of organics, if needed. The particles of different density were then separated in heavy liquid (bromoform) and the light fraction was discarded. The heavy fraction was washed with alcohol for removing the residue of bromoform), weighed and inspected under the microscope. Each sample was subjected to picking procedure and gathering conodont elements three times, first two producing the majority of conodont elements and the third used for additional check of picking efficiency.

Distribution of conodonts

The correlation of the Kukruse and Haljala Stages to the conodont zonations in shown in the Table 1. The conodont fauna of the kukruse and Haljala stages is mostly dominated by *Amorphognathus* and *Baltoniodus* whilst the 'Uppermost *Baltoniodus* range' is dominated by several simple-cone taxa (Männik 2004). The biodiversity is low, with gradual increase towards the 'Upper *alobatus* range' and subsequent drop higher up (Männik & Viira, 2012).

Amoprphognathus tvaerensis Conodont Zone corresponds to interval from the first appearance of *A. tvaerensis* up to the first appearance of its successor species *Amorphognathus superbus*. *A. tvaerensis* Zone is subdivided into three subzones of the *Baltoniodus* lineage (in ascending order): *Baltoniodus varabilis*, *B. gerdae* ja *B. alobatus* subzones (Bergström, 1971). Dzik (1999) adds "*A. ventilatus*" zone between the *A. tvaerensis* and *A. superbus* zones, corresponding to the interval from the first appearance of *A. ventilatus* up to the first appearance of its successor species *A. superbus*. There are additional zones between the disappearance of *A. tvaerensist* and the first appearance of *A. ventilates* in Estonia, comprising the Haljala and Keila stages (Männik, 2007).

The 'Uppermost *alobatus* range' is an unofficial regional unit that corresponds above the disappearance level of *Amorphognathus tvaerensist*. The boundary of this unit coincides with the upper boundary of Idavere Substage (Männik, 2007).

The 'Uppermost *Blatoniodus* range' is another inofficial regional unit above the "uppermost *alobatust* range" that is dominated by coniform taxa (*Decoriconus*, *Drepanoistodus*, and *Panderodus* etc.). The Ramiform elements are extremely rare, only some *Baltoniodus* sp. fragments can be found. The unit corresponds to the interval from the uppermost Haljala up to the lowermost Oandu stages (Männik, 2007).

Systematic description

In the descriptions below, traditional Pa, Pb, Pc, M, Sa, Sb, Sc notation introduced by Sweet and Schönlaub (1975) and modified by Cooper (1975) and Sweet (1981, 1988) are used. S elements are not distinguished as they give no additional information on biozonation and are very similar in the *Amorphognathus* and *Baltoniodus* lineage. P, M and S notation does not relate to actual positions of the conodont elements within the apparatus, but merely expresses a locational analogy (Purnell et al., 2000). Biological terminology advocated by Purnell et al. (2000) was not adopted as anatomical orientation of the elements is not known. Simple coniform elements (simple cones with a cusp and a base) have no stratigraphic importance and not described here.

Phylum **Chordata**
Class **Conodonta**
Order **Prioniodontida** Dzik, 1976
Family **Balognathidae** Hass, 1959
Genus *Amorphognathus* Branson & Mehl, 1933

Type species: *Amorphognathus ordovicicus* Branson & Mehl, 1933.
Diagnosis: See Bergström, 1962, p. 32-34.
Occurrence in the Baltic region: Kukruse Stage – Porkuni Stage

Amorphognathus tvaerensis Bergström, 1962
Plate I, figures 1-7

1962. *Amorphognathus tvaerensis* n. sp.; Bergström, p. 36-37, PI. 4: 7-10.
1971. *Amorphognathus tvaerensis* Bergström; Bergström, p. 135-136, Pl. 2: 10-11.
1976. *Amorphognathus tvaerensis* Bergström; Dzik, Text-fig. 27: g-q.
1994. *Amorphognathus tvaerensis* Bergström; Dzik, Pls 22: 8-22; 23: 1- 2; Text-figs 19-20, 21a, 22 (lower part)
2006. *Amorphognathus tvaerensis* Bergström; Viira et al., Pl. 1, figs. 1-9, 11, 13-15.

Type horizon and locality: Boulder of the *Ludibundus* limestone (early Caradoc) from the Tvären area, Sweden.
Diagnosis: See Bergström, 1962, p. 36-37.
Holotype: Pa element (Bergström 1962, pl. 4, figs 7-10).
Remarks: Bergström (1971) reconstructed the apparatus including Pa, Pb, M, Sa, Sb, and Sd elements. Pa and M elements are diagnostic for the species. S elements of apparatus are quite similar to the corresponding elements of the species of *Baltoniodus*.

My specimens do not differ from those described Bergström 1962, 1971; Dzik, 1976, 1994 and Viira et al., 2006. Plate I figure 14 shows a Pb element of *Amorphognathus* sp. with unusual two bigger cusps.
Occurrence in the Baltic region: Kukruse and Haljala stages

Genus *Baltoniodus* Lindström, 1971

Type species: *Prioniodus navis* Lindström, 1955, p. 590.
Diagnosis: Bergström, 1971, p. 144-145.
Occurrence in the Baltic region: Volkhov Stage – Keila Stage.

Baltoniodus variabilis (Bergström, 1962)
Plate I, figures 9-11, 13

1962. *Prioniodus variabilis* sp. n.; Bergström, p. 51-52, Pl. 2: 1-7.
1971. *Prioniodus variabilis* Bergström; Bergström, p. 147-148, Pl. 2: 2.
1976. *Prioniodus variabilis* Bergström; Dzik,Text-fig. 24: h-l.
1994. *Baltoniodus variabilis* (Bergström); Dzik, Pl. 19: 1-9; Text-figs 14c, 15.

Type horizon and locality: Boulder of the *Ludibundus* limestone (Early Caradoc) from the Tvären area, Sweden.

Diagnosis: See Bergström, 1971, p. 148.
Holotype: *Prioniodus variabilis* Bergström, 1962, p. 51.
Remarks: Interpretation of an apparatus is provided by Bergström (1971) and the elements are illustrated by Dzik (1976).
My specimens do not differ from those described in Bergström, 1962, 1971 and Dzik 1976, 1994. The Pb element in the Plate I figure 11 shows no significant difference from Pb element of *B. alobatus* (Plate II, fig. 6-9), exept for the cusp that is slightly smaller in Pb element of *B. variabilis*.
Occurrence in the Baltic region: Uhaku and Kukruse stages.

Baltoniodus gerdae (Bergström, 1971)
Plate I, figures 8

1971. *Prioniodus gerdae* sp. n.; Bergström, p. 146, Pl. 2: 3.
1976. *Prioniodus gerdae* Bergström; Dzik,Text-fig. 25: a-f.
2008. *Baltoniodus gerdae* Bergström; Viira, Fig. 6: M, N, R.

Type horizon and locality: Sample Ög61-96 taken 11.34-11.50 m above the base of Dalby Limestone, Smedsby Gard drillcore, Östergötland, Sweden.

Diagnosis: See Bergström, 1971, p. 146.
Holotype: *Prioniodus gerdae* Bergström, 1971, p. 146
Remarks: Interpretation of an apparatus is provided by Bergström (1971) and the elements are illustrated by Dzik (1976).

Single Pa element found shows no difference from those described in the papers above. Variable width of the marginal edge seems to be usual. *Baltoniodus* sp. M element in the Plate I figure 12 could belong to *B. gerdae*, but it’s difficult to confirm, due to a similarity with M elements of other *Baltoniodus* species.
Occurrence in the Baltic region: Kukruse and Haljala stages.

Baltoniodus alobatus (Bergström, 1971)
Plate II, figures 1-14

1971. *Prioniodus alobatus* n. sp.; Bergström, p. 145-146, Pl. 2: 4.
1994. *Baltoniodus alobatus* Bergström; Dzik, Pl. 19: 10-15; Text-figs 14d.

Type horizon and locality: Sample D60-160 taken 15.30-15.35 m above base of the Dalby Limestone, Fjacka, Dalarna, Sweden.

Diagnosis: Bergström, 1971, p. 145.
Holotype: *Prioniodus alobatus* Bergström, 1971, p. 145-146.
Remarks: Interpretation of an apparatus is provided by Bergström (1971) and the element illustrations given by Dzik, 1976.
My specimens do not differ from those described in Bergström, 1971 and Dzik, 1994. The M element in the Plate II figure 10 bears small denticles on the posterior part of the base and M element in the figure 11 bears small denticles at the very end of anterior part of the base, a feature that wasn’t seen in other M elements.
Occurrence in the Baltic region: Haljala Stage.

Results

The summary on dissolution process and technical results from the lab are given in the table 3.

The occurrence of conodont species in the samples are summarized in the table 4.

Conodont biostratigraphy of the Peetri section and associated biozones are shown in the fig. 5. All conodont biozones in the lower part of Upper-Ordovician were represented. Sample density in this interval was less than 0,5 m.

The following biostratigraphic units were identified (fig. 5): *(1) Amorphognathus tvaerensis* CZ with all three subzones – *Baltoniodus variabilis*, *B. gerdae*, *B. alobatus* – described in it, (2) 'Uppermost *Balotniodus alobatus* range' and (3) probably also the 'Uppermost *Baltoniodus* range'. The index species of *Amorphognathus tvaerensis* CZ appears 1.41-1.48 m below the base of the lower bentonite in the section and disappears 0.02-0.06 m below the base of it. Conodont identified as *Amorphognathus* sp. could also be elements of *A. tvaerensis*. If it is so the *A. tvaerensis* CZ correspond to the interval 1.68-1.78 m below the base of the lower bentonite up to the level 0.65-0.75 m above the base of this bentonite. *Amorphognathus* sp. disappears together with *Baltoniodus* at 0.65-0.75 m above the base of the lower bentonite. The index species of the *Baltoniodus variabilis* Subzone occurs only in the interval 1.68-1.78 m below the base of lower bentonite. The index species of the *B. gerdae* Subzone has been found only in the interval 1.41-1.48 m below the base of lower bentonite. The index species of the *B. alobatus* subzone appears in the same interval and disappears 0.02-0.06 m below the base of the lower bentonite. The occurrence of two *Baltoniodus* species together in the interval 1.41-1.48 m below the base of lower bentonite probably indicates that the boundary between these two biozones falls into the sampled interval. The lower boundary of the 'Uppermost *B. alobatus* range' is marked by the disappearance of *A. tvaerensis* at 0.10 m interval right above the lower bentonite and its upper boundary by disappearance of *B. alobatus* at 0.65-0.75 m above the base of the lower bentonite.

Conodont species with simple coniform elements were abundant throughout the section (Table 4). The sample TC14-8 was dominated by simple cone taxa, like it is characteristic of the ‘Uppermost *Baltoniodus* range’ (Männik & Viira, 2012). However, no specimens which might belong to the *Baltoniodus* lineage were found in this sample, leaving the correlation of this level problematic.

Table 3. Technical results of the sample preparation.

Sample:	TC14 - 1	TC16 - 1	TC14 - 2	TC14 - 3	TC14 - 4	TC14 - 5	TC14 - 6	TC14 - 7	TC14 - 8
Weight (g)	3656,8	2200,8	3023,2	3831,4	3973,4	3440,3	3255,0	3386,9	4047,0
Acetic acid treatment period (month)	8	2	6	7	10	7	8	7	9
Heavy fraction (g)	1,01	0,92	1,64	2,19	0,31	3,74	0,86	9,49	3,05
Grams of heavy fraction per 1 kg sample	0,28	0,42	0,54	0,57	0,08	1,09	0,26	2,80	0,75
Number of conodont elements gathered	515	283	46	167	349	530	576	229	172
- elements identified at genus level	264	192	38	110	260	351	322	164	126
- unidentified elements	251	91	8	57	89	179	254	65	46
% of identified elements at genus level per sample	51	68	83	66	74	66	56	72	73
Picking efficiency results:									
Number of additionally found conodont elements	32	21	9	14	23	29	20	35	11
% from whole sample	6	7	20	8	7	5	3	15	6

Table 4. Distribution of identified conodont taxa and their abundance in samples in the Peetri section.

Sample:	TC14 - 1	TC16 - 1	TC14 - 2	TC14 - 3	TC14 - 4	TC14 - 5	TC14 - 6	TC14 - 7	TC14 - 8
Species									
Amorphognathus sp.	39					47	38	15	
Amorphognathus tvaerensis		47	11	23	21				
Baltoniodus alobatus		20	9	14	28	93	64	39	
Baltoniodus gerdae		1							
Baltoniodus variabilis	90								
Simple cone taxa:									
Cornuodus longibasis	7	9	2	3		5	5	3	
Decoriconus pesequus							1		
Drepanoistodus suberectus	20	19	8	15	50	32	75	32	44
Oslodus semisymmetricus	2	8		9	14	5	13	2	2
Panderodus spp.	41	43	5	23	61	64	42	28	21
Semiacontiodus spp.	52	35	3	23	23	87	37	39	38
Scabbardella sp.									16
Venoistodus balticus	13	10			55	15	36	4	5
Walliserodus sp.					8	3	11	2	

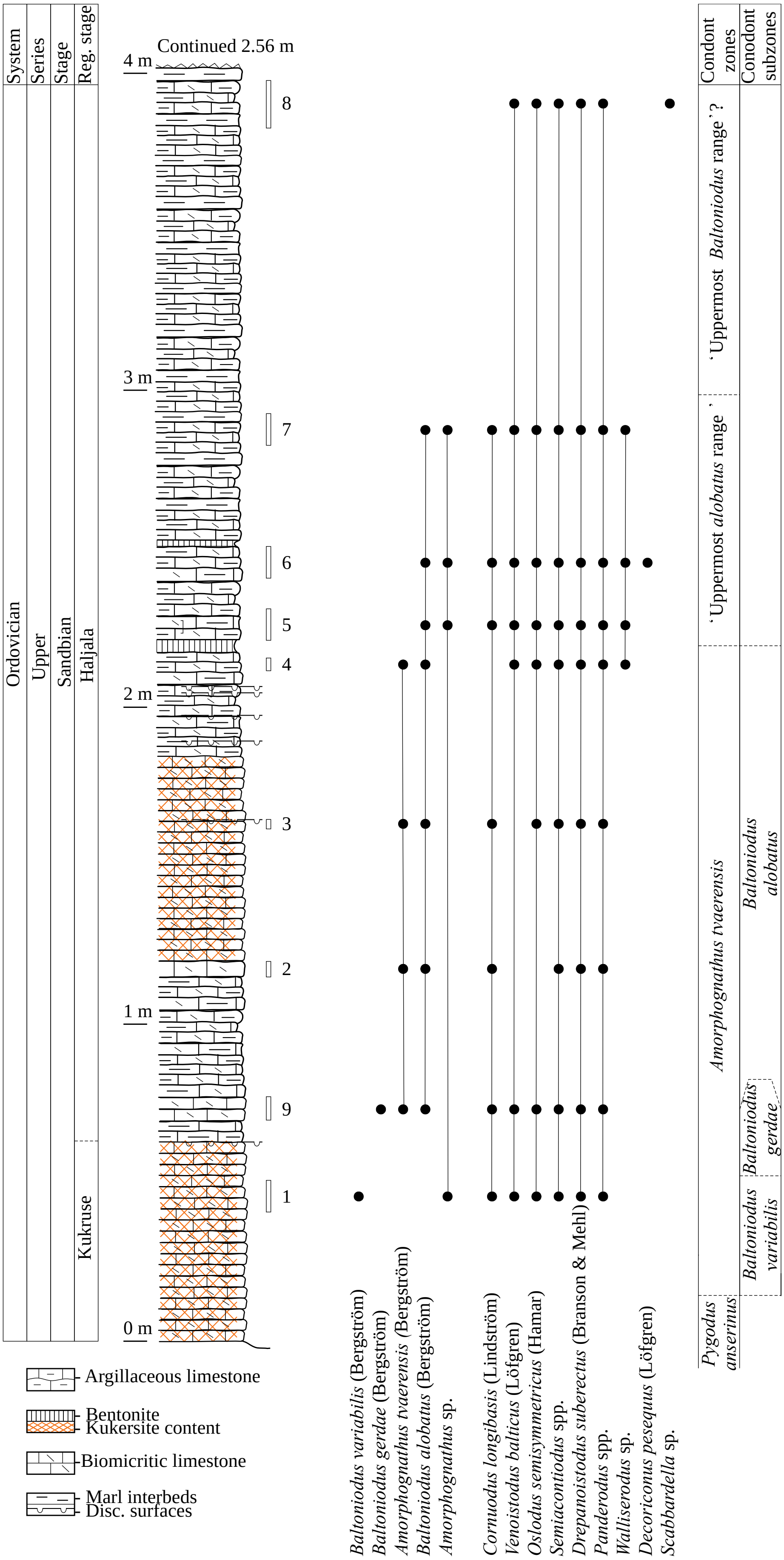

Figure 5. Conodont biostratigraphy in the Peetri section.

Discussion

The *Amorphognathus tvaerensis* Conodont zone (CZ) and the ‘Uppermost *B. alobatus* range’ correspond to the interval from the middle Kukruse Stage up to the upper Haljala Stage (Männik & Viira, 2012). This conclusion is based on detailed studies of conodont successions in the Taga-Roostoja drillcore in the NE Estonia (Viira & Männik, 1999), in the Ruhnu drillcore in the SE Estonia (Männik, 2003) and in the Mehikoorma drillcore in the SE Estonia (Männik & Viira, 2005), but also by comprehensive biostratigraphical study of the kukersite oil shale basin by Männil (1986).

In the kukersite oil shale basin (NE Estonia - Männil, 1986) the *A. tvaerensis* CZ is marked as an interval corresponding to the middle and upper parts of the Kukruse Stage and to the lower to middle parts of the Haljala Stage. The *B. variabilis* Subzone is equivalent to the middle and upper parts of the Kukruse Stage. The *B. gerdae* Subzone corresponds to the uppermost part of the Kukruse Stage and the lowermost part of the Haljala Stage. Lower boundary of the Haljala Stage falls in the lower part of *B. gerdae* subzone. The Idavere Substage of the Haljala Stage correlates with the *B. gerdae* Subzone and with the lowermost interval of *B. alobatus* Subzone. Boundary between the substages of the Haljala Stage falls in the lower part of the *B. alobatus* Subzone. Study of the Taga-Roostoja drillcore (Viira & Männik, 1999) confirms the results obtained by Männil (1986). Compared to southern Estonian sections, distinguishing biozones is more difficult here, because of scarce material.

In northern Estonia, the lower boundary of the Haljala Stage falls in the lower part of *B. gerdae* Subzone and the Idavere Substage is a part of the *B. gerdae* Subzone, ranging possibly also into the *B. alobatus* Subzone. Results from the southern part of Estonia (Männik, 2003; Männik & Viira, 2005) show the *Baltoniodus variabilis* Subzone to be equivalent to the upper part of the Kukruse Stage. Lower part of Haljala stage, Idavere Substages correlates with an interval from the middle *B. gerdae* subzone up to middle or topmost part of the ‘Uppermost *Balotniodus alobatus* range’.

As the lower boundary of the Haljala Stage is drawn within the *B. gerdae* Subzone, it should be looked for 1.41-1.67 m below the base of lower bentonite in the

Peetri section. The Idavere Substage ranges from *B. gerdae* Subzone, i. e. from 1.41-1.67 m below the base of lower bentonite, up to the middle or topmost part of 'Uppermost *B. alobatus* range' and the boundary between substages could be placed in the interval 0.04-0.76 m above the base of lower bentonite if considering the studies from south Estonia (Männik, 2003; Männik & Viira, 2005). This means that strata corresponding to the Idavere Substage are present in the Peetri section, and their thickness is not less than 1.45 m, but may be even more and reach 2.43 m.

In the previous studies (Rõõmusoks, 1970; Nõlvak & Hints, 1996) the lower boundary of the Haljala Stage was drawn at the level of a discontinuity surface above the uppermost kukersite-bearing interval. The data obtained in course of this study place the lower boundary of the Haljala Stage 1.40-1.56 m lower in the section. This also means that the uppermost 0.65 m thick kukersite rich interval in the section corresponds to the Haljala Stage (fig. 6). This indicates that thickness of the Haljala Stage is less reduced in NW Estonia than previously thought (see Hints et al., 1994). As all known conodont-based biostratigraphical units in the boundary interval of the Kukruse and Haljala stages are represented in the Peetri succession, extent of the hiatus at the boundary between these stages in NW Estonia (e.g. Nõlvak & Hints, 1991) needs further. All this points at the fact that stratigraphy in general in the Kukruse-Haljala boundary interval in NW Estonia requires further attention.

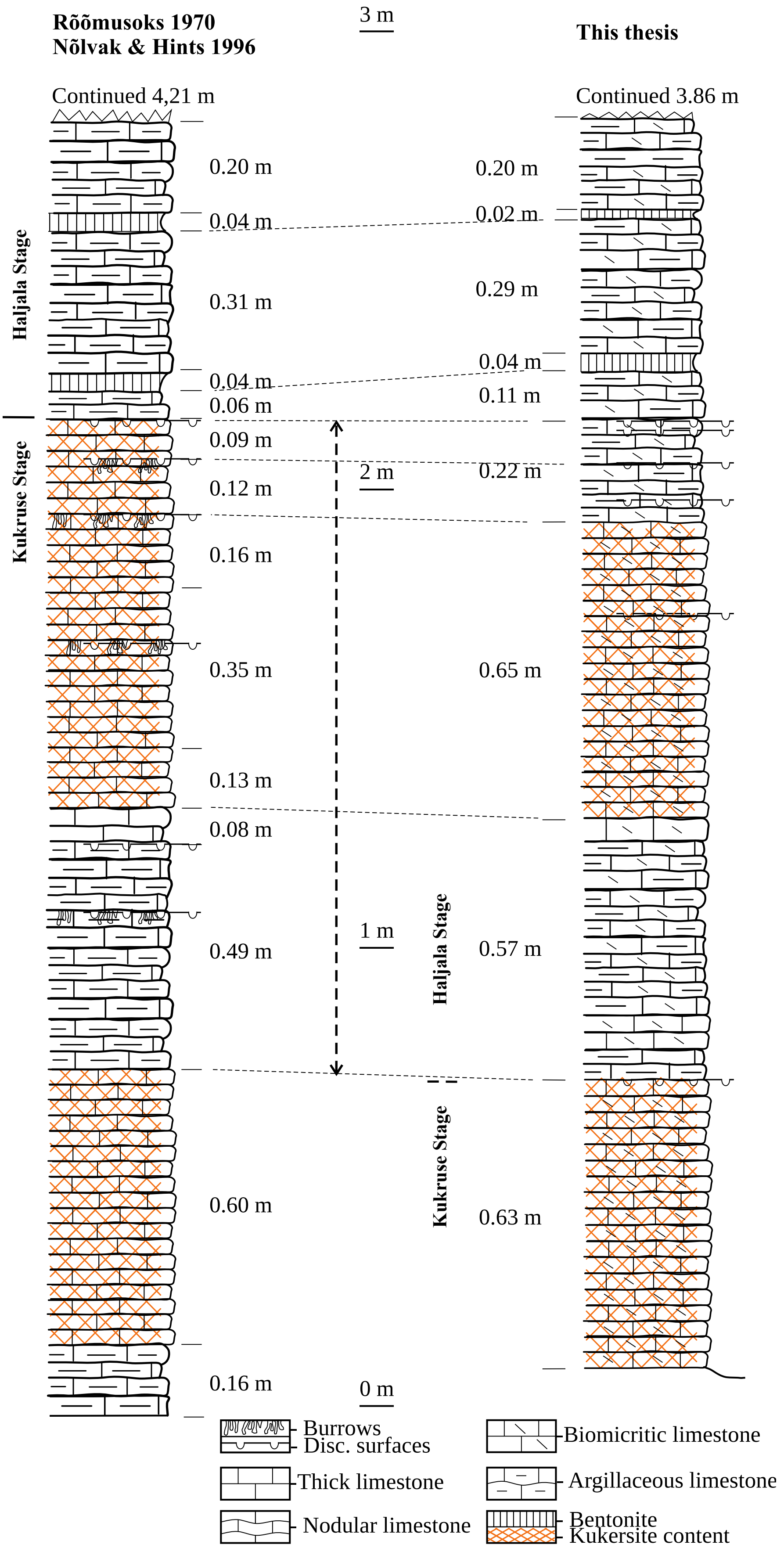

Figure 6. Comparison of the chronostratigrpahic subdivisions of the Peetri section by Rõõmusoks and subsequent authors with results of the present study.

The succession at Peetri is remarkably condensed. The inclined shaft section at Peetri had 0.89 m of strata above the lower bentonite layer in 1920 (fig. 3). This was reduced to 0.14 m for 1970 when the same section was described by Rõõmusoks, with total of 0.75 m seemingly worn away. The deep drench section holds 4.80 m of succession on the top of the base of lower bentonite layer 1970 (Nõlvak & Hints, 1996). This is reduced to 4.41 m above the bentonite in 2014, with total of 0.39 m worn away. Slight differences between the positions of bentonites in the described successions (fig. 3) are likely due to measurement errors. Discontinuity surfaces 0.06-0.33 m below the lower bentonite layer are in good correlation in different descriptions (fig. 6). The Interval between the lower boundary of the upper kukersite-rich interval and the upper boundary of the lower kukersite-rich interval has the same thickness (0.57 m) in different descriptions (fig. 6).

Additional conclusions can be made when Table 3 results are discussed. Higher ratio of heavy fraction in samples is likely due to pyrite content that increases the quantity of heavy fraction per 1 kg of sample (Table 3). Majority of samples dissolved in acid during a relatively long period (6-10 month), with exception of the sample TC16-1 that was fully dissolved within two months. The latter sample was treated separately, it was of a reduced size and acid was replaced more often. Lower dissolution time might not necessarily be a direct result of different sample composition or lower weight.

Amount of clay in samples varied significantly between samples and noticeably more argillaceous samples (TC14-1, 3, 4, 6, 8) took longer time to dissolve. These samples contained also smaller amount of heavy fraction (0.08-0.75 g), compared to the samples with lower clay content (0.54-2.80 g) (Table 3). The clay content in samples seems to influence the dissolution period and shows positive correlation with the ratio of heavy fraction.

Even though number of conodont elements per samples varied between 46-576 (Table 3), this variation was not related to the sample weight or clay content. Element abundance has no significant relationship to the rock type, but may refer to the differences in sedimentation rates. Samples with higher abundance of elements and lower sample weight suggest low sedimentary rate or higher compaction. Higher abundance could also refer to better life conditions or more oxygen-rich near-bottom waters.

Percentage of the elements identified at the genus level varied between 51-83 %, showing a slight relationship to the total number of elements per sample (Table 3). With the exception of sample TC14-3, the samples with higher element counts show lower percentage of unidentified elements. Larger element counts come together with a higher amount of unidentified elements. Percentage of additional conodont elements found in course of picking efficiency check varied between 3-20 % of the total number of recovered conodont elements (Table 3). This shows that extra check is recommended when dealing with samples with lower conodont abundance and samples with larger content of heavy fraction.

When comparing thicknesses of the *Amorphognathus tvaerensis* CZ, its subzones and the 'Uppermost *B. alobatus* range' in different sections, the section in NW Estonia seems still to be slightly more condensed than in the other parts of Estonia (Table 5). It seems that the *B. gerdae* Subzone gains thickness towards south Estonia and the intervals corresponding to the *A. tvaerensis* CZ and 'Uppermost *B. alobatus* range' increase towards East Estonia.

Table 5. Thickness (approximate values, meters) of conodond zones and subzones intervals based on data from drill cores (Viira & Männik, 1999; Männik, 2003; Männik & Viira, 2005) and this thesis. (Thickness of the A. tvaerensis CZ corresponds to the sum of B. Variabilis, B. Gerdae and B. Alobatus values; 'Upper. alo.' = 'Uppermost *Baltoniodus alobatus* range')

	Peetri (NW Estonia, this thesis)	Taga-Roostoja (NE Estonia)	Ruhnu drillcore (SW Estonia)	Mehikoorma (SE Estonia)
B. Variabilis	0,5	8	3	6
B. Gerdae	0,25	0,6	2	4,5
B. Alobatus	1,5	3	3	2,5
'Upper. alo.'	0,7	1,2	0,5	1,5

Conclusions

This study addressed conodont biostratigraphy in the Kukruse-Haljala boundary interval in NW Estonia. Due to the lack of reliable biostratigraphic criteria position of the stage boundary in the succession has been problematic for long time. One of the best sections in NW Estonia exposing this interval is the Peetri section.

Here the lower boundary of the Haljala Stage has drawn at the top of the thick kukersite-rich interval attributed to the Kukruse Stage. The new results indicate that the boundary is at a lower level in the section and upper part of the kukersite-rich interval exposed belongs to the Haljala Stage. This, and existence of strata of the Idavere Substages in section shows that the stratigraphy in the Kukruse-Haljala interval is still problematic and should be re-addressed. The presence of a complete succession of conodont zones in this interval in the Peetri section indicates that the hiatus at the base of the Haljala Stage in NW Estonia is probably smaller than considered earlier

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Appendix

Plate 1

Each scale bar is 100 µm.

Figures 1-7. *Amorphognathus tvaerensis* Bergström, 1962.

1 – Upper view, Pa element, sample TC14-3, Peetri shaft outcrop, Haljala Stage.
2 – Upper view, Pa element, sample TC16-1, Peetri shaft outcrop, Kukruse or Haljala Stage.
3 – Upper view, Pa element, sample TC16-1, Peetri shaft outcrop, Kukruse or Haljala Stage.
4 – Lateral view, Pb element, sample TC14-2, Peetri shaft outcrop, Haljala Stage.
5 – Lateral view, Pb element, sample TC14-3, Peetri shaft outcrop, Haljala Stage.
6 – Lateral view, Pb element, sample TC16-1, Peetri shaft outcrop, Kukruse or Haljala Stage.
7 – Lateral view, M element, sample TC14-3, Peetri shaft outcrop, Haljala Stage.

Figure 8. *Baltoniodus gerdae* (Bergström, 1971).

8 – Upper view, Pa element, sample TC16-1, Peetri shaft outcrop, Kukruse or Haljala Stage.

Figures 9-11, 13. *Baltoniodus variabilis* (Bergström, 1962).

9 – Upper view, Pa element, sample TC14-1, Peetri shaft outcrop, Kukruse Stage.
10 – Upper view, Pa element, sample TC14-1, Peetri shaft outcrop, Kukruse Stage.
11 – Lateral view, Pb element, sample TC14-1, Peetri shaft outcrop, Kukruse Stage.
13 – Lateral view, M element, sample TC14-1, Peetri shaft outcrop, Kukruse Stage.

Figure 12. Baltoniodus sp.

12 – Lateral view, M element, sample TC16-1, Peetri shaft outcrop, Kukruse or Haljala Stage.

Figure 14. Amorphognathus sp.

14 – Lateral view, Pb element, sample TC14-5, Peetri shaft outcrop, Haljala Stage.

Plate 1

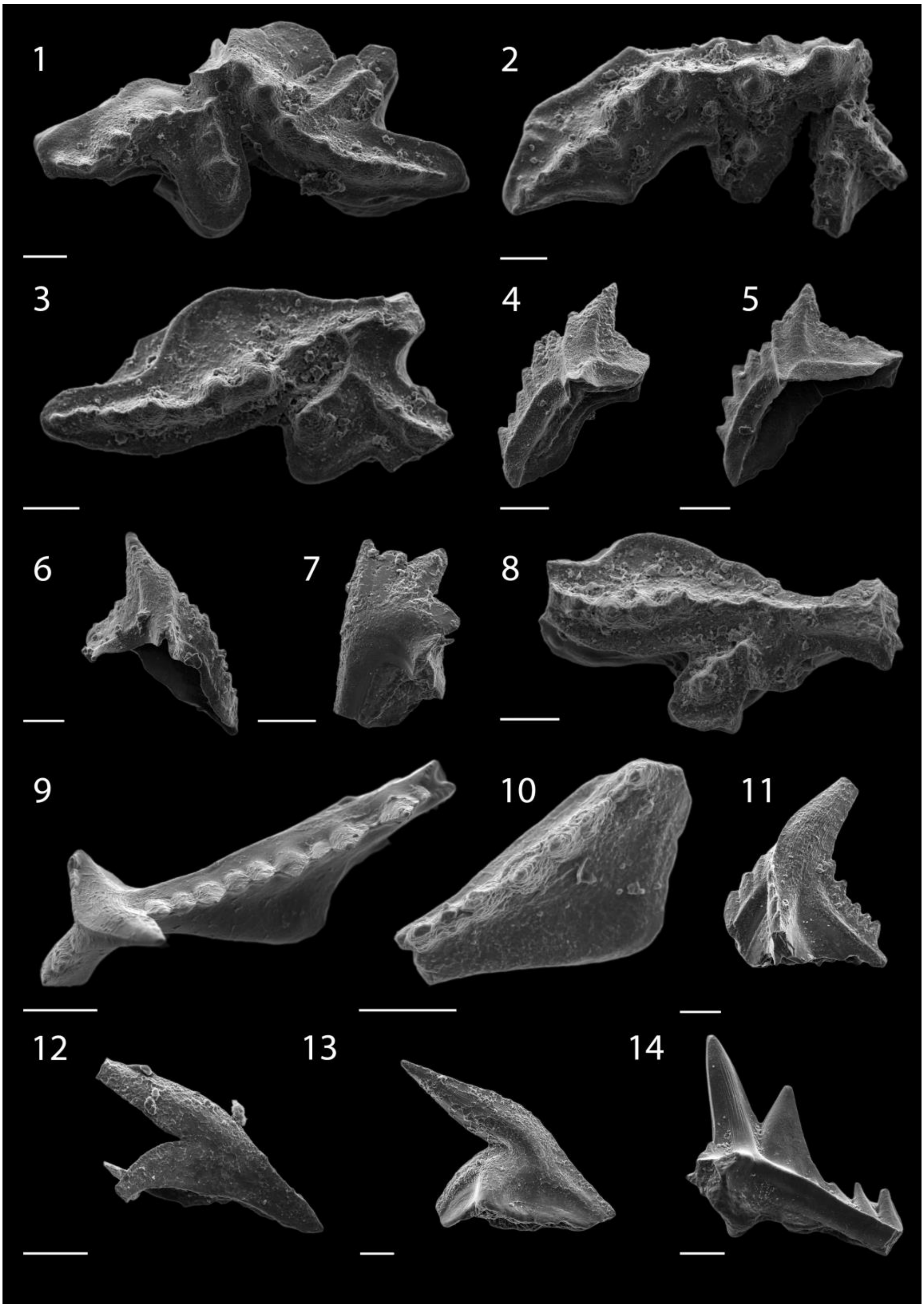


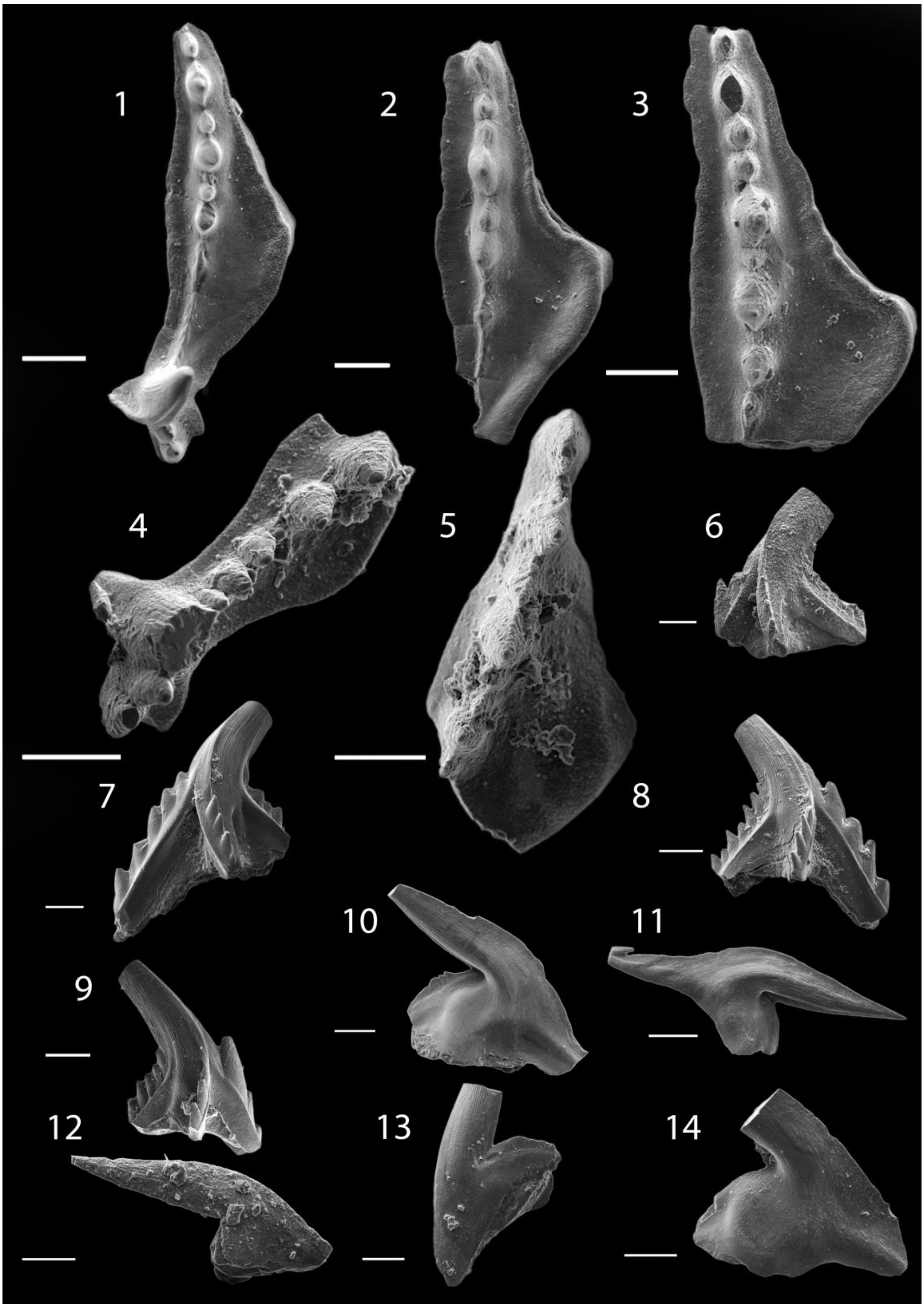
Plate 2

Each scale bar is 100 µm.

Figures 1-14. *Baltoniodus alobatus* (Bergström, 1971).

1 – Upper view, Pa element, sample TC14-4, Peetri shaft outcrop, Haljala Stage.
2 – Upper view, Pa element, sample TC14-5, Peetri shaft outcrop, Haljala Stage.
3 – Upper view, Pa element, sample TC14-7, Peetri shaft outcrop, Haljala Stage.
4 – Upper view, Pa element, sample TC14-2, Peetri shaft outcrop, Haljala Stage.
5 – Upper view, Pa element, sample TC16-1, Peetri shaft outcrop, Kukruse or Haljala Stage.
6 – Lateral view, Pb element, sample TC14-2, Peetri shaft outcrop, Haljala Stage.
7 – Lateral view, Pb element, sample TC14-4, Peetri shaft outcrop, Haljala Stage.
8 – Lateral view, Pb element, sample TC14-5, Peetri shaft outcrop, Haljala Stage.
9 – Lateral view, Pb element, sample TC14-7, Peetri shaft outcrop, Haljala Stage.
10 – Lateral view, M element, sample TC14-4, Peetri shaft outcrop, Haljala Stage.
11 – Lateral view, M element, sample TC14-4, Peetri shaft outcrop, Haljala Stage.
12 – Lateral view, M element, sample TC14-2, Peetri shaft outcrop, Haljala Stage.
13 – Lateral view, M element, sample TC14-5, Peetri shaft outcrop, Haljala Stage.
14 – Lateral view, M element, sample TC14-7, Peetri shaft outcrop, Haljala Stage.

Plate 2



Haljala lademe alumine piir Loode-Eestis konodontide leviku alusel

Tõnn Paiste

Kokkuvõte

Käesolev töö kajastab konodondi biostratigraafiat probleemse Kukruse-Haljala stratigraafilise intervalli kohta Loode-Eestis. Peetri kõvik on väheseid paljandeid mis sobib antud probleemi lahendamiseks, kuna võimaldab suuremate proovide võtmist konodondi uuringute jaoks.

Peetri kõvikul paljanduvad Kukruse ja Haljala Haljala lademete piirikihid. Traditsiooniliselt on piiriks loetud kukersiiti sisaldavast intervallist kõrgemale jääv tugevaim püriidistunud katkestuspind. Uued andmed näitavad, et nimetatud lademete piir läbilõikes asub allapool ja et ülemine kukersiidirikas intervall vastab Haljala lademe basaalsele osale. Ka ilmnes, et Haljala Lademe alumisele osale vastav Idavere alamlade on läbilõikes esindatud ja lünk lademete piiril on ilmselt mahult väiksem, kui seni arvatud. On ilmne, et Kukruse-Haljala lademe piiriintervalli stratigraafia Loode-Eestis vajab täiendavat uurimist.

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