A siliciclastic shallow-marine turbidite on the carbonate shelf of the Ordovician Baltoscandian palaeobasin

Kairi Põldsaar[a], Leho Ainsaar[a], Reet Nemliher[b], Oive Tinn[a] and Girts Stinkulis[c]

[a] Department of Geology, Institute of Ecology and Earth Sciences, University of Tartu, Ravila 14A, 50411 Tartu, Estonia; kairi.poldsaar@ut.ee, leho.ainsaar@ut.ee, oive.tinn@ut.ee
[b] Republic of Estonia Environmental Board, Narva St. 7a, 10117 Tallinn, Estonia; reet.nemliher@keskkonnaamet.ee
[c] Department of Geology, Faculty of Geography and Earth Sciences, University of Latvia, Jelgavas St. 1, LV-1004, Riga, Latvia; girts.stinkulis@lu.lv

Abstract. A metre-scale thick siltstone–sandstone lobe is described within the Dapingian outer ramp argillaceous limestone facies of the Baltoscandian palaeobasin. This bed is referred to as the Volkhov Oil Collector in previous studies due to its hydrocarbon accumulation potential. It formed on the palaeoslope of the regional Jelgava Depression, which represents an elongated axial region of the deepest part of the Ordovician Baltoscandian sedimentary basin. Sedimentological and petrological analysis of this siliciclastic bed in core sections shows that it was deposited as a result of a single event of turbidite flow. The internal structure of the turbidite bed follows the classical Bouma divisions of the turbidite sequence model. The triggers of this single siliciclastic turbidite bed within a tectonically inactive shallow carbonate basin are analysed. It is concluded that a rare tsunami might have eroded and transported sediments in suspension from land to shallow sea. Suspension fallout would have evolved into a density flow and later into a turbidity current that travelled into the deeper parts of the basin, depositing siliciclastic material at the slope of the Jelgava Depression. The occurrence of the Volkhov Oil Collector turbidite bed on the tectonically relatively stable and flat-bottomed Baltoscandian palaeobasin suggests that turbidite events can take place in rare cases also in epicontinental environments.

Key words: siliciclastic turbidite, tsunami, shallow-marine, carbonate ramp, Middle Ordovician, Baltoscandian palaeobasin.

INTRODUCTION

Turbidity currents are subaqueous sediment gravity flows that are generated by landslides, slumps or density-based avalanches (Mutti et al. 1999). In the broadest terms, the prerequisites for turbidity currents to occur are (1) an accumulation of loose sediment on a subaqueous slope and (2) a trigger that initiates the down-hill movement of that sediment. The most common triggers that can start subaqueous mass movements include sediment over-loading, liquefaction, excess pore pressure and earthquakes (Guyard et al. 2007).

Deposits of turbidity currents, i.e., turbidites, can be found in different geological settings such as lakes, reservoirs, delta fronts and continental shelves (Walker 1976). However, earthquake-triggered turbidites are classically most often described from deep-water environments near foreland basins, continental rises and abyssal planes (e.g. Shepard 1951; Bouma 1962). Consistently, thick turbidite successions are best preserved in quiet deep-water settings, where bottom reworking by other types of currents is the smallest (Walker 1976). Therefore, turbidite successions are often used as a tool for describing the tectonic history of thrust-and-fault regions (e.g. Olabode 2006; Strasser et al. 2006; Goldfinger et al. 2012).

Turbidites have less frequently been reported from areas of high sediment supply, such as subaqueous river mouths during flooding where turbidity currents are initiated solely by gravitational failure (Chan & Dott 1983; Heller & Dickinson 1985; Guyard et al. 2007). Turbidite currents can also be related to storm events (Mulder et al. 2001; Bakhtiar & Karim 2007). In some instances turbidites have been associated with tsunami waves (e.g. Polonia et al. 2013) and even with marine meteorite impact events (e.g. Norris & Firth 2002; Dypvik & Jansa 2003).

We studied the genesis of a single shallow-water siliciclastic bed, also called the Volkhov Oil Collector (Yakovleva 1977), in the tectonically stable Ordovician

Baltoscandian palaeobasin. The occurrence of a Bouma sequence within the Volkhov Oil Collector was suggested already by Ainsaar et al. (2002a), but here we present detailed sedimentological evidence confirming a turbidite origin of this bed. Implications of this study are related to the extensive understanding of the sedimentary dynamics of the Baltoscandian basin during the Ordovician, as well as to shallow-marine carbonate marine environments generally.

GEOLOGICAL BACKGROUND

The Baltoscandian region was tectonically inactive throughout most of the Palaeozoic (Nikishin et al. 1996). During the Ordovician, a shallow sea covered the interior of the craton. This sea extended at least from present Norway to NW Russia and covered the East Baltic area and northeastern Poland (Fig. 1A; Nikishin et al. 1996). At that time, the Baltica palaeocontinent was situated in the southern temperate climate zone. Because of that specific geographical position, the rate of overall carbonate deposition in the Baltoscandian basin was only a few millimetres net per thousand years (Jaanusson 1973). The Baltoscandian sea also had a very flat seabed and a low depth gradient, which is reflected in a very smooth lateral sedimentation trend from inner ramp pure bioclastic carbonates towards outer ramp argillaceous limestones and marls (Fig. 1A; Jaanusson 1973).

Because of the flat relief of the surrounding land areas and tectonic stability of the interior of the Baltica craton, the erosion rate in the surrounding land areas and sediment input into the basin were very low during the Ordovician (Jaanusson 1973). However, the importance of terrigenous material (clay), as well as the probable slope of the basin floor, increases successively towards the western margin of the craton, towards the Caledonide mountain range (Jaanusson 1982). Furthest to the west, in the Jämtland region (Sweden), thick turbidite sequences (Föllinge Formation) were deposited in a series of interconnected basins east of the probable chain of islands which supplied terrigenous clay (Jaanusson 1982; Karis & Strömberg 1998). The Föllinge turbidites are strictly limited to the fringes of the Baltoscandian basin and spread into the foreland basin north of the Jämtland (Sweden) area (Karis & Strömberg 1998). Elsewhere, the Middle and Upper Ordovician carbonate succession of Baltoscandia almost lacks coastal siliciclastic sand facies and is particularly poor in sand-sized or coarser siliciclastic material throughout the basin (Jaanusson 1973). The few exceptions include the Volkhov Oil Collector described here, the inner ramp facies deposits of the Pakri Formation (Kunda Regional

Stage, Darriwilian) in northwestern Estonia (Põldsaar & Ainsaar 2014) and the Late Ordovician (Sandbian) ejecta blanket surrounding the Kärdla meteorite crater in the West Estonian Archipelago (Ainsaar et al. 2002b).

The Volkhov Oil Collector bed is stratigraphically located in the upper part of the Kriukai Formation and is of late Dapingian to earliest Darriwilian age (Fig. 2). The Kriukai Formation consists of a 13–32 m thick succession of reddish-brown argillaceous carbonates which were deposited in outer ramp settings (Ulst et al. 1982). The reddish carbonates of the Kriukai Formation are northwards gradually replaced by light grey glauconitic and bioclastic middle- and inner-ramp carbonates (Estonian Shelf facies; Fig. 1A). The boundary between the Kriukai and overlying Šakyna formations marks a distinctive lithological change from red-coloured argillaceous carbonates to light greenish-grey glauconite-bearing limestones in Latvia and southern Estonia (Ulst et al. 1982). A similar change can be traced basinwide to Sweden, where the reddish Lanna Limestone and basal Holen Limestone are followed in the succession by the light-coloured Täljsten interval (Lindskog et al. 2014). The change in the depositional patterns has been suggested to be a result of temporary global climatic cooling (Rasmussen et al. 2016) and a consequent sea-level lowstand in the Volkhov–Kunda boundary interval (Dronov et al. 2011).

According to drill core data, the Volkhov Oil Collector bed spreads on the northern flank of the east–westerly elongated Jelgava Depression (Fig. 1A; Lashkov & Yakovleva 1977). The Jelgava Depression is a tectonic structure that marks a relatively deeper part of the Baltoscandian basin from late Tremadocian to early Silurian times. It was the depocentral area for the Middle Ordovician sediments (Poprawa et al. 1999).

A vast area of the Lower and Middle Ordovician sedimentary gap (Gotland elevation) extends northwestwards from the Jelgava Depression between the islands of Gotland and Hiiumaa (Fig. 1A). In the area of the Gotland elevation, the Darriwilian deposits are directly underlain by the Tremadocian or Cambrian sandstones and shales (Thorslund & Westergård 1938).

The distribution and lithology of the Volkhov Oil Collector were briefly described by Lashkov & Yakovleva (1977). The Volkhov Oil Collector bed is visually distinctive in core sections. It appears as a 0.1–0.8 m (occasionally 1.5 m) thick grey- to brown-coloured, oil-saturated sand- and siltstone interlayer within the notably red-coloured strata of the Kriukai Formation marls and limestones (Lashkov & Yakovleva 1977). It is distributed in the Western Latvian mainland within an area of 1000 km^2 as a sedimentary lobe, with laterally fining grain size until complete thinning out of the bed (Fig. 1B; Yakovleva 1977). The distribution of the Volkhov Oil
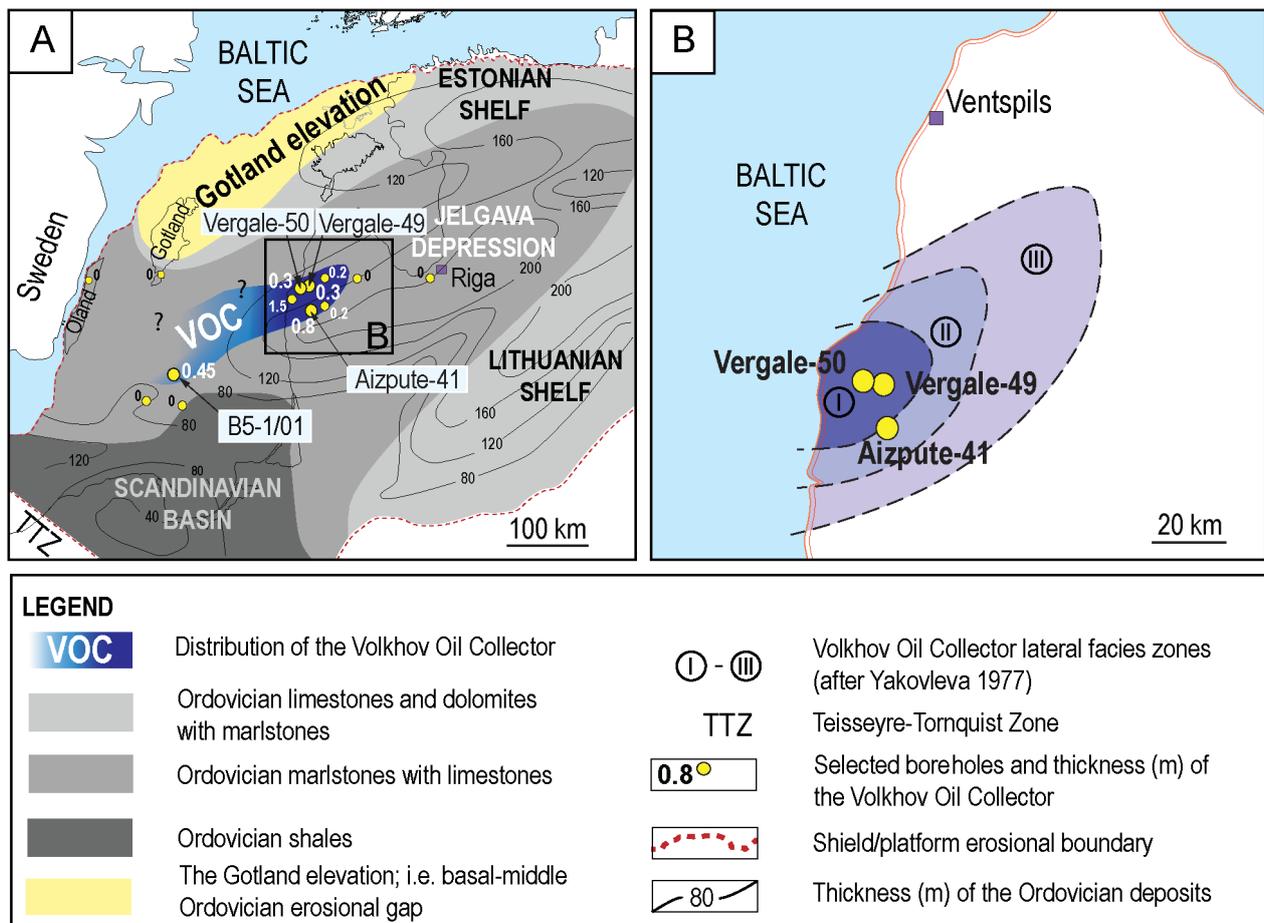
Fig. 1. Location of the study region. **A**, Ordovician marine deposits in Baltoscandia with general facies distribution and thickness (isopachs by Poprawa et al. 1999). The distribution area and thickness of the Volkhov Oil Collector bed are based on drill core data by Yakovleva (1977) and Domżalski et al. (2004). The basal Middle Ordovician erosional gap area (i.e. the 'Gotland elevation') is modified from Suuroja et al. (2003). **B**, sketch-map showing the lateral facies distribution (facies I–III) of the Volkhov Oil Collector (after Yakovleva 1977) with localities of the studied drill cores.

Collector in the submarine Baltic Sea proper is unclear, but it may be correlated to one of the sandstone layers described by Domżalski et al. (2004) from the B5-1/01 drill core 250 km west of the Latvian coast (Fig. 1A).

MATERIAL AND METHODS

The material for this study was obtained from three drill cores of western Latvia – Vergale-49, Vergale-50 and Aizpute-41 (Fig. 1). In the Aizpute-41 core, the thickness of the Volkhov Oil Collector is 60 cm, and the section is relatively complete. In Vergale-50, the available core for the Volkhov Oil Collector bed is 25 cm thick, while about 10–15 cm of the most oil-bearing basal part of the bed was not recovered during the drilling. From

the Vergale-49 core, a single 3-cm sandstone sample was available.

X-radiography of core slabs was utilized to analyse the internal sedimentary architecture of the Volkhov Oil Collector. X-ray images were taken with a Siemens Ysio digital radiography solution. Acquisition parameters were adjusted according to varying thicknesses of the radiographed specimens. The exposure length ranged from 11 to 21 msec at 5–10 mAs tube anode current. X-ray radiographs were taken from the full length (60 cm) of the Volkhov Oil Collector bed in the Aizpute-41 drill core and from the lowest 6 cm in the Vergale-50 drill core (the upper part of the collector interval was too thinly cut up for these measurements).

Eight rock samples with an average weight of 30 g were collected from the Volkhov Oil Collector in the

Fig. 2. Lower and Middle Ordovician stratigraphy in western Latvia and Estonia (modified from Meidla et al. 2014). The approximate stratigraphic position of the Volkhov Oil Collector (VOC) is indicated.

Vergale-50 core and dissolved in 3% hydrochloric acid for grain-size distribution analysis. The oil-bearing sandy material was treated with 30% hydrogen peroxide to disaggregate the particles before further study. Insoluble residues were fractioned by gravity sedimentation and dry sieved into grain-size fractions according to the Wentworth scale (Wentworth 1922). Two thin sections were prepared from the lower sandier part of the Collector bed in the Vergale-49 and Vergale-50 cores. Petrological studies were conducted under a light microscope using conventional petrographic and mineralographic methods.

Additionally, nineteen carbonate rock samples, at approximately 1-m intervals, were collected from limestone beds of the Vergale-50 drill core above and below the Collector for micropalaeontological analysis based on ostracods. These samples were disintegrated using sodium hyposulphite with repeated heating and cooling (Meidla 1996).

RESULTS AND INTERPRETATIONS

Stratigraphic position

The stratigraphic age of the Volkhov Oil Collector is determined by its position in the upper part of the Kriukai Formation, which has been roughly correlated with the Volkhov Regional Stage (Ulst et al. 1982; Hints et al. 2010). In the studied sections, the Volkhov Oil Collector bed is situated 12–15 m below the base of the Šakyna Formation which is a distinct lithostratigraphic boundary between reddish argillaceous limestone and overlying grey-coloured limestone. According to biostratigraphic data, the boundary of the Volkhov and Kunda regional stages is positioned slightly (a few metres) below the base of the Šakyna Formation in southern Estonia (Põldvere et al. 1998) and its equivalent, the Täljsten unit in Sweden (Lindskog et al. 2014). The global Dapingian–Darriwilian stage boundary is situated below the Volkhov–Kunda regional stage boundary (Meidla et al. 2014). Thus, the stratigraphic position of the Volkhov Oil Collector is close to the aforementioned global stage boundary and obviously below the Volkhov–Kunda regional stage boundary. The identified ostracod species *Conchoprimitia social*, *Protallinnella grewingkii*, *Aulacopsis simplex* and *Unisulcopleura punctosulcata* from the limestones below and above the Volkhov Oil Collector in the Vergale-50 core section are common for upper Dapingian and lower Darriwilian strata in Latvia and southern Estonia (Tinn et al. 2010). However, these species do not allow for a more precise definition of the stratigraphic position of the Volkhov Oil Collector.

Lithology

Four vertically successive sedimentary units within the Volkhov Oil Collector have been distinguished in the Vergale-50 and Aizpute-41 drill cores. Each unit exhibits a clear set of sedimentary structures and a specific lithology that correlate well between the two cores. According to their sedimentary features and lithology, these units closely follow the classical divisions of the turbidite sequence (Walker 1976) and are labelled here as units B to E (Figs 3–5).

Visual inspection of the cores, as well as grain-size distribution analysis, confirms that in both core sections the Volkhov Oil Collector bed exhibits a clear fining-upward trend in grain size (Fig. 3). The non-carbonate component of the Volkhov Oil Collector bed in the Vergale-50 core is mostly (~55–85%) composed of clay and silt fractions (grain size < 0.063 mm). Only the lower part (unit B) contains a considerable amount (~85%) of fine to medium sand (grain size 0.063–0.5 mm) or coarse sand (grain size 0.5–1 mm) (Fig. 3). The overall
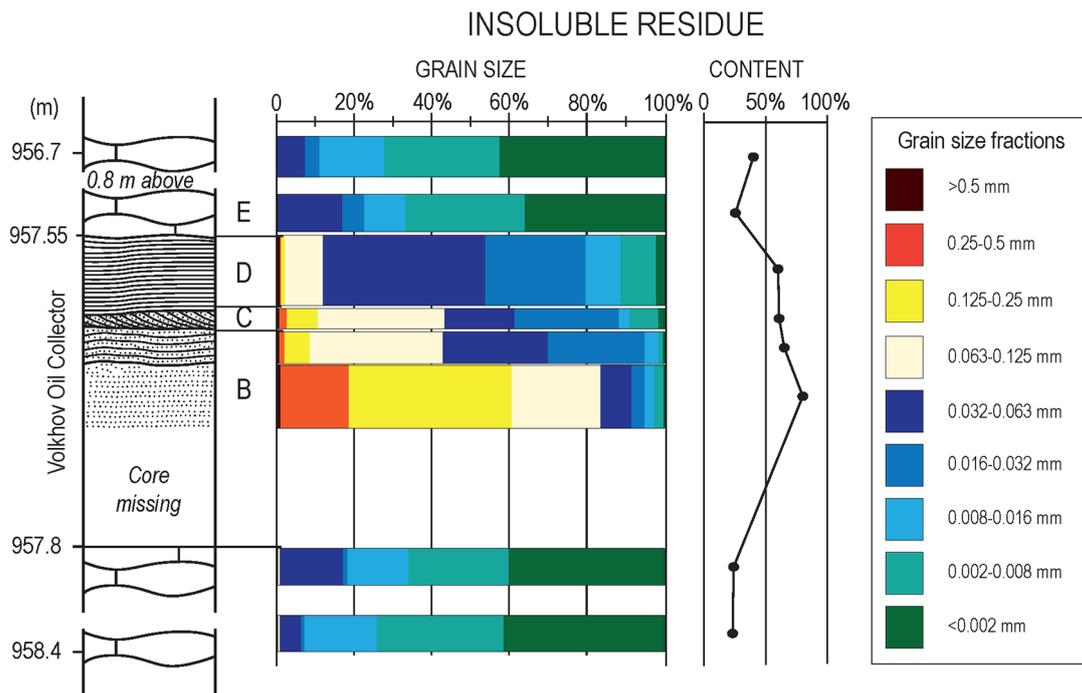
Fig. 3. Grain size distribution and content of insoluble material of the Volkhov Oil Collector in the Vergale-50 core section. Note the gradual decrease in both the grain size and content of siliciclastic material from the bottom to the top of the bed.
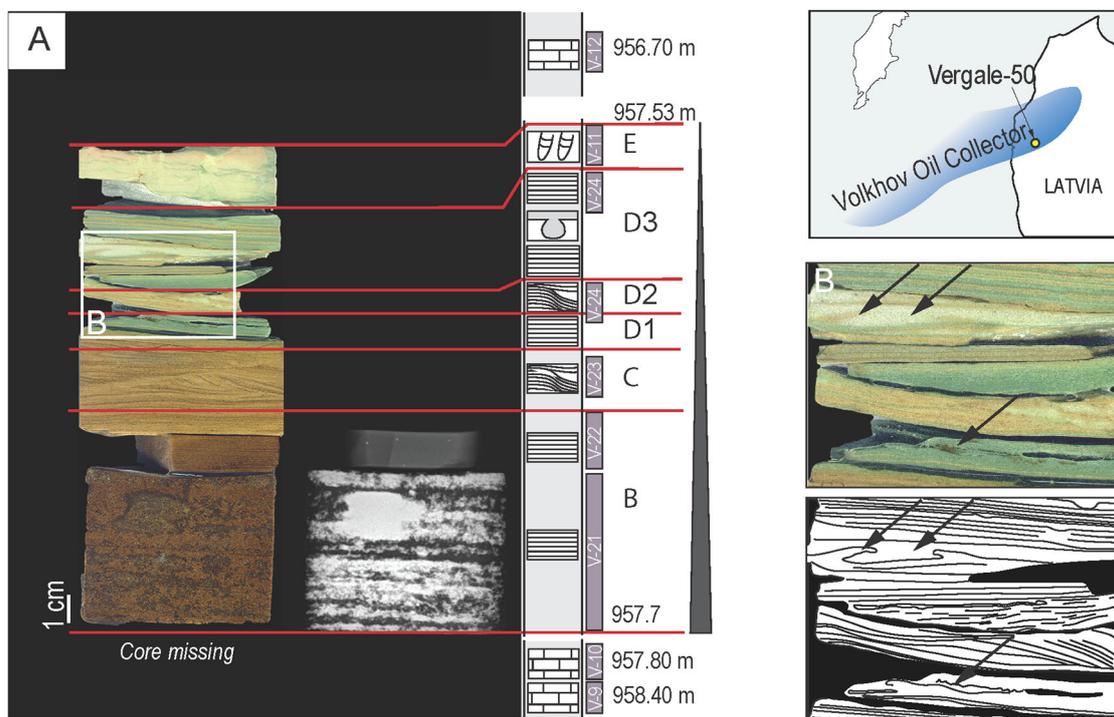

Fig. 4. The Volkhov Oil Collector in the Vergale-50 drill core. **A**, a colour photograph (left) and X-ray radiograph (right) of the lower part of the collector bed. Changes in sedimentary features and lithological patterns are indicated by red horizontal lines. Locations of grain size analysis samples are shown by numbered boxes. Identified units are marked with capital letters B to E. The general grain-size trend is shown by a vertical grey arrow. Lighter shades indicate denser materials and vice versa on X-ray radiographs. **B**, close-up and line-drawing of small sedimentary features in the upper part of the collector bed. Soft-sediment deformation features (load casts, flame structures) are indicated by black arrows. For legend see Fig. 5.

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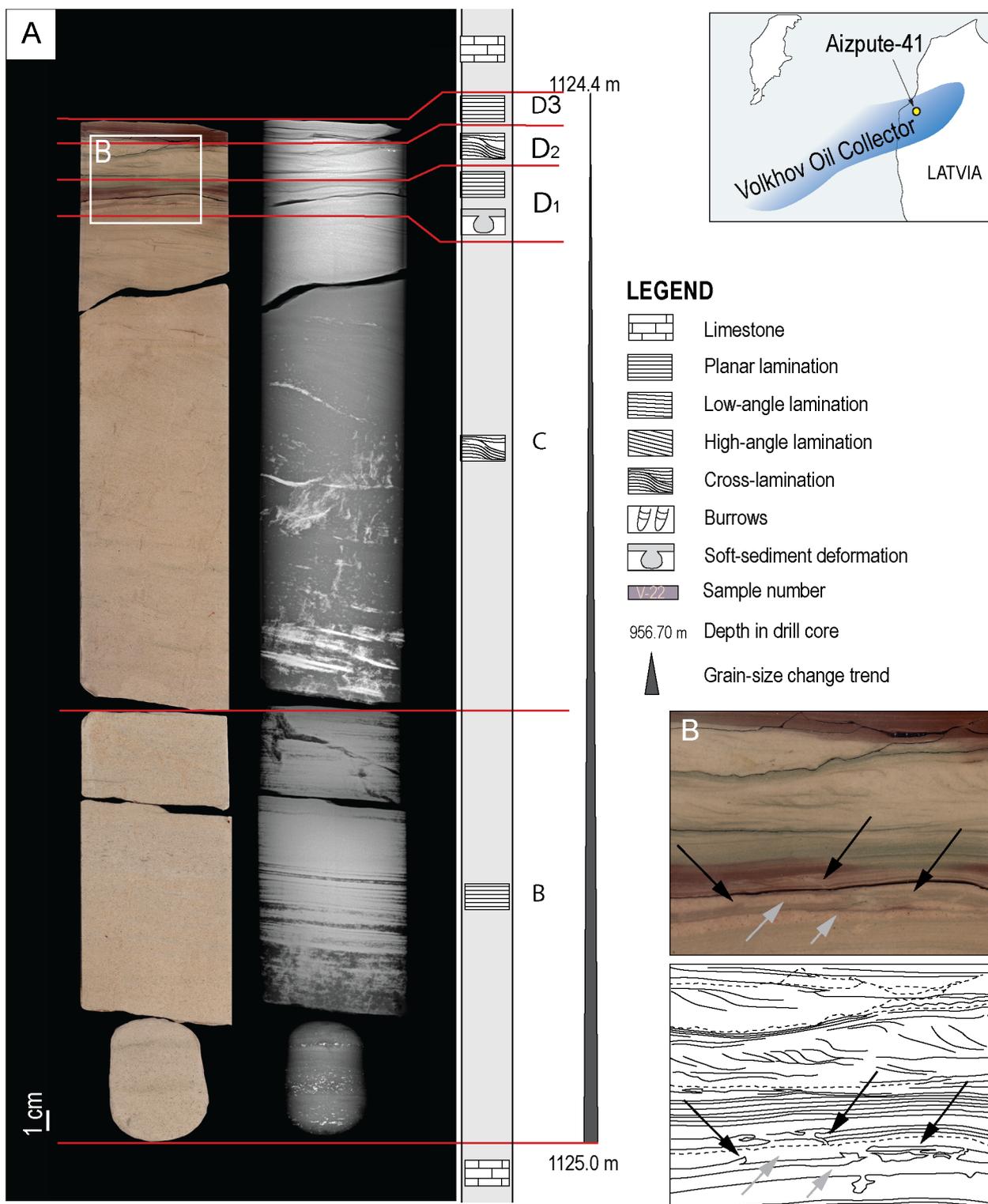**Fig. 5.** The Volkhov Oil Collector in the Aizpute-41 drill core. **A**, a colour photograph (left) and X-ray radiograph (right) of the collector bed. **B**, close-up and line drawing of small sedimentary features in the upper part of the collector bed. Soft-sediment deformation features are indicated by black arrows, and grey arrows point to thin layers of liquefied sediment in between the distorted laminae.

sand and silt content decreases from the base of the bed to the top. The fine sand and silt content is 84% in the lowermost part of the bed (unit B), decreases to 41% in the middle (unit C) and to 10% in the upper section (unit D) of the bed (Fig. 3). In the topmost part (unit E) the sediment is gradually replaced by calcareous silt and eventually by pure limestone. Also, the overall content of the insoluble residue shows a clear upward decreasing trend from 77% in the lowest part (unit B) to 25% in the topmost part (unit E; Fig 3). Regrettably, the basal contact of the Volkhov Oil Collector bed is not observable in any of the studied cores, but a marked lithological difference between the basal part of the collector and underlying limestone is obvious.

The Bouma sequence of the Volkhov Oil Collector

The lowest part (unit B) of the Volkhov Oil Collector in both the Vergale-50 and the Aizpute-41 core sections is represented by planar-laminated to sub-parallel laminated fine to medium-grained medium- to moderately-well sorted sandstone (Figs 4A, 5A). Horizontal or sub-parallel lamination within this unit accounts for the high-velocity downstream movement of the very low-amplitude bed (Bouma 1962). This part of the bed deposited in the higher flow regime of the turbidity current (Allen 1982). The parallel lamination appears due to the collapse of laminar sheared layers that are reworked by turbulent bursts to form laminae (Sumner et al. 2008). X-ray radiography emphasizes rough internal lamination within the Vergale-50 core (Fig. 4A). Thin section analysis shows semi-angular to rounded sand grains in this unit. The sediment additionally contains skeletal fragments (mainly detritus of trilobites), feldspar, some mud-agglomerates and more than 2% glauconite grains, all bound by a calcite matrix (Fig. 6). Also, 3–5 mm thick intercalating laminae of smaller and coarser material are discernible in thin sections (Fig. 6B). The notably alternating composition of the sediment (more carbonate intraclasts along with more carbonate cement vs almost only quartz and feldspar grains along with less cement) accents even further these laminae. Unit B is 6 cm thick in the Vergale-50 core and 21 cm thick in the Aizpute-41 core. In the Vergale-50 core, the lowest part of this unit is notably oil-saturated and dark brown in colour (Fig. 4).

Usually, the lowest part of a turbidite bed (Bouma division A) is represented by massive to normally graded coarse-grained sandstone that is often eroded into underlying strata (Sanders 1965). Grain size and overall cohesion of the sediment both gradually increase towards the bottom of the turbidite bed. An increase in cohesion and grain size towards the bottom is due to a basal over-pressured granular flow of turbidity currents,
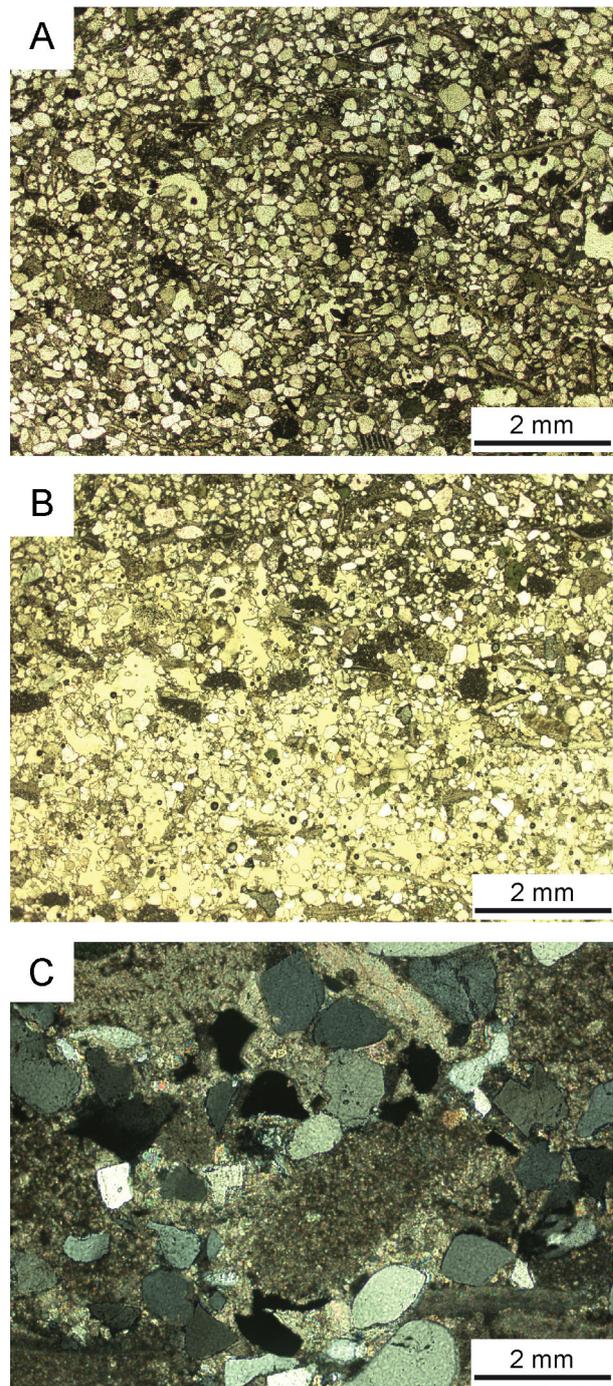
Fig. 6. Thin section photographs of the lowest part of the B unit of the Volkhov Oil Collector in the Vergale-50 core section. **A**, the sediment is medium-sorted, containing semi-rounded to angular-quartz grains, glauconite, skeletal fragments. **B**, lamination of finer/denser (upper part of the photo) and coarser quartzitic sediment (lower part of the photo). **C**, close-up of the thin section (crossed nicols) shows a large mud-roll in the middle of the picture in between the sub-rounded to angular quartz grains.

which is driven by inertial forces and excess pore pressures (Mutti et al. 1999). This basal part is also called the turbidite 'reservoir facies' (Mutti et al. 1999). Because of the cohesion and poor sorting it provides excellent hydrocarbon accumulation potential. Ainsaar et al. (2002a) noted such a unit initially in the Vergale-50 core. However, X-ray radiography showed crude lamination within this part of the bed (unit B; Fig. 4A), hence suggesting that it represents the division B rather than A of the Bouma sequence. Unit A was not found in the Aizpute-41 core section either. Most turbidites found in nature have incomplete sequences (Middleton & Hampton 1973). The base-cut turbidite successions represent the residual deposits of a waning and depletive turbulent flow. In this stage, the deposition takes place through the traction and fallout process and sands and muds are deposited characteristically without the accumulation of the basal A division (Mutti et al. 1999).

Unit C is 1.5 cm thick in the Vergale-50 core and 25 cm thick in the Aizpute-41 core. This unit is characteristically low-angle planar cross-laminated (Figs 4A, 5A). It is composed of medium- to moderately well-sorted fine- to very fine-grained sandstone/siltstone. Unit C corresponds well to the Bouma division C, which is formed due to a tractional reworking of the deposit in the lower turbidity flow regime (Sanders 1965), thus forming cross-bedded or ripple-laminated layers (Sumner et al. 2008).

Unit D is 4.5 cm thick in the Vergale-50 core and 4 cm thick in the Aizpute-41 core (Figs 4A, 5A). This succession is composed of millimetre-thick alternating layers of fine-grained limy siltstone and clay with various sedimentary features present. These features include planar cross-lamination, small-scale soft-sediment deformation features (flattened load casts, dewatering dikes and flame structures *sensu* Owen 1987), climbing ripples and wavy lamination (Figs 4A, 5A). These textures correspond to the Bouma division D (Figs 4, 5). Wavy-lamination and climbing-ripples reflect the migration and simultaneous vertical aggradation of bed loads. Decelerating flows and waves in non-cohesive sediments produce both wavy lamination and climbing ripples. The formation of climbing ripples is often (but not only) associated with turbidity currents (Mutti 1977). Small (millimetre-scale) load casts and flame structures (Figs 4B, 5B) occur in the D3 sub-division in the Vergale-50 section. These structures form in a low or zero shear resistance situation induced by liquefaction of sandy or silty sediment in reversed density gradient systems (e.g. Anketell et al. 1970) and due to unequal density loading or both (Allen 1982). Soft-sediment deformation structures are not exclusive to gravity-flow

sediments. They are often related to flow deposits such as turbidites (e.g. Moretti et al. 2001), tsunamiites (Matsumoto et al. 2008) and tidalites (Greb & Archer 2007; Põldsaar & Ainsaar 2015) because those sediments are highly plastic and mobile when liquefied (Kuenen 1953).

The topmost unit E is at least 2 cm thick in the Vergale-50 drill core. It is composed of ungraded carbonate mudstone with abundant trace fossils (Fig. 4A). This unit is comparable to the Bouma division E, which represents the very last stage of particle fallout from suspension in the waning current. In this stage, a gradual shift from the deposition of fine-grained low-density mud to 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 division D, or easily eroded by subsequent currents (Bouma 1962). Also, the bioturbation patterns indicate deposition during a single short-lived sedimentary event, rather than deposition during a more extended period in nearshore facies as suggested by Domżalski et al. (2004). Unlike in most nearshore facies deposits, the ichnofabrics are present here only in the uppermost part of the bed (unit E) (Fig. 4A) where the burrowing animals can live after the turbid flow ceases and deposition is gradually replaced by slow settling of pelagic muds.

DISCUSSION

Depositional environment

Based on the presence of clearly flow-induced sedimentary structures and a lithology that closely follows the classical Bouma turbidite sequence, we are convinced that the Volkhov Oil Collector represents a single shallow-marine siliciclastic turbidite. A comparison of the sedimentary structures in the Volkhov Oil Collector with the classical turbidite divisions is given in Fig. 7 and these divisions correspond almost exactly. Also, the lateral geometry of the Volkhov Oil Collector bed (Fig. 1) resembles well a traditional turbidite lobe as described, for example, by Normark (1970). Accordingly, turbidites are characteristically laterally extensive, convex upward, sandstone lobes (i.e. fans) which generally record distinctive facies associations and sedimentary successions in the inner, middle and outer fan settings. A similar morphology is witnessed in the Volkhov Oil Collector bed which is sandier and thicker in the central part of its distribution area, whilst its sand content and
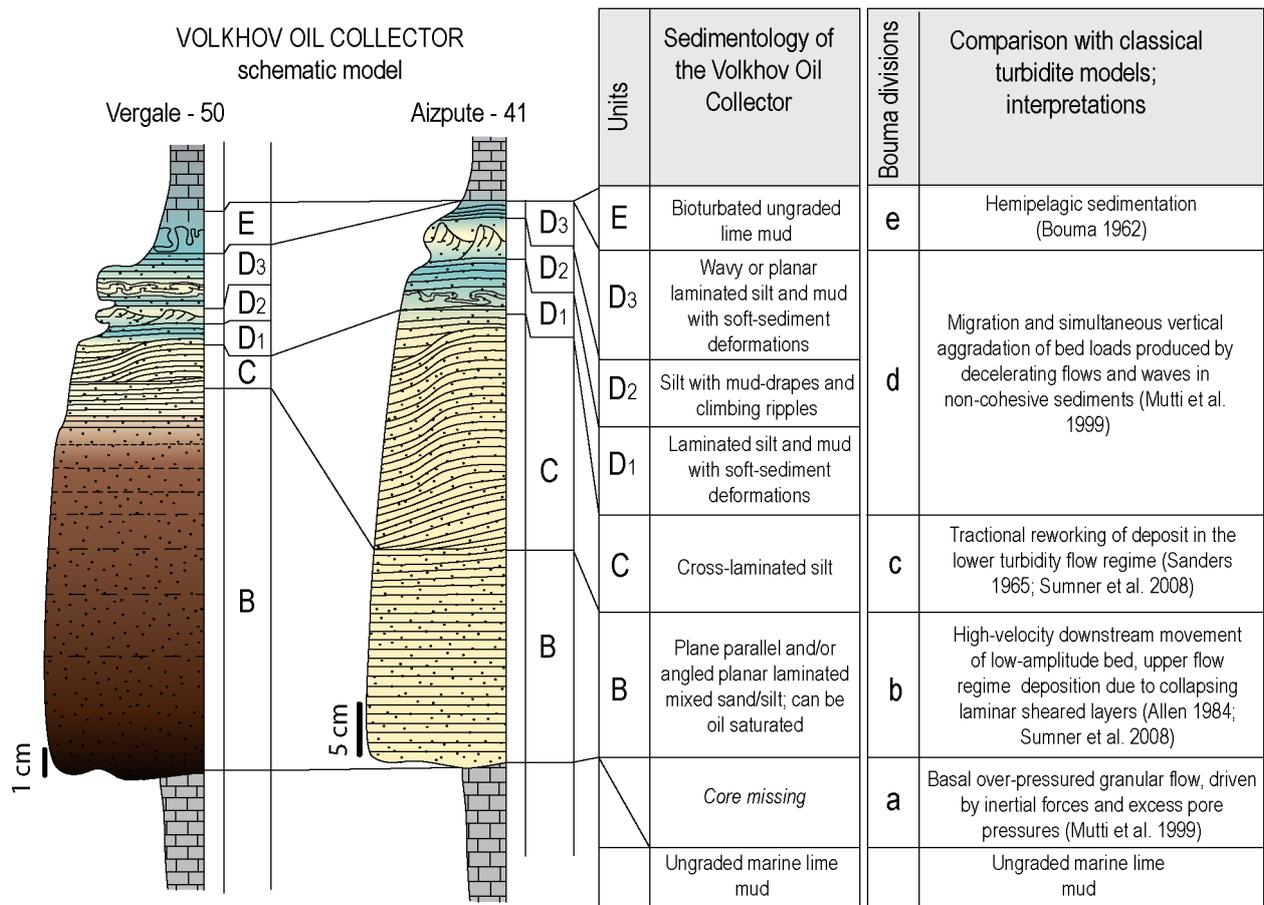
Units	Sedimentology of the Volkhov Oil Collector	Bouma divisions	Comparison with classical turbidite models; interpretations
E	Bioturbated ungraded lime mud	e	Hemipelagic sedimentation (Bouma 1962)
D3	Wavy or planar laminated silt and mud with soft-sediment deformations	d	Migration and simultaneous vertical aggradation of bed loads produced by decelerating flows and waves in non-cohesive sediments (Mutti et al. 1999)
D2	Silt with mud-drapes and climbing ripples		
D1	Laminated silt and mud with soft-sediment deformations		
C	Cross-laminated silt	c	Tractional reworking of deposit in the lower turbidity flow regime (Sanders 1965; Sumner et al. 2008)
B	Plane parallel and/or angled planar laminated mixed sand/silt; can be oil saturated	b	High-velocity downstream movement of low-amplitude bed, upper flow regime deposition due to collapsing laminar sheared layers (Allen 1984; Sumner et al. 2008)
	Core missing	a	Basal over-pressured granular flow, driven by inertial forces and excess pore pressures (Mutti et al. 1999)
	Ungraded marine lime mud		Ungraded marine lime mud

Fig. 7. Schematic cross sections of the Volkhov Oil Collector bed in the Vergale-50 and Aizpute-41 drill cores. The sedimentary textures are compared with the classical turbidite model by Bouma (1962).

thickness decrease semi-radially towards the distal regions until gradually thinning out (Fig. 1B; Yakovleva 1977).

An alternative hypothesis about the genesis of the Volkhov Oil Collector has previously been suggested by Domżalski et al. (2004). These authors discovered two oil-enriched sandstone beds from the covalent stratigraphic succession in the offshore drill core B5-1/01 (Fig. 1A) in the southern part of the Baltic Sea (Domżalski et al. 2004). Agewise and lithostratigraphically, either of these sandstone beds could possibly correlate to the Latvian Volkhov Oil Collector bed (Domżalski et al. 2004). However, these sandstone beds were discussed to have formed as a response to a major Ordovician sea-level regression event that enabled the deposition of a normal nearshore facies in the deeper part of the basin (Domżalski et al. 2004).

Indeed, several widespread sea-level falls are interpreted to have taken place in the Baltoscandian palaeobasin during the Middle Ordovician (e.g. Dronov et al. 2011). However, these events are represented merely by sedimentary gaps on the inner-middle carbonate ramp, whereas the deeper shelf succession remained almost unaffected by any sea-level fluctuations (Dronov et al. 2011). Hence, the major Ordovician sea-level falls (sequence boundaries; Dronov et al. 2011) are not witnessed in the sedimentary record as regional facies shifts of coastal sands into the deeper part of the carbonate shelf. The only well-studied quartz sand accumulation from this period – the Pakri Formation (Kunda Stage, Darriwilian), which has also been considered as a rare remnant of the nearshore facies (Jaanusson 1973), is restricted to the inner or middle ramp settings in northwestern Estonia. The only notable basinwide Middle Ordovician lithological change in the deeper shelf setting is marked by a clear shift from red-coloured argillaceous limestones to light-coloured glauconite-bearing limestones (the Šakyna Formation in Latvia and the equivalent Täljsten Bed in Sweden), which appears well above the prominent Volkhov–Kunda sequence boundary (Fig. 2; Dronov et al. 2011; Lindskog

et al. 2014). However, according to the stratigraphic position, the Volkhov Oil Collector bed is older than the Volkhov–Kunda sequence boundary (regional stage boundary) and the regression episodes in early Kunda time. Furthermore, the occurrence of a single layer of quartz sand in the deeper part of the basin with clear flow-induced sedimentary structures (i.e. angled- and cross-lamination; Figs 4, 5), normal grading and lack of shore-facies sedimentary features (i.e. bioturbation, wave ripples, thick-walled macrofauna, etc.) indicates a short-lived gravitational settling event of sediment from suspension, rather than a gradual shift of the shore facies within the basin.

Provenance assessment

The palaeogeographic position of the Volkhov Oil Collector bed on the northern flank of the Jelgava Depression suggests a provenance area of the transported material upslope further to the north or northwest. Considering the dynamics of turbidity currents, large-scale submarine erosional features and channels characteristically occur upstream of the turbidite flow tract (Mutti et al. 1999). These are the locations where the passing turbulent flow erodes large amounts of particles into the moving sediment–water mass. A Lower Ordovician to lower Middle Ordovician erosional area, the Gotland elevation, has been described less than 100 km north-northwest from the Volkhov Oil Collector distribution area (Fig. 1A; Thorslund & Westergård 1938). The Gotland elevation could be a potential provenance area for the Volkhov Oil Collector sediments. The other nearby siliciclastic provenance areas, the Pakri Formation and the Kärdla ejecta blanket in northwestern Estonia, are of Darriwilian and Sandbian age, respectively, and hence younger than the Volkhovian turbidite. As for the rest of the basin, it must be remembered that even the shallowest part of the basin was composed of stable carbonates that were relatively resistant to erosion. On the other hand, for a far-travelling turbidite to form in a low-relief and shallow-water setting, a considerable bed erosion must have taken place at the earlier stages of the flow that would incorporate substantial amounts of fine-grained sediment into the upper and turbulent part of the flow and hence increase its density, thickness and velocity, i.e. its effectiveness (Mutti et al. 1999). The material of the Volkhov Oil Collector must therefore have been eroded from land areas, i.e. the Gotland elevation or the mainland much further away.

Trigger assessment

The usual prerequisite for the initiation of turbidite flow is the accumulation of loose sediment on a subaqueous slope. However, the floor of the Baltoscandian carbonate basin was relatively flat with only slight tilting ($6'$–$18'$) towards the basin centre; also the surrounding land areas were low (Jaanusson 1973). Even the submarine slopes of the major tectonic feature, the Jelgava Depression, were not considerably steep. The shortest slope distance from top to base was approximately 50 km. Even when considering a vastly exaggerated water depth of 1 km in this depocentral region, the dip of a slope would still be less than 2%. The smooth bathymetry of the basin and the lack of loose siliciclastic sediment on the basin floor did not favour the formation of sediment flows due to seismic shaking or due to any other subaqueous slope processes. For these reasons, we disregard both earthquake-induced direct shaking and spontaneous liquefaction or other non-tectonic slope failures as likely triggers of the Volkhovian turbidite flow.

Well-known turbidite triggers that do not necessarily require the presence of subaqueous slopes are hyperpycnal flows and large storms. However, both of these processes are usually recurrent in nature and it would be expected to see more of the corresponding deposits in the sedimentary succession. No such indications are known from the region within the Middle Ordovician sediments.

Considering that the Volkhov Oil Collector is a single event bed with siliciclastic material most likely originating from a land area relatively far from its final deposition site, we suggest a rare tsunami as the trigger of the turbidite. Turbidites can be an indirect result of the action of tsunami waves on the sea floor (e.g. Kastens & Cita 1981; Mörner 2013; Polonia et al. 2013) or tsunami-like meteorite impact resurge waves (e.g. Dypvik et al. 2004; Schulte et al. 2012). Furthermore, 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 & Spiske 2012; Tamura et al. 2015). For example, the in-flow wave of the 2011 Tohoku-oki tsunami reworked sandy sediment 20–30 m deep on the Sendai Bay floor (Tamura et al. 2015), eroded coastal sand dunes and reshaped the coastline (Nakamura et al. 2012). High-energy tsunami waves can even cause the erosion of bedrock platforms (Aalto et al. 1999) and upper surfaces of stable calcareous muds (Kastens & Cita 1981). The water always accelerates during the tsunami return flow (i.e. tsunami backwash) and is able to carry a high concentration of the eroded sediment in suspension (Shanmugam 2008; Weiss 2008; Tamura et al. 2015). The suspended backwash sediment will be redeposited relatively close to the coast due to a hydraulic jump and energy loss at the original coastline (Weiss 2008). However, the fallout sediment layer can then move independently from the rest of the tsunami wave to deeper water due to the net density contrast (Weiss 2008). Given the right

conditions (i.e. sufficient amount of fines in suspension), the fallout sediment layer can eventually transform into turbidity current. This scenario illustrates a very likely transport mechanism of a large volume of siliciclastic material from the Gotland elevation (or other coastal areas) into the nearshore waters of the Baltoscandian basin and from there, further to the Jelgava Depression area.

Considering the geological background of the Ordovician Baltoscandian basin, we suggest either a rare catastrophic earthquake or a yet unknown marine bolide impact event as the most likely causes of a tsunami-triggered turbidite in this region. The possibility of rare large tectonic events taking place within periods of tens of millions of years cannot be excluded even within generally stable areas such as the Baltoscandian basin during the Early Palaeozoic (Tuuling & Vaher 2018). Catastrophic earthquakes within stable intracratonic areas might be rare, but they are still widespread and may affect every continent (e.g. Stein et al. 1989). A large volcanic explosion or seismic ruptures somewhere out of the Baltoscandian shelf, for example in the Armorican volcanic arc, could also have caused earthquakes with potential tsunamis to travel deep into the Baltoscandian shelf sea. 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 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 & Jansa 2003). Many impact events have been confirmed during the Ordovician period when a meteorite struck the Baltoscandian shallow sea (e.g. Ormö & Lindström 2000). Distinct impact resurge deposits (e.g. graded bedding, turbidite-like sediments) are known from the Tvären (Lindström et al. 1994), Lockne (Lindström & Sturkell 1992) and Målingen (Ormö et al. 2014) structures, all located in Sweden. Additionally, the Darriwilian seismites layer (the Pakri Formation) in northwestern Estonia has been related to a yet unknown meteorite impact (Alwmark et al. 2010; Põldsaar & Ainsaar 2014). Although none of these impact events coincides with the deposition of the Volkhov Oil Collector turbidite, they clearly illustrate the potential of impact-triggered seafloor disturbances that are preserved within the sediments of the Baltoscandian basin. Further studies are required to verify links between the deposition of the Volkhov Oil Collector and an ancient meteorite impact (i.e. presence of shocked quartz grains, iridium anomalies, etc. within the sediments) or a large tectonic earthquake.

CONCLUSIONS

The siliciclastic bed of the Volkhov Oil Collector, deposited along the gentle slope of the Jelgava Depression within a carbonate outer ramp environment, was studied in core sections from western Latvia. The internal sedimentary structures of the Volkhov Oil Collector indicate deposition from suspension fallout during a single short-lived event. From a detailed sedimentological study of the cores we tentatively conclude:

(1) the Volkhov Oil Collector bed represents a unique shallow-marine siliciclastic turbidite bed within the Ordovician Baltoscandian palaeobasin, with its sedimentary structures closely following the units of the classical turbidite model by Bouma (1962);

(2) the most plausible trigger of a siliciclastic turbidite within the given geological and sedimentological background could be a rare tsunami;

(3) a tsunami event can explain the erosion of a substantial amount of siliciclastic sediment from the coastal area (e.g. Gotland elevation or coastal areas further away) and transportation of this material into nearshore waters, where the evolution into turbidity current would transport the sandy sediments into deeper parts of the basin;

(4) the finding of the Volkhov Oil Collector siliciclastic turbidite on the tectonically stable shallow carbonate ramp suggests that tsunami-induced turbidites can take place in rare cases also in epicontinental environments.

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Terrigeenne madalmere turbidiit Ordoviitsiumi Baltoskandia paleobasseini karbonaatsel šelfil

Kairi Põldsaar, Leho Ainsaar, Reet Nemliher, Oive Tinn ja Girts Stinkulis

On analüüsitud Kuramaa ja ümbritseva Läänemere akvatooriumi puursüdamikes kirjeldatud Kesk-Ordoviitsiumi Dapingi vanusega õhukest aleuriidi-liivakivikihti, mida on nimetatud Volhovi naftakollektoriks (Volkhov Oil Collector) selle fossiilse süsivesiniku kogumise potentsiaali tõttu. Kiht moodustus Volhovi eal regionaalse Jelgava alangu jalamile Baltoskandia paleobasseini sügavamas telgmises osas. Kolme Lääne-Läti puursüdamiku sedimento-loogilised ja petroloogilised analüüsid näitavad, et liivakiht settis üksiku turbidiitse settevoolu tagajärjel. Turbidiidikihi sisemine tekstuur järgib klassikalist Bouma turbidiitse kihijärjestuse mudelit. On arutletud üksiku terrigeense turbidiidi-voolu põhjustajate üle tektooniliselt passiivses ja suhteliselt madalas karbonaatses basseinis. Ühe võimalusena on järeldatud, et üksik erakordne tsunami võis kulutada ja transportida setendeid rannikulähedaselt maismaalt madalasse merre. Kujunenud suspensioon võis liikuda esmalt setete massvooluna, mis seejärel arenes turbidiidivooluks, liikudes basseini sügavamasse ossa ja setitades aleuriidi-liivakihi Jelgava alangu jalamile. Volhovi naftakollektori turbidiidi-kihi esinemine tektooniliselt passiivses ja lauge põhjareljeefiga Baltoskandia paleobasseinis näitab, et turbidiidi sünd-mused võivad harukordsetel juhtudel aset leida ka epikontinentaalsetes keskkondades.