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Department of Geology, Institute of Ecology and Earth Sciences, Faculty of Science and Technology, University of Tartu, Estonia.

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LIST OF ORIGINAL PUBLICATIONS

This thesis is based on the following published papers, which are referred to in the text by their Roman numerals. The papers are reprinted by kind permission of the publishers.

I **Põldsaar, K.** and Ainsaar, L. 2014. Extensive soft-sediment deformation structures in the early Darriwilian (Middle Ordovician) shallow marine siliciclastic sediments formed on the Baltoscandian carbonate ramp, northwestern Estonia. Marine Geology, 356, 111–127.

II **Põldsaar, K.** and Ainsaar, L. 2015. Soft-sediment deformation structures in the Cambrian (Series 2) tidal deposits (NW Estonia): Implications for identifying endogenic triggering mechanisms in ancient sedimentary record. Palaeoworld, 24, 16–35.

III **Põldsaar, K.**, Ainsaar, L., Nemliher, R., Tinn, O. and Stinkulis, G. 2019. A siliciclastic shallow-marine turbidite on the carbonate shelf of the Ordovician Baltoscandian palaeobasin. Estonian Journal of Earth Sciences, 68, 1–14.

Author's contribution:

Paper I: The author was primarily responsible for planning original research, data collection and fieldwork, the interpretation of results, and writing of the manuscript.

Paper II: The author was primarily responsible for planning original research, data collection and fieldwork, the interpretation of results, and writing of the manuscript.

Paper III: The author was primarily responsible for structural analysis of drill core slabs and the writing of the manuscript.

1. INTRODUCTION

In basin analysis, it is equally important to understand the large-scale geological development of the basin, as well as to detect single short-lived events within a given time-frame. A geological process can proceed continuously for decades or millennia, like for example, uninterrupted sedimentation of mud and other particles in a tropical carbonate sea. However, there are short-lived geological events that disrupt the normal slow advance of geological processes. These take place instantaneously in a geological sense and can synchronously affect large areas. Such events are typically triggered by the physical environment and reflect either local or intra-basinal processes, or are associated with regional or global mechanisms (Einsele et al. 1996). Geological events often leave their signatures within the regular sedimentary succession as so-called ‘event horizons’. The volume, frequency, and facies of sedimentary event deposits can be used to analyse for example the tectonic history of the region (e.g. McLaughlin and Brett 2004; Obermeier et al. 2005; Koç Taşgin et al. 2011), the bathymetric configuration of the basin (Mutti et al. 1999), or even past climate conditions (e.g. Asikainen et al. 2007; Vierek 2013).

Sedimentary events are controlled by pre-event sedimentation, the triggering and sediment transport mechanism, and mode of final deposition (Einsele et al. 1996). Usually, the background sedimentary equilibrium is restored immediately after cessation of the event. As a result, event horizons often clearly stand out from the rest of the sedimentary succession as bounded layers of deformed sediment (i.e. seismites or other liquefaction-induced soft-sediment deformation horizons; e.g. Lowe 1975; Allen 1982), as layers with anomalous lithology or specific sedimentary characteristics (e.g. turbidites, tsunamiites), or as layers of exceptional palaeontological or mineralogical-geochemical composition (e.g. volcanic ash beds).

In this thesis, three unusual sedimentary phenomena are studied from the Lower Palaeozoic succession of the Baltic Basin: (1) the Cambrian Series 2 (Dominopolian) tidalites with large-scale soft-sediment deformation structures in NW Estonia (Põldsaar and Ainsaar 2015 – PAPER II); (2) a peculiar single sandstone–siltstone lobe within the Middle Ordovician (Dapingian) outer ramp argillaceous limestone facies in Latvia and the submarine Baltic Sea proper (Põldsaar et al. 2019 – PAPER III); and (3) a widespread deformation of the nearshore sandy facies of the Lower Ordovician Pakri Formation in NW Estonia and West Estonian archipelago (Põldsaar and Ainsaar 2014 – PAPER I). The geographical locations of the studied event horizons are illustrated in Figure 1.

The Baltic Basin is widely recognized to have been tectonically inactive for most of the early Palaeozoic (e.g. Poprawa et al. 1999; Nielsen and Schovsbo 2011; Šliaupa and Hoth 2011). However, a few recent studies have revealed periods of regional tectonic activity in the craton interior (e.g. Tuuling and Vaher 2018) that disturbed the overall tectonic stability of this region. Moreover, the area suffered from several meteorite impact events during the Palaeozoic that were capable of generating specific event beds and large-scale sediment deformations (Dypvik et al. 2008).

This thesis focuses on the lithology and sedimentary properties of exceptional sedimentary layers (i.e. event beds) that interrupt the succession of normal background shallow-marine calcareous deposits of the early Palaeozoic Baltoscandian Basin. The main aims of the thesis are:

1) to map, describe, and interpret the sedimentary properties of selected event horizons within different ancient epicontinental marine facies environments of the Baltic Basin;
2) to test the three-stage process suggested by Owen et al. (2011), the facies–trigger–criteria assessment, when considering some key criteria for distinguishing between seismic and aseismic soft-sediment deformation triggers on an ancient continental shelf basin;
3) to analyse the possible sources and triggers of these unusual palaeotectonic or other sedimentary events.

The results of this research permit us to decipher the geological conditions that prevailed within the Baltoscandian Basin during the deposition of the studied sedimentary units and discuss the scope and impact of their triggers.

2. GEOLOGICAL SETTING

2.1. General geological setting

Epicontinental sedimentary basins started to develop on the Baltica palaeo-continent after its detachment from the Rodinia supercontinent at the end of the Neoproterozoic era. The craton of Baltica became tectonically inactive soon after the Ediacaran–early Cambrian Timanide Orogeny (Nikishin et al. 1996). Periods of regional tectonic activity on all its other margins are believed to have had virtually no influence on the conditions in the craton's interior (Nielsen and Schovsbo 2011). Hence, the current understanding is that the Baltic Basin remained tectonically quiescent for most of the early Palaeozoic.

The Baltic sedimentary basin (called also the Baltoscandian Palaeobasin for the Ordovician Period) developed on the southern flank of the Fennoscandian Shield (Fig. 1). The deposits of the basin represent its long-lasting subsidence history from Late Precambrian to Phanerozoic as an epicontinental sea and the subsequent foreland basin to the Caledonian mountain range. The siliciclastic and carbonate deposits reach the maximum thickness (>4 km) in the south-western part of the basin where the sedimentary succession is also most complete. The thickness of sediments gradually decreases to around 2 km in south-western Latvia and is less than 100 m in northern Estonia. In the study region (Estonia, Latvia, north-western Russia; Fig. 1) there occur only the Ediacaran and Palaeozoic deposits (Cambrian to late Devonian; Nikishin et al. 1996). In the internal platform areas, including the study region, the sediments are generally well preserved and unaffected by deep burial diagenesis and tectonic dislocations.

The Early Palaeozoic sedimentary succession of the Baltic Basin preserves an exceptional record of facies and biotic changes induced by the solitary drift of the Baltica plate from high southern latitudes to equatorial tropics (Torsvik et al. 1992; Cocks and Torsvik 2005). The Neoproterozoic–Cambrian sediments of the basin represent the evolution of the sedimentary environment from continental alluvial fans to a shallow marine (proximal shelf) cold-water terrigenous platform.

The Early Cambrian sea was a wave-dominated open-marine tidal shelf where frequent storms had a great influence on sediment deposition (Nielsen and Schovsbo 2011; Põldsaar and Ainsaar 2015 – PAPER II). During the following periods, the sedimentation continued in a basinal facies of a shallow sea. The Cambrian and Early Ordovician siliciclastic platform was gradually replaced by a temperate-climate carbonate ramp during the Middle Ordovician (Nestor and Einasto 1997).

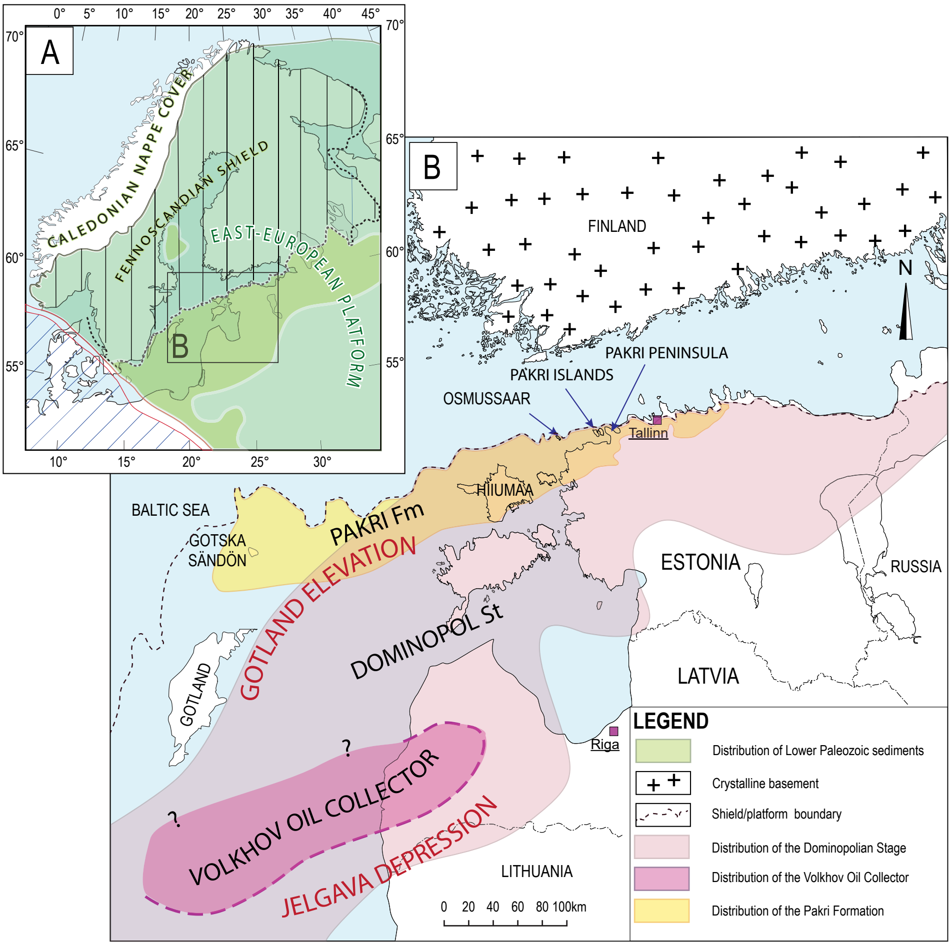

Figure 1. Location map of the study area: (A) generalised map of the Baltoscandian area; (B) schematic distribution of the studied sedimentary units: the Cambrian Dominopolian clastic sediments are indicated by light pink, the lime-rich sandstones of the Middle Ordovician Pakri Formation by yellow, and the Volkhov Oil Collector sandstones by dark pink colour. Locations of the Jelgava depression and Gotland elevation are also shown. (Modified from Põldsaar and Ainsaar 2014 – PAPER I; Nielsen and Schovsbo 2011; Põldsaar et al. 2019 – PAPER III).

The rate of overall carbonate deposition in the Ordovician sea was very low – only a few millimetres net per a thousand years (Jaanusson 1973). Therefore, the entire Ordovician sedimentary succession is only 40–160 m thick. Furthermore, because also the erosion from surrounding lowlands was extremely low, the Middle and Upper Ordovician carbonate succession almost lacks coastal sand facies and is particularly poor in sand-sized or coarser siliciclastic material throughout the basin area (Jaanusson 1973). Only a few unusual sandstone layers interrupt the profoundly calcareous Ordovician sedimentary succession of the basin. These are the event beds of the Middle Ordovician Pakri Formation and the Volkhov Oil Collector (Põldsaar and Ainsaar 2014, 2015 – PAPERS I, II; Põldsaar et al. 2019 – PAPER III) studied here, and the Late Ordovician (Sandbian) ejecta blanket which surrounds the Kärdla meteorite crater in the West Estonian archipelago (Ainsaar et al. 2002). Furthest to the west, in the Jämtland region (Sweden), thick turbidite systems were deposited during the Ordovician (Karis and Strömberg 1998).

The carbonate deposition rate considerably accelerated during the Silurian when Baltica drifted to the equator, and tropical carbonates started to accumulate in a shallow-self environment (Nestor and Einasto 1997). As a result, the thickness of the Silurian strata reached >3 km in the south-western part of the basin (Poprawa et al. 1999).

The Baltic sedimentary basin had an extremely flat relief (e.g. Martinsson 1974). Even the dip of the slopes of the major tectonic structure within the basin – the Jelgava Depression (Männil 1966) – is less than 2 per cent (Põldsaar et al. 2019 – PAPER III). The Jelgava Depression is an elongate south-westerly to north-easterly oriented structure that marks a relatively deeper part of the Baltic Basin (Fig. 1) from late Tremadocian to early Silurian times. It acted as a depocentral area for the Middle Ordovician sediments (Poprawa et al. 1999).

Despite the overall smooth topography and low erosion, the Lower and Middle Ordovician sediments are missing in a vast area of a sedimentary gap, where are missing in the middle of the basin. This region is called the Gotland elevation (Männil 1966). It extends north-westwards from the Jelgava Depression between the islands of Gotland and Hiiumaa (Fig. 1). In the area of the Gotland elevation (the 'Gotland–Gotska Sandön rise' of Jaanusson 1973; the 'Gotland–Hiiumaa uplift zone' or 'Gotland–Hiiumaa structural zone' or 'Gotland structure' of Suuroja et al. 2003), the lower Darriwilian deposits are directly underlain by Tremadocian or Cambrian sandstones and shales (Männil 1966).

2.2. Stratigraphy

In the study region (Estonia, Latvia), the Cambrian System is mostly represented by the deposits of Stage 2 of the Terreneuvian and Stage 3 of the Series 2 (Fig. 2). The studied Tiskre and Lükati formations of the Dominopol Stage (Series 2) in northern Estonia are represented by normal shallow-marine siliciclastic sediments. The Dominopolian sediments cover the hiatus on the top of the Terreneuvian (Stage 2) massive Blue Clay succession of the Lontova Regional Stage and are also overlain by a hiatus covered by younger sandy sediments of the Furongian Series (Fig. 2; Mens and Pirrus 1997b). The Dominopol Stage (Lükati and Tiskre formations) is widely distributed in the Cambrian palaeobasin (Fig. 1). It reaches up to 40 m in thickness in North Estonia but thins out quickly to the south (Mens and Pirrus 1997a).

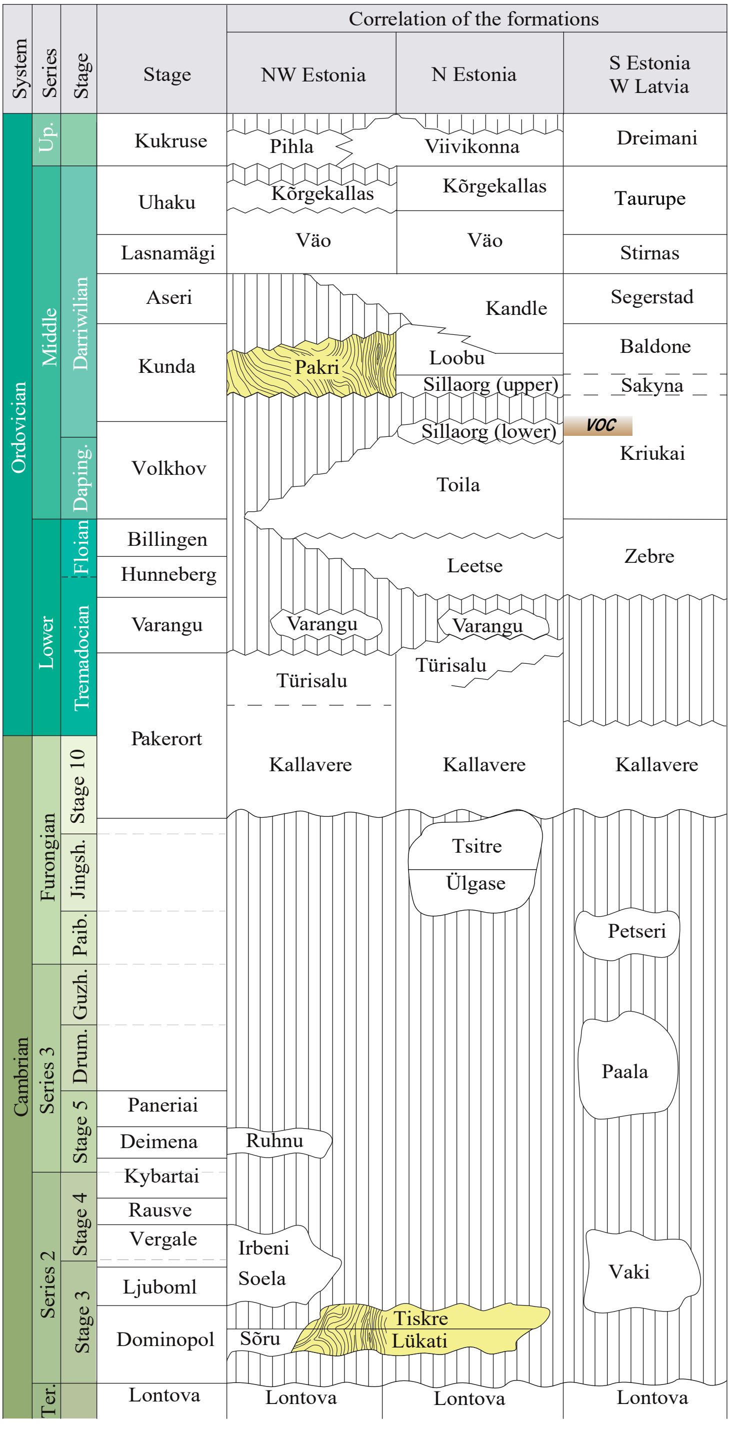

Figure 2. The Cambrian and Lower and Middle Ordovician stratigraphy in Estonia and Latvia; approximate stratigraphic position of the Volkhov Oil Collector (VOC) is shown. (Modified from Meidla 2017; Meidla et al. 2014).

The lower part of the studied Cambrian interval (Lükati Formation) was deposited under supra-tidal facies settings and is composed of interbedded greenish-grey argillaceous rocks and very fine-grained layers of cemented sandstone (Mens and Pirrus 1997a). The upper part of the interval (Tiskre Formation) is composed of light-coloured massive-to-thick-bedded stacked sandstone sequences with thin interbeds of greenish-grey argillaceous rocks. In some localities, medium-bedded rhythmites occur instead (Põldsaar and Ainsaar 2015 – PAPER II). These sediments represent open-sea storm-influenced tidalites with a gradually decreasing influence of storms upwards in the section as the basin gradually subsided (Põldsaar and Ainsaar 2015 – PAPER II). The rest of the Cambrian Period is poorly represented in the study area with numerous sedimentary gaps and patchy occurrence of sediments (Fig. 2).

The Cambrian sandy sediments are overlain by different Lower Ordovician (Tremadocian) siliciclastic sediments throughout the study area. Carbonate deposition replaced siliciclastic sedimentation in late Floian time. This depositional change is represented by the appearance of glauconiferous limestones of the Toila Formation in northern Estonia and concurrent deeper ramp red limestones of the Kriukai Formation in South-Estonia and Latvia.

The Middle Ordovician Dapingian and Darriwilian sediments in Latvia are represented by a nearly continuous succession of argillaceous limestones, dolomites, and marlstones that were deposited in a deeper part of the carbonate ramp setting. The entire Dapingian to the earliest Darriwilian is represented by the 13–32 m thick Kriukai Formation. This succession consists of reddish-brown argillaceous dolomite with dolomitic marlstone interbeds. Approximately 3–5 m below its upper boundary there appears a distinctive 0.1–0.8 m (occasionally 1.5 m) thick, notably oil-saturated, sandstone–siltstone interlayer – the Volkhov Oil Collector (Fig. 1; Yakovleva 1977). The collector bed is grey to dark brown in colour and, thus, stands out from the rest of the red-coloured carbonates of the Kriukai Formation (Lashkov and Yakovleva 1977).

The boundary between the Kriukai and the overlying Šakyna formations is marked by a change in the deposition patterns in early Kunda (early Darriwilian) time. The Pakri Formation (Kunda Regional Stage) studied here is composed of up to 4.5 m thick lime-rich quartzose sandstone that spreads as a roughly south-west oriented 30–40 km wide belt over 300 km from north-western Estonia to the island of Gotska Sandön (Fig. 1; Põldsaar and Ainsaar 2014 – PAPER I). Abundant nearshore fossil fauna and convenient belt-like arrangement along the theoretical palaeoshoreline have allowed previous researchers to conclude that the sand-rich sediments of the Pakri Formation represent rare remains of the Ordovician nearshore facies in the Baltoscandian Palaeobasin (Orviku 1960; Männil 1966). The Pakri Formation is composed of a layered sedimentary succession where weakly consolidated dark-coloured organic-rich sandstone layers alternate with firmly cemented light-coloured lime-rich sandstone layers (Põldsaar and Ainsaar 2014 – PAPER I).

The Middle Ordovician succession in northern Estonia is upwards followed by a less than 1 m thick layer of oolitic limestone (Aseri Regional Stage), and an up to 12 m thick succession of bioclastic limestones of the Lasnamägi–Uhaku regional stages (Fig. 2).

3. MATERIAL AND METHODS

The material studied in this thesis originates from three different sedimentary deposits of the Baltoscandian Palaeobasin – (1) the Cambrian (Dominopol) Lükati and Tiskre formations in northern Estonia; (2) the Volkhov Oil Collector bed within the Middle Ordovician (Dapingian) Kriukai Formation in western Latvia; and (3) the Middle Ordovician (Darriwilian) Pakri Formation in north-western Estonia and the West Estonian archipelago (Fig. 1).

This study is based on a metre- to centimetre-scale description of rock lithology and sedimentary structures and textures. The main focus is on documenting, mapping, and analysing various soft-sediment deformation structures, and other directional primary and secondary sedimentary structures in outcrops and drill cores. The Cambrian Lükati and Tiskre formations were studied in outcrops, the Volkhov Oil Collector is accessible only in drill cores, and the Pakri Formation was studied both in outcrops and in cores. Altogether 21 drill cores were investigated in north-western Estonia, Hiiumaa Island in the West Estonian archipelago, and in western Latvia. In addition, 14 outcrop localities with a combined length of approximately 20 km were studied. All outcrops are tens of metres to several kilometres wide and 1 m to over twenty m high.

The studied Middle Ordovician and Cambrian outcrops are part of the over 1200 km long series of cliffs (the Baltic Klint) between Öland Island in Sweden and Lake Ladoga in Russia (Fig. 1). The results of this study were combined with previously published core and outcrop descriptions from Estonia and Latvia and with a detailed lithological description of the Gotska Sandön core from the unpublished core-log of Valdar Jaanusson.

The sediments of the Pakri Formation are deformed throughout the majority of their distribution area (Põldsaar and Ainsaar 2014 – PAPER I) except for the most distal part of the formation on Hiiumaa Island. Deformations were also the primary study focus in the case of the Cambrian Lükati and Tiskre formations (Põldsaar and Ainsaar 2015 – PAPER II). The studied deformations are represented in both cases by the so-called soft-sediment deformation structures (e.g. Owen et al. 2011). In this study, we used the three-stage process – the 'facies–trigger–criteria assessment' by Owen et al. (2011), to identify the triggers of soft-sediment deformations both in the Ordovician Pakri Formation and in the Cambrian Tiskre and Lükati formations.

The material of the Volkhov Oil Collector was obtained from three West Latvian drill cores: Vergale-50, Vergale-49, and Aizpute-41 (Fig. 1). In addition to the lithological descriptions, we used here also X-radiography analysis, grain-size analysis, the petrological study of thin sections, and micro-palaeontological analysis in order to study the genesis of the Volkhov Oil Collector bed (Põldsaar et al. 2019 – PAPER III).

4. RESULTS AND INTERPRETATIONS

4.1. Soft-sediment deformation structures

The largest number of different soft-sediment deformation structures occur within the Pakri Formation (Põldsaar and Ainsaar 2014 – PAPER I). These are well represented also within the Cambrian tidalites (Põldsaar and Ainsaar 2015 – PAPER II), but are small and insignificant in the Volkhov Oil Collector bed (Põldsaar et al. 2019 – PAPER III). The minor soft-sediment deformation structures of the Volkhov Oil Collector are not discussed in detail here further.

Altogether thirteen types of soft-sediment deformation structures were identified within the studied sediments (summary in Table 1). According to their genesis, these structures broadly categorize as load structures (*sensu* Owen 2003) and as dewatering structures (*sensu* Allen 1982). Individual deformation types described in the study are the following:

(a) load structures:
- (1) simple and pendulous load casts (Fig. 3B),
- (2) flame structures (Fig. 3A–C),
- (3) attached and detached pseudonodules (Fig 3A, C),
- (4) ball-and-pillow morphology (Fig. 3D),
- (5) contorted heavy mineral lamination (Fig. 3E),
- (6) convolute lamination (Fig. 3F),

(b) dewatering structures:
- (7) homogenised sediment (Fig. 4A, D),
- (8) dish-and-pillar structures (Fig. 4A),
- (9) water-escape channels (Fig. 4B),
- (10) large sedimentary dikes (Fig. 4B, C),
- (11) stress pillars (Fig. 4D),
- (12) sand volcanoes (Fig. 4E, F),
- (13) autoclastic breccias (Fig. 4C).

Additionally, complex deformation zones have been described locally both from the Pakri Formation and from the Cambrian tidalites, where the above-mentioned deformation types occurred simultaneously (Põldsaar and Ainsaar 2014, 2015 – PAPERS I, II).

The observed soft-sediment deformation structures vary in their sizes and morphologies in the Pakri Formation as well as in the Tiskre and Lükati formations. However, the most profound difference between these two sedimentary systems lies in the distribution patterns of the deformations. Soft-sediment deformations within the Pakri Formation encompass the entire up to 4 m thick sedimentary succession. The deformed horizon is laterally consistent and can be traced over a vast geographical area (over 9000 km^2; Põldsaar and Ainsaar 2014 – PAPER I). Deformations are always bound by undeformed layers from the top and below (except for the most severely deformed Osmussaar Island area, where also the brittle destruction of older strata is observed; Suuroja 1999; Põldsaar and Ainsaar 2014 – PAPER I). Furthermore, the extent of deformation decreases radially away from a single epicentral region on Osmussaar Island, enabling the distinction of three laterally spreading regional deformation zones (see fig. 11 in Põldsaar and Ainsaar 2014 – PAPER I). In the Cambrian tidalites, on the contrary, the soft-sediment deformations occur at multiple stratigraphic heights within the up to 40 m thick sedimentary succession. These deformation horizons lack consistency and can be traced only 50–60 m (sometimes more) along the outcrop wall before they fade away along with the sedimentary lenses that contain them (Fig. 4G; Põldsaar and Ainsaar 2015 – PAPER II). New deformation horizons reappear and disappear along several tens of kilometres of the studied outcrop walls, however, those individual deformation horizons are almost never vertically correlated to one another. Unlike in the Pakri Formation, the extent and complexity of deformations in the Cambrian tidalites can alternate within metres along the outcrop wall (Põldsaar and Ainsaar 2015 – PAPER II).

Of the first category soft-sediment deformation structures, the load structures are the most numerous deformations both in the Ordovician shallow-marine sandy carbonate and in the Cambrian tidalites. These deformations form most readily in sandy sediments in a low or zero shear resistance situation. Load features (Fig. 3 A–F) commonly induced by liquefaction and fluidization in reversed density gradient systems (Anketell et al. 1970) and due to unequal density loading, or the both (Allen 1982). Morphological complexities of load deformations depend on the dynamic viscosities of the liquefied sediment layers (e.g. Anketell et al. 1970; Mills 1983) and the duration of the liquefied state (Owen 2003). Load structures driven by density contrast can be considered as a deformation series, where deformation structures increase in complexity from simple and pendulous load casts to pseudonodules (pillows) and eventually to a ball-and-pillow structure (Fig. 3A–D; Owen 2003) because a prolonged liquefaction state or a stronger acting stress will result in more complex deformation features.

Such a prolonged liquefaction state could have easily occurred both in the Pakri Formation and in the Cambrian tidalites, because the alternating fine-grained sandy limestone layers (in shallow-marine carbonates) and clayey silt intra-layers (in tidalites) would have acted as low-permeability horizons and inhibited quick regain of equilibrium during the liquefaction of the unlithified sedimentary pack.

The truncated and ‛dragged-along’ appearance of the upper parts of the flame structures was observed within the Cambrian tidalites (Fig. 3B, C, F). This is a likely result of normal sediment current shear and erosion during the deposition of the overlying sedimentary laminae. The tip of each flame trails towards the down-flow direction of the run-up current and indicates opposing flow directions within successive deformation horizons (i.e. tidal currents). Synsedimentary flame structures with similar asymmetrical morphologies have previously been documented, resulting directly from tidal bores (Greb and Archer 2007) and tsunami deposits (Matsumoto et al. 2008) and produced experimentally from turbidity currents (Moretti et al. 2001)

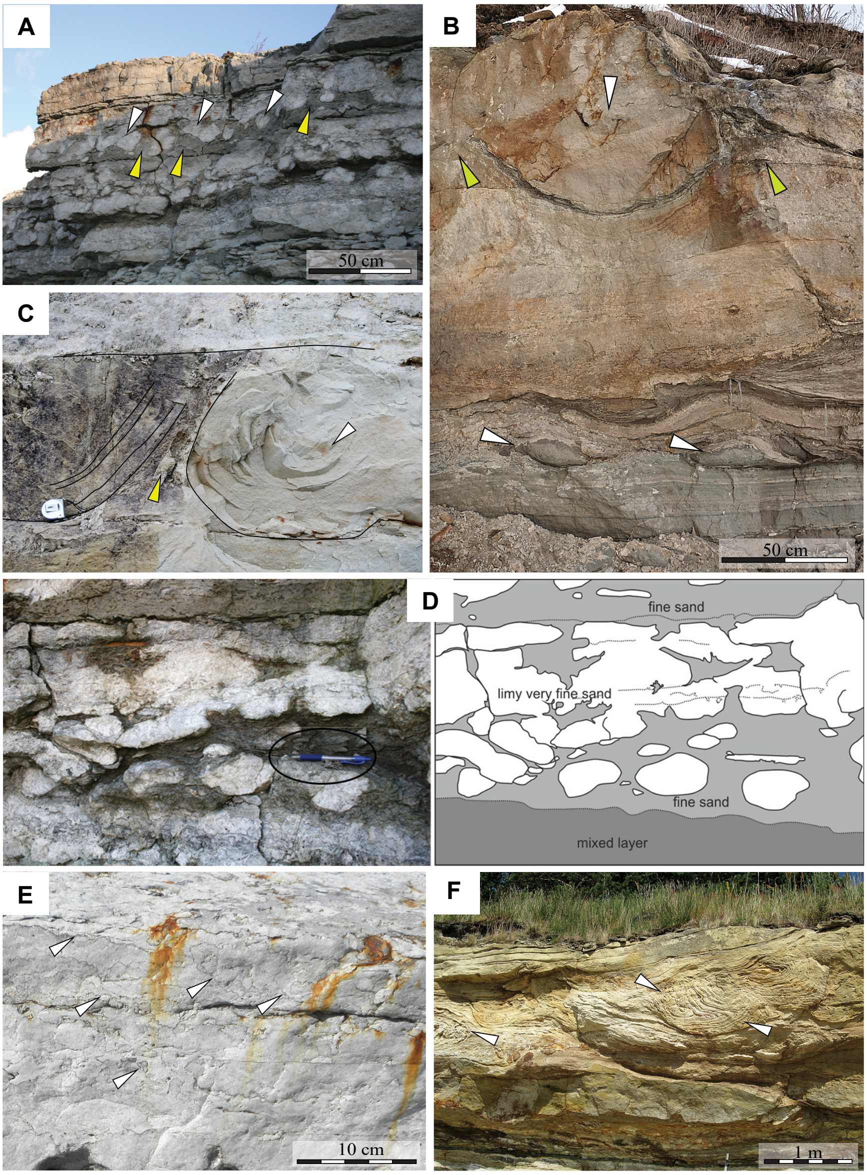

Figure 3. Examples of load structures: (A) pendulous load casts (white arrows) alternating with complex flame structures (yellow arrows), Pakri Formation; (B) simple load casts (upper white arrow), flame-like structures (yellow arrows), and pseudo-nodules (lower white arrows) within different stratigraphical higths in the Cambrian tidalites; (C) a pseudonodule with concentric internal lamination (white arrow) and flame-like upward protrusion of the lower sedimentary layer (yellow arrow) within the Cambrian tidalites; (D) photography (left) of a ball-and-pillow morphology in the Pakri Formation and drawing (right) of the same photo; (E) thin contorted heavy mineral lamination covering the rock face (few sites indicated with white arrows) of the Pakri Formation; (F) convolute lamination (white arrows) in the Cambrian tidalites, palaeoflow from right to left. (Modified from Põldsaar and Ainsaar 2014, 2015 – PAPERS I, II).

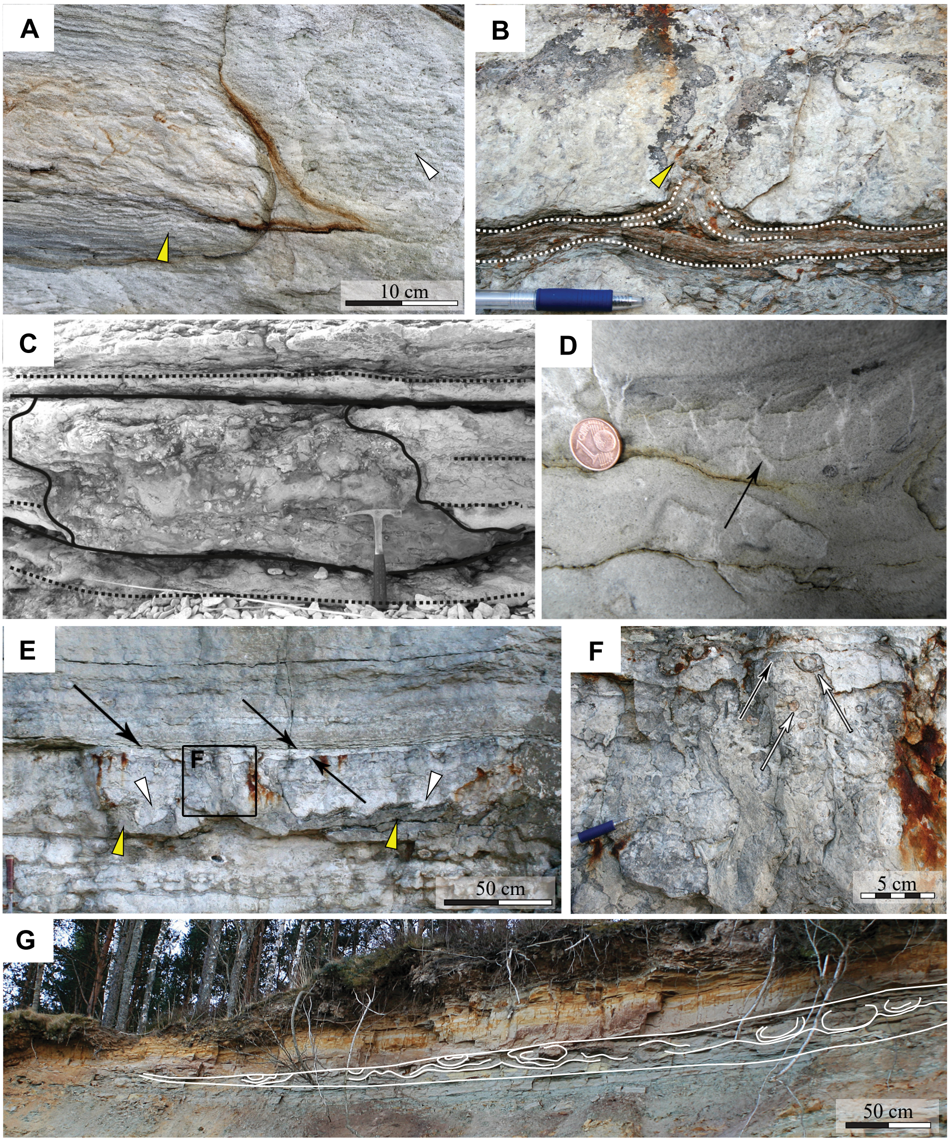

Figure 4. Examples of dewatering structures: (A) homogenized sediment (right-hand side of the photo), note that the original sedimentary lamination preserved on the left-hand side of the photo (yellow arrow) is bent downwards along the dewatering channel in the middle of the picture, miniature dish-and-pillar structures can be observed within he homogenized sediment, Cambrian Tiskre Formation; (B) dewatering channel (yellow arrow), Pakri Formation; (C) large sedimentary dike with brecciated dike infill on Osmussaar Island, Parki Formation; (D) stress pillars (black arrow) within the sedimentary dike infill of the Pakri Formation; (E) cross-section of a sand volcano in the Pakri Formation, volcano ejectite is the light-coloured layer between the black arrows, white arrows point to additional load structures, yellow arrows to flame structures; (F) close-up of the risen sand volcano neck (black arrow) on (E), white arrows point to bioclastic xenoliths; (G) example of a soft-sediment deformation horizon and its thinning out within the Cambrian tidalites. (Modified from Põldsaar and Ainsaar 2014, 2015 – PAPERS I, II).

Table 1. Description and mechanism of deformation of the observed soft-sediment deformation structures in the Pakri Formation (Fm), Lükati and Tiskre formations, and Volkhov Oil Collector (VOC). Data is combined from Põldsaar and Ainsaar (2014, 2015) and Põldsaar et al. (2019).

Load structures	**Description**	**Mechanism of deformation**	**Driving force**	**Pakri Fm**	**Lükati Fm**	**Tiskre Fm**	**VOC**
Load casts	Downward displacement of discrete masses of sediment into underlying liquefied sediment without detachment from the source bed	Gravitationally unstable density gradient	Thixotropy, loading, liquefaction	+	-	+	+
Flame structures	Upward diapiric or flame-like protrusions of sediment into overlying less permeable sediment without cutting the overlying layer	Gravitationally unstable density gradient	Thixotropy, loading, liquefaction	+	-	+	+
Pseudonodules	Downward displacement and full or partial detachment of discrete masses of sediment into the underlying (liquefied) sediment	Gravitationally unstable density gradient	Thixotropy, loading, liquefaction	+	+	+	-
Ball-and-pillow structures	Displacement and vertical stacking of isolated discrete masses of silty sediment foundering into the underlying liquefied layer of sediment	Gravitationally unstable density gradient	Thixotropy, loading, liquefaction	+	+	+	-
Contorted heavy mineral lamination	Groups of thin (>1 mm) bent or severely deformed heavy mineral laminae that do not generally lose their lateral continuity regardless of the extent of contortion	Loading and vertical shear stress	Liquefaction	+	-	-	-
Convolute lamination	Groups of bent or severely deformed thin (tidal) laminae that do not easily lose their lateral continuity regardless of the extent of contortion	Loading and vertical shear stress	Liquefaction	+	-	+	-
Dewatering structures							
Homogenized sediment	Zones of partly or fully liquefied or fluidized sediment with structureless appearance	Vertical shear stress	Liquefaction and/or fluidization	+	-	+	-
Dish-and-pillar structures	Flat to concave-upward, argillaceous laminations (dishes) approx. 2 cm in width, accompanied by vertical cross-cutting columns and sheets of massive sand (pillars) (<0.5 cm high). Associated with homogenized sedimentary beds	Vertical shear stress	Liquefaction and/or fluidization	+	-	+	-
Water-escape channels	Uo to 20 cm long channel-like structures near the upper surfaces of (tidal) laminated beds, filled with homogenized liquefied sediment and sunken lithoclasts wrenched off from upper bedding boundary.	Vertical shear stress	Liquefaction and/or fluidization	+	-	+	-
Autoclastic breccias	Brecciation of indurated sediments, found within small-scale (tidal) lamination as well as within large sedimentary dikes	(Semi)brittle deformation due to shear stress, or external mechanisms	Various natural forces incl.liquefaction, fluidization	+	-	+	-
Large sedimentary dikes	Upward narrowing fractures, cutting several bounding horizons of distinct lithology, filled with homogeneous sediment and lithoclasts wrenched off from dike walls or from lower-lying sediments, internal laminations are parallel to the dike walls	Vertical shear stress	Liquefaction and fluidization	+	-	-	-
Sand volcanoes	Localized dome-like openings to the surface of the deformed sedimentary bed, the mouth of the feeder dike is often surrounded by outflow sand	Vertical shear stress	Fluidization	+	-	-	-
Stress pillars	Groups of light-coloured narrow sand bands up to 5 cm in length. Usually paced approximately 1 cm from each other and inclined at high angles to the walls of dikes.	Hydroplastic shear	Fluidization, hydroplastic shear	+	-	-	-

The soft-sediment deformation structures of the second category, the dewatering structures, develop within cohesive plastic sediment either as a result of current forces (Sanders 1965) or due to pressure release during spontaneous liquefaction and fluidization (Dzulynski and Smith 1963). Dewatering structures are often characteristic of flysch-, turbidite-, and tidal deposits because those sediments, when liquefied, are highly plastic and mobile (e.g. Kuenen 1953). However, dewatering structures are often described also in seismites (e.g. Ghosh et al. 2012) and tempestites (e.g. Alfaro et al. 2002). Similarly, the tilting of load structures, and the unidirectional tilting and stretching of dewatering structures can indicate normal sediment current drag during liquefaction deformation. Like the tilted flame structures, also the tilting of the convolute lamination can often be observed within the Cambrian tidalites (Fig. 3F; Põldsaar and Ainsaar 2015 – PAPER II) but not regularly in the Pakri Formation (Põldsaar and Ainsaar 2014 – PAPER I).

The most profound dewatering structures that were described in this study were sedimentary dikes (Fig. 4B, C), sand volcanoes (Fig. 4E, F; found only in the Pakri Formation; Põldsaar and Ainsaar 2014 – PAPER I), and secondary homogenization of strata (Fig. 4A; found both in the Pakri Formation and in the Cambrian tidalites; Põldsaar and Ainsaar 2014, 2015 – PAPERS I, II). Sedimentary dikes and sand volcanoes (often accompanied by autoclastic breccias, Fig. 4C) form when sediment is subject to a hydraulic gradient when liquefied under a fine-grained low-permeability sedimentary cap (Lowe 1975; Obermeier and Pond 1999; Obermeier 2009)

Sedimentary dikes, sand volcanoes, and dish-and-pillar structures in the Pakri Formation are often related to the secondary homogenization of sediment (Põldsaar and Ainsaar 2014 – PAPER I). In this case, the sediment has lost some of its original properties due to rearrangement of the sedimentary matrix during liquefaction or fluidization and appears structureless.

In some instances, the homogenized sediment is accompanied by dish-and-pillar structures (Fig. 4A; noted both in the outcrops of the Cambrian tidalites and in the cores of the Pakri Formation; Põldsaar and Ainsaar 2014, 2015 – PAPERS I, II) or stress pillars (Fig. 4D; noted in the large sedimentary dikes of the Pakri Formation; Põldsaar and Ainsaar 2014 – PAPER I). Dish-and-pillar structures are thin, flat to concave-upward, laminations that are cross-cut in a regular manner by vertical or nearly vertical columns and sheets of massive sand (called ʽpillars'; Lowe and Lopiccolo 1974). These features are always post-depositional and form during the gradual compaction and dewatering of the rapidly deposited, under-consolidated, or liquidized beds (Lowe and Lopiccolo 1974).

Stress pillars (Fig. 4D) are parallel, light-coloured bands of sand, spaced about 1 cm from each other. These structures represent fluidization along flow paths that develop within sediments undergoing hydroplastic shear (Lowe 1975).

Local lenses or pockets of homogenized sediment are also common in the Cambrian tidalites (Põldsaar and Ainsaar 2015 – PAPER II). Spatial variations within the observed structureless sediment suggest that homogenization occurred in both cases after the deposition of the original sediment as a result of particle movement during the complete liquefaction or fluidization of the sediment (Lowe 1975).

4.2. Sediment gravity flow structures

Sediment gravity flow structures are found within the Volkhov Oil Collector bed, which represents deposition under a single sediment gravity flow event. Sediments of the Volkhov Oil Collector are composed of medium- to fine-grained sand and silt which exhibit a clear upward fining grain-size trend (Fig. 5). Four vertically succeeding sedimentary units (B to E) were documented in the studied Vergale-50 and Aizpute-41 cores (Fig. 5; Põldsaar et al. 2019 – PAPER III). Each unit exhibits a clear set of sedimentary structures and a specific lithology that closely follow the divisions of a classical turbidite succession (Fig. 5; Põldsaar et al. 2019 – PAPER III), i.e. the Bouma sequence (Bouma 1962).

In both core sections (Vergale-50 and Aizpute-41) the lowest part (unit B) of the collector bed is represented by massive to normally graded coarse-grained poorly sorted sandstone that is eroded into underlying strata (Põldsaar et al. 2019 – PAPER III). Cohesion and grain size increase towards the bottom of the bed due to a basal over-pressured granular flow of the turbidity current, driven by inertial forces and excess pore pressures (Mutti et al. 1999). The upward following section (unit D) is composed of wavy lamination and climbing ripples (Põldsaar et al. 2019 – PAPER III) representing the migration and simultaneous vertical aggradation of bed loads which is often associated with decelerating turbidity currents (Mutti 1977). The middle part of the bed (unit D) also contains various soft-sediment deformation structures (load structures; Põldsaar et al. 2019 – PAPER III). Soft-sediment deformation structures are often related to turbidites because those sediments are highly plastic and mobile when liquefied (Kuenen 1953). The topmost part of the Volkhov Oil Collector (unit E) is composed of ungraded carbonate mudstone with abundant trace fossils (Põldsaar et al. 2019 – PAPER III). This unit is comparable to the Bouma E division (Bouma 1962) which represents the very last stage of particle fall-out from suspension in the waning current. In this stage, a gradual shift from the deposition of fine-grained low-density mud to the settling of hemipelagic mud and eventually to normal pelagic sedimentation takes place (Mutti et al. 1999). The corresponding unit is not identified in the Aizpute-41 core section. However, this unit is often missing in turbidites, not well differentiated from the Bouma D division, or easily eroded by subsequent currents (Bouma 1962).

Also, the bioturbation patterns within the Volkhov Oil Collector indicate deposition during a single short-lived sedimentary event, because the ichnofabrics are present only in the uppermost part of the bed (unit E) where the burrowing animals can live after the turbid flow ceases and deposition is gradually replaced by slow settling of pelagic muds (Põldsaar et al. 2019 – PAPER III).

The lateral geometry of the Volkhov Oil Collector bed resembles a traditional turbidite bed (Fig. 1; Põldsaar et al. 2019 – PAPER III). Accordingly, turbidites are characteristically laterally extensive, convex upward, sandstone lobes (i.e. ‘fans’; Normark 1970). These lobes generally record distinctive facies associations and sedimentary successions in the inner, middle, and outer fan settings (Normark 1970). Like classical turbidite lobes, the Volkhov Oil Collector bed is sandier and thicker in the central part of its distribution area, and its sand content and thickness decrease gradually and semi-radially towards the distal regions (Yakovleva 1977).

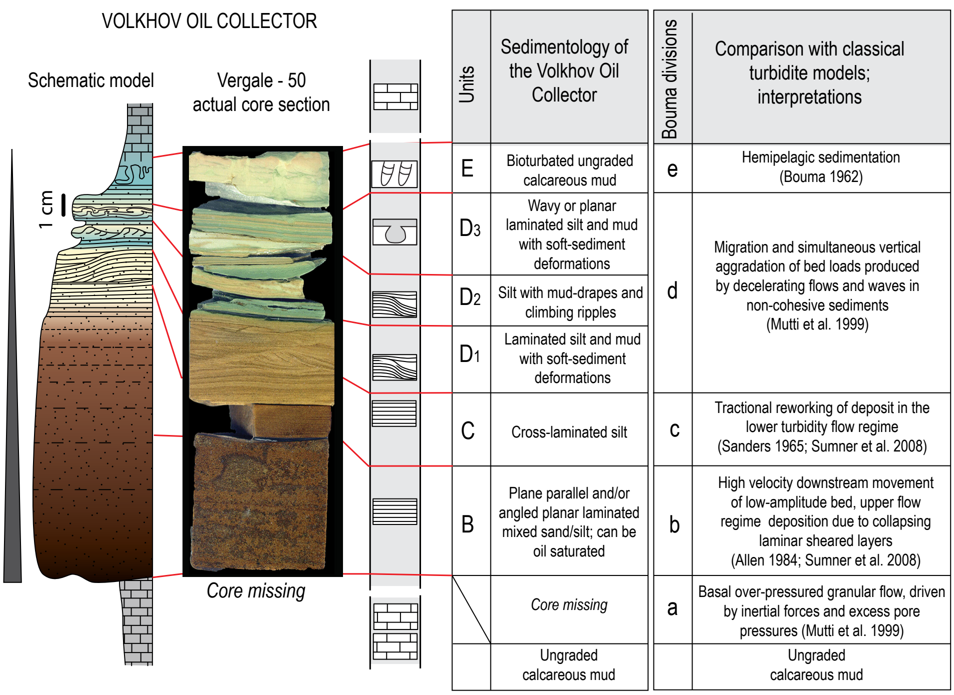

Figure 5. Schematic cross-section and photograph of the Volkhov Oil Collector in the Vergale-50 core section. The sedimentary textures are compared with the classical turbidite model by Bouma (1962). The elongated arrow in front of the schematic model indicates smooth grain-size decrease from the bottom to the top of the bed. (Modified from Põldsaar et al. 2019 – PAPER III).

5. DISCUSSION

The prevailing views on the development of the the Baltic Basin stress its tectonical quiescence in the Lower Palaeozoic. The deformation features described above suggest, however, that some unusual geological events disrupted this overall stable path. In order to understand the nature of these features and to identify the probable triggers of these deformations, an analysis of primary and secondary sedimentary structures of sedimentary beds combined with case-by-case facies analysis and assessment of other available geological criteria is required.

5.1. Deciphering the triggers of event horizons

5.1.1. Triggers of soft-sediment deformation

Identifying the triggers of soft-sediment deformation is not always a straightforward task. Sedimentary layers that have been deformed *in situ* by some geological process only tell about the early consolidation history of those particular sediments (Allen 1982). Soft-sediment deformation takes place penecontemporaneous to deposition and prior to the lithification of the sediment. Water-saturated sandy sediments are most readily deformed when liquefied (i.e. when in a quick-sand state) due to the application of some sort of shock. This can happen for instance due to the motion of ground during earthquakes, but also when the stress is applied by cyclic storm waves, tides, or similar high-energy hydrodynamic processes. Often sediment deformation will take place without any obvious event but simply due to the loading of sediments under their own weight when they are deposited rapidly and in bulk, for instance in delta fronts of large rivers. Similar-looking soft-sediment deformation structures can be caused by different natural processes and occur in a variety of geological environments.

In order to distinguish the soft-sediment deformation triggers for both the Middle Ordovician Pakri Formation and the Cambrian Lükati and Tiskre formations, the three-stage assessment process (facies–trigger–criteria assessment) suggested by Owen et al. (2011) was tested.

The Cambrian sea of the Baltic Basin was as wave-dominated shallow sea where storms had large influence on the depositional pattern (Nielsen and Schovsbo 2011). During the Dominopolian, the study area in north-western Estonia remained in the open-coast tidal flat facies setting (Põldsaar and Ainsaar 2015 – PAPER II). The Pakri Formation, on the other hand, was deposited as nearshore facies of the Ordovician carbonate sea in shallow subtidal depositional environment.

Although the above formations deposited in different facies settings, the soft-sediment deformation structures within these are similar in type and in both cases the primary deformation mechanism was liquefaction (Põldsaar and Ainsaar 2014, 2015 – PAPERS I, II). This was concluded by analysis and description of the various soft-sediment deformation types that occur widely in both the Pakri Formation and the Lükati and Tiskre formations (summary in Table 1). In both cases the various load structures can be considered as part of a deformation series (see also Anketell et al. 1970; Owen 2003). The initial phase of liquefaction exhibited the contortion of lamination and formation of simple load casts. Either a stronger driving force or a longer duration of liquefaction resulted in structures with more complex morphologies along the deformation series. Even larger initial stresses were required to form the ball-and-pillow morphologies in the Pakri Formation and the metres high load casts and flame structures within the Cambrian tidalites (see further Põldsaar and Ainsaar 2015 – PAPER II).

It is possible that load structures, such as those observed both in the Pakri Formation and in the Cambrian tidalites, could have also formed due to other mechanisms, for example thixotropy and mere loading of sediment on reversed density gradient (Anketell et al. 1970); however, the accompanying dewatering structures in these cases are always a clear indication of liquefaction and/or fluidization of the sediment. For example, structureless and homogenized sediment, observed both in the Pakri Formation and in the Cambrian tidalites, forms in the course of particle movement during complete liquefaction of the sediment (Lowe 1975). Homogenization is often accompanied by dewatering induced dish-and-pillar structures in both cases.

A major difference between the soft-sediment deformation types of the Pakri Formation and the Cambrian tidalites is the presence of large sedimentary dikes and sand volcanoes in the former. Sedimentary dikes and sand volcanoes form when external net inflow of pore fluid is available during sediment liquefaction (Owen 1996). The upward component of fluid drag eventually balances or exceeds the particle weight, so that the intrastratal water movement becomes turbulent and sediments become fluidized (Lowe and LoPiccolo 1974; Lowe 1975; Owen 1996). In the last two deformation stages of the Pakri Formation liquefaction was accompanied by large-scale fluidization of the sediment. Where the fluid pressure exceeded the strength of the overlying semi-permeable layers, forceful (brittle or semi-brittle) rupture occurred and the water–sediment slurry was forced from the sediments onto the seabed of that time. This process resulted in the erosion and mobilization of sediment from the liquefied zones leaving voids in the underlying horizons, which then collapsed due to overburden weight and caused further distortion and brecciation (Chaney and Fang 1991). Such a deformation path is exceptionally preserved on Osmussaar Island (Fig. 1) where the Pakri Formation together with the underlying sediments is most severely deformed, brecciated, and penetrated by large sedimentary dikes. Because the applied stress became extremely large in this location, the pore pressure built-up and liquefaction were instantaneous. In such a case it is possible that a downward component of the hydraulic gradient (Maltman and Bolton 2003) was introduced in the dissipation of excess porewater pressure and the resulting sediment mobilization. This mechanism can explain the incorporation of older, already lithified, sediments into the deformation process without the need for these sediments to be also liquefied during the deformation event.

Numerous earlier papers have shown through laboratory tests and field studies (e.g. Terzaghi et al. 1948; Kuenen 1958; Seed and Lee 1966, 1971; Anketell and Dzulynski 1968; Anketell et al. 1969, 1970; Ishihara and Li 1972; Stewart 1975; Youd and Hoose 1977; Chaney and Fang 1991; Owen 1996) that the most common deformation mechanism in water-saturated sandy sediments is inevitably liquefaction, especially where those sediments are capped by or containing low-permeability layers (e.g. Obermeier and Pond 1999). The mechanism of sediment liquefaction is explained in detail for instance by Lowe (1975, 1976) and Chaney and Fang (1991).

Owen et al. (2011) state that only when the deformation mechanism has been correctly identified, further analysis of deformation triggers can commence. According to these authors triggers of liquefaction can either be external to the depositional environment (i.e. allogenic triggers, including earthquakes and extra-terrestrial impacts) or part of it (i.e. autogenic, including cyclic liquefaction by storms, impact of breaking waves, turbulent pressure fluctuations in strong water flows, tsunamis, tidal shear, rapid sediment loading, periglacial thawing in poorly drained sediment, or groundwater movement). However, as the morphology of the resulting deformation structures is independent of the trigger, further analysis of the depositional environment and trigger-by-trigger assessment of the evidence must be utilized in order to determine whether external or internal forces were related to liquefaction. Eventually, the most probable triggers are validated with other available criteria such as the spatial distribution of the deformations, tectonic background of the basin, etc.

The following considerations enabled us to discuss a clearly external deformation trigger in the Pakri Formation case: (1) the observed soft-sediment deformation involved the sediments of the Pakri Formation with a single event of liquefaction, i.e. the deformation horizon is bound by undeformed sedimentary layers from top and below (except for Osmussaar Island; Fig. 2) there is no over-printing of older deformation types by younger ones; (2) a single deformation horizon occurs over a vast geographical area (at least over 6000 km^2, but possibliy even over 9000 km^2) and is laterally consistent; (3) the sediments of the Pakri Formation lack sedimentological indications of storm events, slumping, rapid deposition, etc., which could indicate deformation due to internal mechanisms; (4) there is clear lateral zonality of the deformations within the Pakri Formation from the most deformed central region on Osmussaar Island (see Fig. 11 in Põldsaar and Ainsaar 2014 – PAPER I) outwards to the marginal and less deformed areas; (5) similar large-scale deformations (esp. sedimentary dikes, sand volcanoes, and ball-and-pillow morphologies) are often observed within the seismically triggered soft-sediment deformation horizons (e.g. Potter and Pettijohn 1963; Jewell and Ettensohn 2004; Van Loon and Maulik 2011).

In the Cambrian tidalites, the following criteria strongly favour the internal (i.e. non-tectonic) origin of the observed soft-sediment deformation structures: (1) there is no good correlatability nor wide distribution of individual deformation horizons within the studied outcrops; (2) soft-sediment deformation horizons randomly appear and disappear along the outcrop walls at various stratigraphical heights; (3) some of the observed soft-sediment deformation structures are genetically related to tidal deposits (tidal bundle successions), whilst others are bound by the walls of tidal channels; (4) autoclastic breccias and water-escape channels are rare, whilst large sedimentary dikes, sand volcanoes, and thrust faults, which are often related to earthquake seisimiites are not found within these sediments; (5) tidal surges and large storms are both known to trigger liquefaction deformation (e.g. Molina et al. 1998; Alfaro et al. 2002; Greb and Archer 2007; Chen et al., 2011) and were both also frequent in the Cambrian sedimentary environment under consideration.

From the previous, it is evident that distinctly different triggers were responsible for the large-scale soft-sediment deformations within the Middle Ordovician Pakri Formation as compared to the somewhat similar deformations within the Cambrian tidalites of the Tiskre and Lükati formations.

The above geological evidence suggests that the deformation of the Pakri Formation took place during a single high-energy deformation event or closely-timed event series, most probably an earthquake or seismicity caused by a yet unknown meteorite impact (Põldsaar and Ainsaar 2014 – PAPER I). The distribution of deformation patterns within the Cambrian tidalites along with the corresponding sedimentary environment suggests, instead, that the large-scale liquefaction of sediments was triggered by a combination of internal triggers. The acting triggers that could cause the deformations included loading due to rapid deposition, shear caused by tidal bores, and the cyclic loading of storm waves (Põldsaar and Ainsaar 2015 – PAPER II).

5.1.2. The trigger of the single Volkhov Oil Collector turbidite

The clearly flow-induced sedimentary structures that closely follow the Bouma turbidite sequence model (Bouma 1962) along with the lateral turbidite lobe-like geometry of the bed suggest that the Volkhov Oil Collector represents an unusual single shallow-marine siliciclastic turbidite flow (Põldsaar et al. 2019 – PAPER III). Its deposition on the foot of the Jelgava Depression and the missing sediments up-slope suggest a potential sediment provenance area on the Gotland elevation region or shoreward of it. However, despite its convenient spacial arrangement, it is difficult to identify the initial trigger of this particular carbonate shelf-settled turbidite. First, the 'slope' of the Jelgava Depression is too low (much less than 2 per cent) and second, the sedimentary configuration (i.e. lack of loose siliciclastic sediment on the shelf ramp) of the basin does not support the formation of such sediment gravity flows (Põldsaar et al. 2019 – PAPER III).

Based on the analysis of sedimentary environments, it could be suggested that the Volkhovian turbidite is an indirect result of the action of tsunami waves on the sea floor. Such a process has been described for example by Kastens and Cita (1981), Mörner (2008), and Polonia et al. (2013). Therefore, a single turbidite bed lying in between the shelf deposits like the Volkhov Oil Collector might be formed by tsunami-like meteorite impact resurge waves as described by Dypvik et al. (2004) and Schulte et al. (2012).

As tsunamis are highly capable of eroding and incorporating large volumes of sediment in the water wave upon its arrival to shallow coastal waters (e.g. Bahlburg and Spiske 2012; Tamura et al. 2015), it is possible that a tsunami might have cut loose sediments from the hypothetical coastal areas on the Gotland elevation of that time and transported these into nearshore waters. After facing hydraulic jump and energy loss on the original coastline, the fallout sediments can start drifting independently and due to the net density contrast, eventually turn into a turbidity current (Weiss 2008). Provided such a scenario happened, the sediments that were cut loose from the Gotland elevation would have also started to move towards deeper parts of the basin, that is, towards the Jelgava Depression, eventually depositing on the foot of the slope (Põldsaar et al. 2019 – PAPER III).

5.2. Implications of using depositional events and their signatures in an ancient rock record

The study of Middle Ordovician event beds of the Volkhov Oil Collector in Latvia and the Pakri Formation in north-western Estonia undoubtedly shows that some sort of seismic trigger acted in the Baltoscandian Palaeobasin region at the time when these beds were deposited. In the case of the Pakri Formation, a single earthquake of magnitude 7 or higher is suggested to have triggered the widespread deformation of unconsolidated nearshore sediments. For a presumably tectonically inactive region, such a catastrophic earthquake is highly unusual. However, the deposition and deformation of the Pakri Formation closely follow the disruption event of a large parent body in the asteroid belt at ~470 Ma ago. This resulted in a globally increased flux of extraterrestrial L-chondritic material by up to two orders of magnitude (Korochantseva et al. 2007). Furthermore, the narrow interval of the early Darriwilian, Kunda Regional Stage (Fig. 2), has been proven to be enriched with mini meteorites and extraterrestrial chromite in Sweden, north-western Russia, and China (Schmitz et al. 2008; Cronholm and Schmitz 2010; Lindskog et al. 2012) dating the meteorite influx to 466–467 Ma, i.e. to early Darriwilian time. In fact, Suuroja et al. (2003) and Alwmark et al. (2010) have reported meteorite impact proof (shock-metamorphic features in quartz grains and a high abundance of the extraterrestrial chromite) also from the sediments of the Pakri Formation. However, the impact site itself has remained unidentified. These finds along with the tectonically induced sedimentary deformations described here enable us to present a possible relationship between the deposition and deformation of the Pakri Formation to a yet unknown meteorite impact event of the meteoritic bombardment period.

According to the stratigraphic interpretations, the Volkhov Oil Collector turbidite was deposited before the Middle Ordovician L-chondritic shower event. It could still indicate a significant disruption event affecting the stable craton interior. A large volcanic explosion or seismic ruptures somewhere out of the Baltoscandian shelf, for example in the Armorican volcanic arc of that time, could have caused earthquakes with potential tsunamis to travel deep into the Baltoscandian shelf. A recent study by Tuuling and Vaher (2018) shows that a possible source of seismic disturbances can be even closer – the tectonic activation of the highly elevated basement block (i.e. the Valmiera–Lokno uplift) might take part within the latest Precambrian to Early Ordovician and would have caused some tectonic instabilities within the craton interior. Similarly, a marine meteorite impact will cause suspension currents, submarine mass movements, and tsunamis even if the meteorite itself does not reach the seabed to excavate a crater into the bedrock (Gersonde et al. 1997). In the case of a marine bolide impact, the most severe seafloor disturbances would be expected to occur on shelves and neighbouring coastal areas, as the impact effects would depend greatly on water depth and impactor size among other variabilities (Dypvik and Jansa 2003).

Further studies are definitely needed here to fully understand the formation of a unique siliciclastic shallow-marine turbidite such as the Volkhov Oil Collector. There also remains a possibility of finding even more similar event beds because the visual observation of, for example, calcareous turbidites in a calcareous succession may be complicated and the detection of such layers may need additional analysis methods (e.g. X-ray analysis).

The deformations within the Cambrian tidalites were most possibly not related to any abnormal tectonic activities within the basin as these were triggered by purely autogenic processes.

Implications of this study are related to the establishment of reliable and diagnostic criteria for identifying different triggers of sedimentary events, especially those causing soft-sediment deformation in unconsolidated water-saturated sediments. The comparative nature of case-by-case studies is a good aid for future studies while distinguishing endogenic and exogenic triggers of sediment liquefaction. This work was about applying rigorous, holistic approach to the recognition of the triggering agents and particularly the relationship between soft-sediment deformation structures and sedimentary facies.

6. CONCLUSIONS

The aim of this study was to describe, map, and analyse the primary and secondary sedimentary structures of deformed event beds in the Lower Palaeozoic succession in the Baltic Basin. The interior of the Baltica craton is widely considered to have been tectonically inactive during the Early Palaeozoic, but the occurrence of such geological event horizons within the Baltic Basin shows that rare catastrophic events still took place and influenced the overall stable deposition. The selected study objects were the Cambrian tidalites of the Tiskre and Lükati formations in north-western Estonia, the Middle Ordovician (Darriwilian) nearshore siliciclastic facies of the Pakri Formation also in north-western Estonia and the Middle Ordovician (Dapingian) siliciclastic shallow-marine turbidite bed in Latvia and the Baltic Sea proper.

The main conclusions of this study are the following:

(1) large-scale soft-sediment deformation structures within the Middle Ordovician Pakri Formation and the Cambrian tidalites were induced by profound liquefaction during or shortly after these sediments were deposited;

(2) the triggers of the deformation in these cases were distinctly different although the resulting deformation structures were relatively similar in type; in the case of the Pakri Formation an exogenic trigger such as a single catastrophic earthquake, possibly caused by a meteorite impact, can be suggested, whilst in the Cambrian tidalites case a complex of endogenic triggers (i.e. storm-wave loading, tidal bores, and sediment loading) is the most possible cause of the observed deformations;

(3) the Volkhov Oil Collector bed represents a unique single siliciclastic turbidite bed within the carbonate ramp deposits of the Ordovician Baltoscandian Palaeobasin and was most likely triggered by an earthquake-induced tsunami;

(4) the occurrence of exogenically triggered siliciclastic event beds (the Pakri Formation and the Volkhov Oil Collector) on the tectonically stable epicontinental carbonate ramp suggests that the geological quiescence of the deposition on intercratonic basins is easily disrupted and recorded in distinctive event beds that would enable tracing such events over tens of millions of years.

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SUMMARY IN ESTONIAN

Settedeformatsioonide ja gravitatsiooniliste settevoolude tekstuurid Balti basseini Vara-Paleosoikumi läbilõigetes

Settebasseini geoloogilise kujunemisloo kirjeldamisel on ühtmoodi oluline mõista nii pikemaajalisi geoloogilisi protsesse kui ka märgata taustafoonist eristuvaid ootamatuid lühiajalisi settesündmusi. Mõlemad võivad anda olulist teavet piirkonna tektoonilise mineviku kohta, kirjeldada basseini batümeetrilist konfiguratsiooni, setteprotsesside dünaamikat või anda informatsiooni mineviku keskkonnatingimustest (nt. Asikainen *et al*. 2007, Vierek 2013).

Balti paleobasseini arengut Paleosoikumi alguses vaadeldakse tüüpiliselt kui tektooniliselt stabiilset perioodi. Siinsed settekivimid on enamjaolt säilitanud oma settimisjärgse oleku ning ei ole mõjutatud tugevatest tektoonilistest häiringutest, hilisdiageneetilistest protsessidest või mattumisega seonduvast moondest. Vaatamata sellele leidub läbilõikes ükskuid anomaalselt deformeeritud või ebahariliku koostisega kihte, mis selgelt eristuvad üldisest settepildist. Sellised settekihid on ilmselgelt tekkinud väga kõrge energiaga geoloogiliste protsesside tulemusena, mis aga ei ole ootuspärased tektooniliselt stabiilsele seisundile Balti paleobasseini varajases ajaloos. Sellised ebaharilikud settekihid on olnud tuntud juba aastakümneid, kuid nende tekkepõhjused ja mehhanismid on olnud siiani ebaselged.

Käesolevas doktoritöös uuriti Balti paleobasseinis Paleosoikumi algul toimunud kolme anomaalse sündmuse tulemusena kujunenud setteid: (1) Kambriumi (Dominopoli) tõusu-mõõna setted (Tiskre ja Lükati kihistud), mis levivad kirde-edela suunalise vööndina üle Loode-Venemaa ja terve Eesti, (2) Kesk-Ordoviitsiumi (Dapingi) vanuseline turbidiidikiht (nn "Volhovi naftakollektor", ingl. *the Volkhov Oil Collector*), mis levib Lääne-Lätis ning sellega piirnevatel aladel Läänemeres ning (3) Kesk-Ordoviitsiumi (Darriwili) rannikuvööndis kujunenud settelääts (Pakri kihistu), mis levib kitsa ribana Loode Eestist kuni Rootsi rannikuni.

Töö põhifookuses oli nn pehmete setete deformatsioonid (ingl. *soft-sediment deformation*) kaardistamine ja kirjeldamine ning nende alusel settedeformatsioonide põhjuste välja selgitamine. Erandina keskendus Volhovi turbidiidi uuring primaarsetele settestruktuuridele, sest pehmete setete deformatsioonide (sekundaarsed struktuurid) osatähtsus selles läbilõikes on minimaalne. Uurimistöö eesmärgiks oli analüüsida primaarseid ja sekundaarseid settestruktuure ning selgitada välja settekeskkonna sisesed (endogeensed) ja/või välised (eksogeensed) põhjused nimetatud kihtide või nendes leiduvate deformatsioonide moodustumisel. Töö laiemaks eesmärgiks oli Balti palaeobasseini tektoonilise arengu ning settedünaamika häiringute mõistmine.

Nii Kambriumi Lükati kihistu setete kui ka Ordoviitsiumi Pakri kihistu puhul oli peamine setete deformatsioone tekitanud mehhanism ajutine setete veeldumine (ingl. *liquefaction*). Veeldumise korral omandavad setted lühiajaliselt nn vesiliiva oleku ja muutuvad voolavaks. Deformatsioonide üksikasjalik kaardistamine ning settekeskkondade täpsem analüüs näitab, et kuigi Lükati ja Pakri kihistu deformatsioonid on morfoloogiliselt ja tekkelt võrdlemisi sarnased, olid setete veeldumise põhjused erinevad. Kambriumi rannikumere tõusu-mõõna setete puhul oli tegemist kombinatsiooniga settekeskkonna sisetekkelistest kõrge hüdrodünaamilise energiaga protsessidest (tormilainetus, kiire settimine ning setete tihenemine/kollaps), mis tingisid poorivee vabanemise ja setete veeldumise (Põldsaar ja Ainsaar 2015 – ARTIKKEL II). Pakri kihistu deformatsioonide kujunemisel mängisid rolli eksogeensed (tektoonilised) protsessid (Põldsaar ja Ainsaar 2014 – ARTIKKEL I).

Primaarsete struktuuride olemus (nn Bouma järjestuse olemasolu; Bouma 1962) nn Volhovi naftakollektoris viitab üheselt selle settekompleksi gravitatsioonilisele settimisele turbidiitvoolust. Turbidiidid moodustuvad eeskätt aktiivsete mäestike ja mandrinõlvade ees paiknevates süvamere basseinides, kus merealused gavitatsioonilised settevoolud tekkivad lahtiste nõlvasetete vabanemisel maalihke või settelaviinina tänu korduvatele maavärinatele. Ordoviitsiumi ajastul kaugele kontinendi sisealadele ulatunud Balti paleobassein paiknes passiivsel mandrinõlval ning selle põhjareljeef oli äärmiselt lauge (kallakus <2%), kus settimiskiirus ulatus vaid mõne millimeetrini tuhande aasta kohta (Jaanusson 1973). Sellistes basseinides ei ole klassikaliste turbidiitvoolude tekkimine tõenäoline. Käesolev uurimus näitab, et kõige tõenäolisem mehhanism sellises settekeskkonnas piisava hulga setete kandmiseks madalmerre ning seal turbidiitvoolu vallandamiseks oli erakorraline tsunamilaine (Põldsaar *et al.* 2019 – ARTIKKEL III).

Laiemas geodünaamilises kontekstis näitavad käesoleva töö tulemused, et erinevalt üldisele arvamusele Balti basseinist kui stabiilsest piirkonnast Vara-Paleosoikumis, mõjutasid erakordsed tektoonilised sündmused aegajalt ka siinset settekuhjumist.

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PUBLICATIONS

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Publications

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2010 „Impact cratering in the planetary system, cratering mechanisms and shock metamorphism“, korraldaja Network on Impact Reasearch, suvekool Lappajärvis, Soomes.

Publikatsioonid

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