Depositional framework of the East Baltic Tremadocian black shale revisited

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Depositional framework of the East Baltic Tremadocian black shale revisited

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Abstract: This article presents a centimetre- to micrometre-scale study of sedimentary fabrics from Lower Ordovician metalliferous black shale from the Baltic palaeobasin. Two sections of the Tūrisalu Fm. NW and NE Estonia were analysed with light microscopy and scanning electron microscopy. This rock unit is characterised by mostly thin bedding (<10 mm), common occurrence of minor erosional features, and a large variety of sedimentary fabrics, including graded, cross-laminated and massive fabrics. Based on this, we suggest that dynamic sedimentation events, rather than commonly assumed slow net sedimentation, may be the dominant mechanism behind the accumulation of these beds. The storm-related near-bottom flows and the bed-load transport of mud particles were likely common distribution agents of organic-rich mud. The mud (re)distribution, mainly via near-bottom flows and controlled by flat seafloor topography and general clastic starvation, might explain the present lateral distribution and diachronous character of the Tūrisalu Fm. Documented traces of microbial mat growth and siliceous sponges in the NW Estonia indicate that in more sheltered settings, biogenic factors played a vital role in developing primary mud characteristics. The geochemical palaeoredox proxies, and high trace metal and organic matter content suggest that mud sedimentation could occur under anoxic conditions. The observed sedimentary fabrics and traces of bioturbation, however, favour prevailing oscillating redox conditions in the lower water column. The recorded heterogeneity of microfabrics indicates that dynamic transport and intermittent deposition together with biogenic factors likely forced the development of an array of unique (bio)geochemical microenvironments for syngenetic trace element sequestration.

Keywords: black shale; sedimentary fabrics; Tūrisalu Fm.; event sedimentation; microbial mat; trace elements.

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1. Introduction

Distal deep marine settings with stratified water columns were long considered a unique environment of black shale formation, and accumulation processes were envisioned as a slow, continuous net sedimentation of fine-grained organic and inorganic particles from a starved, persistently anoxic water column, which resulted in the formation of finely laminated mud intervals (Potter et al. 1980). Reports of shallow-water marginal black shales from many locations (e.g. Leckie et al. 1990; Schieber 1994; Wignall & Newton 2001), as well as the accumulation of a wealth of data in the modern marine research of organic-rich muds and their ancient analogues (e.g. Ganeshram et al. 1999; Lyons & Kashgarian 2005), in modern and ancient mud sedimentology and mudstone lithology (e.g. Traykovski et al. 2000; Schieber et al. 2007; Macquaker et al. 2010a; Ghadeer & Macquaker 2011; Plint et al. 2012), advances in experimental mud research (e.g. Baas et al. 2011; Schieber 2011 and references there in) and in organic-rich mudstone geochemistry (e.g. Algeo & Maynard 2004), organic geochemistry (e.g. Blumenberg & Wiese 2012) and geobiology (e.g. Pacton et al. 2007) have revealed that many variable formation paths might have produced different black shales. Those discoveries indicate that organic-rich mud intervals might form under an agitated water column in shallow settings (e.g. Schieber 1994), and they in places contain event beds, erosion surfaces and other signs of a discontinuous sedimentary record (e.g. Schieber & Yawar 2009). Likewise, the occurrence of black shale does not necessarily reflect a permanently anoxic water column (e.g. Pedersen & Calvert 1990; Murphy et al. 2000; Schovsbo 2001; Egenhoff & Maletz 2012), and typical fossil black shales can contain various signs of benthic life (e.g. Kazmierczak et al. 2012).

The new discoveries allow us to revisit some of the controversial aspects of the sedimentary framework of the black shales that have long been known in Estonian Tremadocian succession. Those organic-rich and metalliferous black shales, formed in proximal settings of the vast
epicontinental sea of the Baltica palaeocontinent during an overall eustatic sea-level rise (Dronov et al. 2011), have been mainly described as shallow-water deposits (e.g. Scupin 1922; Kivimägi & Loog 1972), which accumulated in water depth near storm wave base (e.g. Heinsalu 1990; Artushkov et al. 2000). In basin scale, Schovsbo (2002) places Estonia within the inner-shelf environment of the Cambrian–Tremadocian black shales, i.e. to innermost and shallowest area of black shale formation in the Baltic palaeobasin. However, a considerably deeper water origin of more than 130 m has been suggested by some researchers for considered black shales (e.g. Pukkonen & Ramm 1992). The previous studies have indicated spatial regional-scale lithological heterogeneity and facies differences of the Tūrisalu Fm. between western and north-eastern Estonian settings, as well as the existence of small-scale lithological features, such as the random occurrence of cross-lamination, small ripple marks, irregular silt intercalations, traces of bioturbation and benthic sessile communities (Müürisepp 1964; Kaljo & Kivimägi 1970; Kivimägi & Teedumäe 1971; Kivimägi & Loog 1972; Heinsalu 1990; Pukkonen & Ramm 1992; Loog & Petersell 1995). However, the sedimentary framework behind those lithological features remains poorly understood. Recently, submillimetre- to millimetre-scale vertical lithological heterogeneity has been recognised as a common feature in a wide variety of mudstones, including organic-rich mudstones (Aplin & Macquaker 2011 and references there in). In the case of the Tūrisalu Fm., the existence of pronounced spatial and subtle decimetre-scale vertical trace metal variability has been documented (Pukkonen & Ramm 1992; Soesoo & Hade 2012; Voolma et al. 2013). Whereas the syngenetic enrichment of redox-sensitive trace metals is a widely accepted pathway for metal sequestration in typical black shales (e.g. Algeo & Maynard 2004), the enrichment models are commonly based on the generalisation that sedimentation rates of primary mud remained constant over long periods, there suspension–redeposition of sediments and bioturbation are negligible according to their variable content of redox-sensitive trace elements, such as V, U and Mo, showing general positive covariance with OM abundance (Pukkonen & Ramm 1992). In Estonia, the thickness of the formation remains between 1 and 8 m, generally decreasing eastward and southward from the area of maximum thickness in north-western Estonia. The Tūrisalu Fm. occurs on top of a complex of commonly cross-bedded siltstone and sandstone (Kallavere Fm.) containing debris or rich coquinas of phosphatic brachiopods denoting a large-scale skeletal phosphorite accumulation episode during the Cambrian–Ordovician transition (Ilyin & Heinsalu 1990; Hiller 1993). These siliciclastic deposits also contain interbeds and lenses of black shales. In NW Estonia, a thick organic-rich mudstone bed caps a subaerial regional unconformity at the base of the transgressive Kallavere Fm. (Nemliher & Puura 1996). In NE Estonia, the black shale overlies the siliciclastic beds of the Kallavere Fm., presenting dense interfingerings of siltstone with phosphatic detritus and organic-rich mudstone beds (Heinsalu et al. 2003). The onset of accumulation of primary organic-rich muds of the Tūrisalu Fm. across Estonia was not concurrent (Kaljo & Kivimägi 1970) (Fig. 1C). The older black shales in western Estonia belong to the Cordylodus lindstromi/angulatus condont biozones (Pakerort Regional Stage). Eastwards the black shales become gradually younger, and in NE Estonia, the succession is assigned to the Paltodus deltifer pristinus condont zone (Varangu Regional Stage; Kaljo et al. 1986; Heinsalu et al. 2003). The Varangu age generally denotes a major regressive episode in the region (e.g. Dronov et al. 2011). The upper boundary of the Tūrisalu Fm. comprises a regional unconformity that is capped by organic-poor grey shales or glauconitic sandstones (Heinsalu 1980) and marks a sea-level drop that terminated organic-rich mud accumulation in the proximal settings of the Baltic palaeobasin.

2. Geological background

The black shale of the Tūrisalu Fm. (historically known as Dictyonema shale or Dictyonema argillite, also the term “graptolite argillite” is widely used in recent local literature) is an organic-rich black shale that formed in the proximal settings of the Baltic palaeobasin in the Early Ordovician (Männil 1966) when Baltica was at approximately 40–50° southern latitudes (Fig. 1A and B) (Cocks & Torsvik 2005). Between Mid-Cambrian and Early Ordovician, the Baltica made through anticlockwise rotation. At the beginning of Tremadocian, Baltic palaeobasin was situated at western margins of the continent, facing the Iapetus Ocean in the west and the Tornquist Sea in the south and south-west (Cocks & Torsvik 2005). On a regional scale, the Tūrisalu Fm. is part of a patchy (modern distribution) but vast Mid-Cambrian–Lower Ordovician black shale belt in the Baltoscandian region, extending in the east–west dimension from Lake Onega to Jutland (Andersson et al. 1985; Kaljo et al. 1986). It was accumulated in a large, exceptionally flat-floored epicontinental sea (Nielsen & Schovsbo 2011). Nielsen & Schovsbo (2006) considered the Estonian and Russian Tremadocian black shale to be a shallow-water tongue of the Alum Shale Fm. In Estonia, the almost flat-lying Tūrisalu Fm. occurs within the tectonically undisturbed lower Palaeozoic sedimentary succession, and the entire Palaeozoic sedimentary complex is generally characterised by very low thermal maturity (Kirsimäe et al. 1999). Its distribution in Estonia and Russia has been considered one of the best examples of very shallow-marine near-shore Cambrian and Early Ordovician deposits with siliciclastic sedimentation (Kaljo et al. 1986; Mens & Pirrus 1997; Artushkov et al. 2000).

Dark-brown black shale of the Tūrisalu Fm., which contains fossilised fragments of early planktonic graptolites, is characterised by high OM content ranging from 10% to 20%, fine silt fraction dominating the composition and variable pyrite abundance (Kaljo & Kivimägi 1970; Loog et al. 2001). Another characteristic feature of the black shale is its high but spatially variable content of redox-sensitive trace elements, such as V, U and Mo, showing general positive covariance with OM abundance (Pukkonen & Ramm 1992). In Estonia, the thickness of the formation remains between 1 and 8 m, generally decreasing eastward and southward from the area of maximum thickness in north-western Estonia. The Tūrisalu Fm. occurs on top of a complex of commonly cross-bedded siltstone and sandstone (Kallavere Fm.) containing debris or rich coquinas of phosphatic brachiopods denoting a large-scale skeletal phosphorite accumulation episode during the Cambrian–Ordovician transition (Ilyin & Heinsalu 1990; Hiller 1993). These siliciclastic deposits also contain interbeds and lenses of black shales. In NW Estonia, a thick organic-rich mudstone bed caps a subaerial regional unconformity at the base of the transgressive Kallavere Fm. (Nemliher & Puura 1996). In NE Estonia, the black shale overlies the siliciclastic beds of the Kallavere Fm., presenting dense interfingerings of siltstone with phosphatic detritus and organic-rich mudstone beds (Heinsalu et al. 2003). The onset of accumulation of primary organic-rich muds of the Tūrisalu Fm. across Estonia was not concurrent (Kaljo & Kivimägi 1970) (Fig. 1C). The older black shales in western Estonia belong to the Cordylodus lindstromi/angulatus condont biozones (Pakerort Regional Stage). Eastwards the black shales become gradually younger, and in NE Estonia, the succession is assigned to the Paltodus deltifer pristinus condont zone (Varangu Regional Stage; Kaljo et al. 1986; Heinsalu et al. 2003). The Varangu age generally denotes a major regressive episode in the region (e.g. Dronov et al. 2011). The upper boundary of the Tūrisalu Fm. comprises a regional unconformity that is capped by organic-poor grey shales or glauconitic sandstones (Heinsalu 1980) and marks a sea-level drop that terminated organic-rich mud accumulation in the proximal settings of the Baltic palaeobasin.
Lithology and facies of the Tūrisalu Fm. have been targeted by several studies, including Müürisepp (1960), Kaljo & Kivimägi (1970), Kivimägi & Teedumäe (1971), Heinsalu (1980) and Heinsalu (1990). In western and north-central Estonia, the Tūrisalu Fm. has been described as a considerably homogeneous black shale comprising laminated or massive lithologies (Tabasalu Member). The massive black shale varieties that are dominant in somewhat younger north-central Estonian settings have supposedly accumulated under more active hydrodynamic regime than the beds in the western settings (Pukkonen & Rammo 1992). However, Heinsalu (1990) reported irregular encounters of cross- and wavy-lamination, trace fossils and minor ripple marks in older western Estonian black shales. In NE Estonia, the Tūrisalu Fm. becomes thinner and more variable (Toolse Member). It embodies numerous silt intercalations that are regularly associated with authigenic carbonate or sulphide mineralisation, and the entire Tūrisalu Fm. has been suggested to represent a shallower-water setting and a more variegated sedimentation environment than represented by the Tabasalu Mb. (Kaljo & Kivimägi 1970; Kivimägi & Loog 1972; Loog et al. 2001). For example, in the Toolse area, the Tūrisalu Fm. was divided into four distinct intervals with different textural and structural characteristics and trace metal content (Kivimägi & Teedumäe 1971). Furthermore, Heinsalu et al. (1994) suggested that the areas around Toolse and Rakvere (Rakvere Phosphorite Area) acted as a border zone between subenvironments with different hydrodynamic regimes in this proximal part of the palaeobasin during the Early Tremadocian and that subaerial highs likely existed in this shallow-water area before a main organic-rich mud accumulation episode.

In the rather homogenous mineral assemblages of the Tūrisalu Fm., K-feldspar has been found to be dominant over quartz, illite–smectite and illite (Utsal et al. 1982; Kleesment & Kurvits 1987; Loog et al. 2001). High K-feldspar content is the characteristic feature of the Tūrisalu Fm., distinguishing the complex from the typical Alum Shale Fm. in which K-rich clay minerals (illite and illite–smectite) tend to dominate in mineral assemblages, and which have been reported to present generally lower K₂O/Al₂O₃ molar ratio than Tremadocian black shales from Estonia (Snäll 1988; Lindgreen et al. 2000; Schovsbo 2003). It is remarkable that substantial amounts of K-feldspar in the Tūrisalu Fm. is likely authigenic in origin (Utsal et al. 1982; Loog et al. 2001; unpublished data). For quartz, a genetic link with primary biogenic silica has been
suggested in NE Estonia, where lenticular intercalations of siliceous sponges are common (Miürisepp 1964; Loog & Petersell 1995). The OM of the Türisalu Fm. is N-rich, highly aromatic and, according to previous studies, composed dominantly of transformation–condensation products of marine microbial matter (Klesment & Urov 1980; Sumberg et al. 1990; Lille 2003). From other biogenic components, early planktonic graptolites, fragments of phosphatic lingulid brachiopods, conodonts, acritarchs and polychaete jaws have been reported (e.g. Kaljo & Kivimägi 1970; Kaljo et al. 1986; Paalits 1995; Hints & Nõlvak 2006). A characteristic of the Türisalu Fm. is the absence of calcareous fossils.

![Fig. 2. The cross-section of the Saka and Pakri sections, with sampling intervals, vertical profiles of redox-sensitive trace elements, palaeoredox proxies (after Hatch & Leventhal 1992; Jones & Manning 1994), environmental indices based on data by Voolma et al. (2013) and observed sedimentary fabrics.](image)
3. Materials and methods

This study is based on two sections of the Türisalu Fm. from the Saka Cliff (59.4419°N, 27.2150°E) and the Pakri Peninsula Uuga Cliff (59.3766°N, 24.0364°E). Thick and rather homogeneous Pakri section (Pakerort Stage, Türisalu Fm. and Tabasalu Member (after Mens et al. 1996)) represents transitional black shale setting between western Estonian considerably organic- and metal-rich and the more massive and trace metal poor northern central Estonian settings (cf. Heinsalu 1990; Pukkonen & Rammo 1992). The lithologically more variable Saka section is part of the heterogeneous NE Estonian Toolse Member (Varangu Stage, Türisalu Fm. and Toolse Member (after Heinsalu et al. 2003)) and is known to contain abundant lenses of siliceous spicules and small anthracites (Müürisepp 1964).

For this study, the Pakri and Saka sections were sampled at 20-cm intervals. From each collected field sample, approximately half was crushed and homogenised for major and trace element analyses (Voolma et al. 2013). The rest was used for lithological study. For fabric analysis presented in this article, five to seven subsamples from every field sample were selected randomly, cut perpendicular to bedding and roughly polished. The polished surfaces of the subsamples were scanned with a high-resolution flatbed scanner and studied with a light microscopy (Leica M205 A) to establish small-scale fabrics and stacking successions. In selected subsamples, the morphology of bedding planes was also studied on surfaces that were fractured parallel to bedding. Microfabric study and microanalyses of selected samples from both sections were carried out with a scanning electron microscopy (SEM) (Zeiss EVO MA15) equipped with EDS (Oxford INCA) at the Institute of Geology at Tallinn University of Technology. Fig. 2 presents schematic sections of both study locations, sampling intervals together with enriched trace metal profiles, and some commonly used geochemical palaeoredox and environmental indices based on data of Voolma et al. (2013). Note that the geochemical data are results of analyses of homogenised whole-rock samples, each representing average chemical composition of 20 cm long interval of studied sections. The presented loss on ignition (LOI, at 500°C) values can be used as rough estimates of the OM content. Fig. 2 also summarises the main fabric types recorded in both sections. The studied samples and data are deposited at the Institute of Geology at Tallinn University of Technology.

4. Observations

4.1 Small sedimentary fabrics

The examination of samples from the Pakri and Saka sections demonstrated the existence of submillimetre-to-centimetre range vertical in homogeneity of the black shale. Based on variations in bed thickness and continuity, lamination and bedding boundary characteristics, and the existence of grading and biogenic features, a number of distinct black shale varieties with dominant sedimentary-fabric types were distinguished. However, the listed varieties do not cover the complete array of encountered fabrics, as in several cases beds with mixed characteristic features, or the later overprinting (e.g. diagenetic growth of carbonate concretions and secondary gypsum) of primary fabrics was observed. The samples from both sections were mostly organised into rather thin beds with a common thickness of less than 10 mm. The bed boundaries were traceable by thin silt intercalations or by colour, fabric or macrocomponent contrast between the beds. The thicker average bed sizes of up to 5 cm (and rarely more) were encountered in the upper portion of the Pakri section, in the part dominated by massive varieties.

4.2 Beds with laminated fabrics

Fig. 3A demonstrates black shale samples with millimetre-scale laminated planar fabric, a characteristic of the lowest organic-rich part of the Pakri section, but encountered also at some levels of the Saka section. Those beds were fine grained and well sorted. The lamination appeared as an alternation of darker, more organic-rich, and lighter, less organic containing thin continuous laminae. However, many finely laminated beds from the studied sections appear to present subtle discontinuous lamination with minor asymmetric mud lenses and uneven bedding surfaces (Fig. 3B). Furthermore, in the case of somewhat less sorted samples, low-angle cross-lamination was observed, showing curved down-dipping laminae or inclined non-parallel bedding surfaces (Fig. 3B–D). Few bedding planes of finely laminated beds from the lower part of the Pakri section revealed poorly preserved remains of Rhabdinopora sp. (Pakri 2 and 4).

4.3 Graded beds

In addition to laminated fabrics, graded black shale varieties were regularly encountered in the studied sections. The upward-finishing beds recorded in the Türisalu Fm. had typical average thicknesses between 0.5 and 5 mm and were invariably sharp-based with flat or rough basal surfaces, the latter presenting common scour-like structures. The normal graded fabrics were widespread in the Saka section and in the upper part of the Pakri section. The beds with well-pronounced normal grading (Fig. 4A–D) comprised either couplets of silt- and organic-rich lamina sets or, in some cases, exhibited a triplet motive similar to that described by Macquaker et al. (2010a). In some intervals, the lower lamina sets of such graded beds presented distinct curved ripple-laminated fabrics. The proportion of graded beds from the upper part of the Pakri section and a few subsamples from the middle and upper part of the Saka section showed more gradational changes. In those cases, the grading appeared as a decrease in grain size or in the marine detritus content and as a colour shift from light brown to darker brown, indicating an increase in organic fraction in upper part of beds (Fig. 4E). Sharp and flat lower contacts were the characteristics for such beds.

4.4 Cross-laminated beds with soft sediment deformation structures

High-angle cross-laminated black shales with ripple sets were encountered in distinct intervals of the Pakri section (Pakri 8 and 19; Fig. 5A and B). The curved bedding surfaces, as well as abundant soft sediment deformation features, such as load structures, were typical for such beds, indicating sediment loading on uncompacted and water-enriched mud.

4.5 Beds with massive fabrics

The examination of the upper portion of the Pakri section revealed several intervals dominated by massive and thick beds compared with the rest of the section. The observed lithologies varied from isotropic massive fabric to poorly sorted irregular varieties (Fig. 5C and D), the latter containing detritus of phosphatic brachiopods. The other typical features were the absence of erosional features at the bed base, sharp bedding
boundaries and the irregular thickness distribution of intimately stacked beds. Some massive beds from the middle part of the Pakri section presented different characters with indistinct bedding boundaries and halo zones (see also section on biogenic fabrics).

4.6 Siliciclastic intercalations
The siliciclastic intercalations and lenses with thickness of a few grains to several centimetres were recorded throughout both sections, whereas their frequency was higher in the Saka section. In both sections, the thickest intercalations were confined to the lowermost ~60 cm of the Türisalu Fm. Siliciclastic intercalations were sharp-based and regularly with scoured lower contacts. In addition to angular to subrounded quartz, the thicker studied intercalation contained variegated sulphide paragenesis, rare glauconitic grains and marine detritus including phosphatic brachiopods and conodonts. Rather typical for the siliciclastic beds of the lower part of the Saka section was the occurrence of well-preserved, coarse euhedral muscovite. In the lower part of the same section, thin silty laminae were occasionally observed on the top of gradational upper contact of black shales beds, whereas grain sizes of silt particles matched with those from the underlying strata.

4.7 Beds with biogenic fabrics (biolamination, spiculite lenses and bioturbation)
The studied sections revealed a number of fabrics, which were likely formed by biogenic factors. Throughout the Saka section...
and in some intervals of the Pakri section, beds with wavy-crinkly lamination were observed (Fig. 6C–E). They appeared as very dark brown to black, dense, subparallel curved laminae, best visible at the top lamina set of beds, or as wavy crinkly intercalations in silt interlayers. A different type of supposed biolamination was encountered in some intervals of the Pakri

Fig. 4. Micrographs (A, B, D and E) and scanned image (C) of the studied black shales with normal graded fabrics. A. Pakri 10-1 presents sharp grading with triple fabric (individual lamina sets of single bed marked by numbers) comprising a lower silt-rich, an intercalated silt-rich and an organic/clay-rich lamina set and upper organic/clay-rich lamina set. Note the irregular surface below the bed (black arrows). B. Saka 1-1 presents fabric with a graded appearance, with silt-rich lower and dark organic-rich upper lamina sets (individual lamina sets marked by numbers). Black arrows mark the irregular bedding boundary. C. Succession of graded beds of sample OMS-105 from the uppermost half metre of the Pakri section; the lower silt-rich lamina set shows small-scale hummocky cross-lamination. D. Pakri 13-1 with graded fabric and scour structures (black arrows) at bedding surface; note the irregular thickness of the graded bed. E. Gradually graded bed of Saka 4-1 with smooth lower contact.
section, where firm organic-rich filaments comprised an irregular web in black shale and presented features such as coated mineral grains and vertically oriented filaments (Fig. 6A and B). The additional features of probable biolaminated beds were mica flakes at wavy bed surfaces and the layer-specific distribution of pyrite. In the Saka section, distinctive cross-laminated fabrics were encountered in two intervals in which the thoroughly cross-laminated nature of the beds was traceable thanks to inclined lenses of spicules and quartz (Fig. 7A and B). It is noteworthy that such cross-laminated spicule-rich fabrics occur in an organic-rich and rather metalliferous part of the section (Fig. 2). In the upper part of the Saka section (starting from sample Saka 4), the intercalations commonly comprised rather poor microcrystalline quartz, which is probably a recrystallisation product of biogenic silica (cf. Loog & Petersell 1995). Furthermore, various traces of horizontal bioturbation throughout the studied black shale sections were observed (Fig. 7C–F). At bedding boundaries of finely laminated organic-rich beds of the Pakri section, the pyritised horizontal flattened tubular traces up to a few millimetres thick were occasionally recorded. The features of the traces resemble those of ichnofossil Planolites (e.g. Egenhoff & Fishman 2013). More silty laminated beds and some massive beds in the Pakri section showed discontinuous indistinct laminae, halo zones, partly destroyed probable biolamination, diffused surface boundaries and, less commonly, mottled appearances (see also the massive fabric section). Those fabric elements were likely a product of homogenisation by bioturbation (Fig. 7C and D). In discrete intervals, the Saka section (Saka 6 and 9) yielded rare vertical traces with height of up to a few centimetres, and mottled fabrics, in both cases visible due to the mixing of organic-rich mud, spicules and quartz (Fig. 7E). The observed vertical traces may represent “escape traces” of zoobenthos.

4.8 Microfabrics by SEM

SEM observations were conducted to study how the above-described centimetre- to millimetre-scale features are connected to the micrometre-scale morphology of the deposit. It appears that finely laminated samples (Fig. 8A) are characterised
by anisotropic microfabric with a preferred orientation of platy minerals and bioclastic compounds and evenly distributed regular-size elongated small interparticle micropores (micropores >0.75 μm; pore size classification after Loucks et al. 2009). By contrast, in samples with massive morphology (Fig. 8B), the observed isotropic microfabrics presented a random orientation of mineral platelets and detritus in the matrix and randomly distributed closed interparticle micropores. The probable biolaminated fabrics from the Saka section revealed heterogeneous and highly porous microfabrics (Fig. 8C) with loosely packed and randomly oriented grains and a connected network of large irregularly shaped micropores. SEM studies of supposed biolaminated samples also indicated the presence of abundant curved, convoluted, folded organic-rich filaments, with thicknesses from less than 1 to several tens of microns (Fig. 8D–F). Some samples revealed convoluted homogenous laminae, or few micrometre-thick layers with laminar structures that most likely are remnants of palynomorphs. The presence of
thicker heterogeneous laminae with bumpy surfaces and uneven thickness distribution was also rather a characteristic for biolaminated samples. The conducted SEM–EDS analysis of such filaments suggested a high carbon content and the presence of Si, Fe, S and Al. Similar organic-rich sheaths, commonly partly mineralised by silica or Fe–Al silicates, have been recognised from different silicilastic rocks, including black shales, and interpreted as fossilised remnants of microbial mats (e.g. Noffke et al. 2001; Gorin et al. 2009; Kazmierczak et al. 2012).

5. Interpretation of sedimentary fabrics

The finely laminated fabrics in mudstones are traditionally interpreted as products of slow deposition of fine, loose particles or organomineralic aggregates from a generally stagnant water column (Potter et al. 1980) and widely recognised as a characteristic of black shales. Occurrence of finely laminated beds with discontinuous inclined laminae in the Tu¨risalu Fm., however, suggests that such beds were not formed simply by gravitational settling. Similar low-angle cross-laminated fabrics have been recently recognised in several black shales and interpreted as a product of lateral mud accumulation by near-seabed flows (Schieber et al. 2007; Macquaker et al. 2010a; Ghadeer & Macquaker 2011). The flume experiments by Schieber (2011) demonstrated that flocculated clay–silt particles could sustain integrity under high flow speeds and that such flocs could actually move by bed-load transport. Compaction of water-enriched mud ripples has been shown to result in the formation of microlaminated beds, very similar to those found in black shales (Schieber & Yawar 2009). Moreover, research of modern mud dynamics has revealed many quick dispersal mechanisms, some of which could form widespread “event mud blanklets”, even in the case of low topographic gradient (e.g. Traykovski et al. 2000). Such mechanisms may involve the formation of sediment-laden unidirectional near-bed flows – eroding, dispersing and depositing the sediments during one and the same flow event (e.g. Macquaker et al. 2010a). Wider acknowledgement that dynamically deposited muds could have been voluminously important in the geologic history of shallow seas has been achieved because of several recent studies of ancient low-gradient mud dominated settings. These investigations indicate that the cross-shelf drift of fine cohesive particles in various settings could have been partly or dominantly driven by short-lived sediment-laden currents (Macquaker et al. 2010a; Plint et al. 2012). The encounter of stacked successions of finely parallel and subtle lenticular laminated fabric in the lower part of the Pakri section indicates that the intermittent advective transport-controlled deposition of mud was likely one of the major mechanisms behind laminated mud accumulation. However, the same interval is also characterised by the high content of OM (LOI 500°C) and V, Mo and U (Voolma et al. 2013; Fig. 2), which designate that the sedimentary environment should have been favourable for accumulating and preserving biogenic matter and redox-sensitive trace metal enrichment. Based on the recorded fabric characteristics, it is difficult to adequately differentiate the role of suggested dynamic sedimentation and that of slow background suspension settling in the formation of finely laminated muds. Overall, however, the finely laminated beds likely represent a subenvironment with the lowest hydrodynamic energy among the observed black shale varieties of the Tu¨risalu Fm.

Also, other fabrics observed in the Tu¨risalu Fm., such as normally graded and high angle cross-laminated beds, support organic-rich mud formation by sediment-laden flows. Appearance of grading in marine sedimentary record is typically interpreted as deposition in environment where the speed of sediment-loaded current changes over time (e.g. the formation of tempestites). The occurrence of normal grading with distinct lamina sets in studied section of the Tu¨risalu Fm., together with erosional features on the lower bedding surfaces, suggests that those elements are likely products of the same turbulent near-bed flow event (e.g. Macquaker et al. 2010a). Furthermore, the occurrence of ripple-laminated lamina sets in the lower silt-rich lighter part of graded beds clearly points to the bed-load transport of mud particles. Macquaker et al. (2010a) interpreted normally graded beds composed of three distinct lamina sets as products of wave-enhanced sediment gravity flows. Importantly, such combined flows do not require steep slopes like typical turbidites, but can progress in low-gradient shallow settings thanks to energy derived from orbital motion of surface waves, which help to maintain sediment in suspension (Traykovski et al. 2000; Macquaker et al. 2010a). Dynamically deposited mud beds with thicknesses comparable to those observed in the Tu¨risalu Fm. have been attributed to low-density diluted flows with sediment loads of 1–10 g/l (Mackay & Dalrymple 2011). On the other hand, the absence of erosional features below beds with more gradational grading also observed in the Tu¨risalu Fm., coupled with mostly rather silty composition of such beds, could indicate that the primary mud settled from a suspended sediment (storm) cloud during considerably short time intervals. The observed high-angle cross-laminated fabrics in the Tu¨risalu Fm. unequivocally point to high-energy sedimentation event most likely controlled by surface storm waves. The accompanying soft sediment deformation features in such beds suggest rapid sediment loading on seabed, whereas resistance of those fabrics to later compaction indicates the general grain supported nature of the primary sediments.

Deciphering of formation of observed massive fabrics is more problematic as different pathways and sedimentary settings can lead to formation of massive fabrics in mudstones. Massive varieties could appear as products of the simple gravitational settling of fluidised mud, deposition from fluid mud flows, products of settling from a suspended sediment cloud in slack shallow-water settings (e.g. Traykovski et al. 2000; Baas & Best 2002; Ichaso & Dalrymple 2009; Mackay & Dalrymple 2011) or as products of post-sedimentary homogenisation by bioturba-
The preservation of sharp bedding surfaces in studied black shale samples suggests that the major part of observed massive fabrics in the Türisalu Fm. are likely primary sedimentary features and might thus reflect an accumulation of mud in an environment that was shallow enough to support surficial mud fluidisation by storm waves. However, as shown by studies of modern muddy shallow-marine areas like the Eel river shelf (Traykovski et al. 2000; Macquaker et al. 2010a), the massive fabrics in mud might be as well produced by deposition from dense fluid mud flows, which on the Eel river shelf act as the major agents of offshore transport of cohesive flood sediments. In the case of the Türisalu Fm., considerably immature siliciclastic fresh input into palaeobasin and proximity of terrestrial feeding systems of sediment supply could be argued
based on the heterolithic character of Lower Tremadocian successions and by the abundance of both mica flakes and subangular quartz in siliciclastic intercalations in the studied black shale sections. Those intercalations are traditionally considered to be products of distal storm flows, which very infrequently disturbed the otherwise tranquil environment of black shale accumulation (e.g. Heinsalu 1990). However, as suggested by our study, both siliciclastic intercalations and shale beds likely originated from sediment-laden wave-aided flows, which plausibly controlled cohesive sediment dispersal in the inner-shelf settings of the Tremadocian epicontinental palaeobasin. Gradational silty upper contact of black shale beds observed in the Saka section suggests that additionally to deposition by the storm flows, the winnowing of surface mud by bottom currents could also cause the formation of the observed silty laminae.

Besides physical factors which controlled the accumulation of black shales of the Türisalu Fm., biogenic processes had considerable role on the final character of those beds. Carbon-rich wrinkled structures, similar to those observed in the Saka section have been documented in different siliciclastic rocks including mudstones (e.g. Schieber 1999) starting from Archean (e.g. Noffke 2009). These features have been interpreted as recalcitrant remnants of benthic microbial mats, supposedly produced by phototrophic bacteria, encapsulated into thick films of extracellular polymeric substances (EPSs) or by more complex multitrrophic microbial consortia (e.g. Gorin et al. 2009). EPS is a general term for sticky substances composed dominantly of polysaccharides and secreted by different types of microorganisms (e.g. Decho 1990). The EPS-rich microbial mats are found to be typical for high-energy well-lit shallow-water environments, whereas EPS has a considerable role in biostabilisation of mat-covered seabed (e.g. Noffke 2009). The somewhat different types of supposed biolamination recorded in the Pakri section with vertical organic-rich filaments were probably formed as the result of an upward migration of the microbial mat during its life cycle (Noffke et al. 2001). Synsedimentary detrital grain trapping by sticky mat surfaces and the benthic community-controlled subsurface sulphate reduction could be suggested based on common encounters of abundant mica flakes at wavy mat surfaces and the observed layer-specific distribution of pyrite in biolaminated samples (e.g. Schieber 1999).

The influence of zoobenthos is conventionally considered to be negligible in the case of typical laminated black shales (Wignall 1994); however, our research as well as previous studies (Heinsalu 1990) report traces of bioturbation throughout the Türisalu Fm. Furthermore, recent investigations of Lower Ordovician black shales in Scandinavia have suggested that black shales might actually present abundant traces of bioturbation even in levels rich in graptolite fossils. This is in contrast to commonly upheld notion that such beds should have accumulated in anoxic environment (Egenhoff & Maletz 2012). Although a detailed study of benthic communities in the Türisalu Fm. is beyond the scope of this article, the observed traces of bottom colonisation (bioturbation and sponge spicules) suggest the availability of free oxygen at the sediment–water interface regularly, or at least episodically, throughout the accumulation history of the Türisalu Fm. However, the heterogeneity of the observed biogenic fabrics denotes that the conditions for benthic life varied through time.

The comparison of microfabrics of black shales showed that notable difference exists between samples with distinct small-scale sedimentary features. General feature of all studied black shale varieties was the large volume of micro pores and a low level of compaction, which is consistent with low diagenetic maturity and silt-fraction dominated size fractions of the deposit. SEM observations also confirmed profound effect of biogenic processes, such as in situ formation of microbial mats, on the development of microfabrics of black shales by supporting the formation of highly heterogeneous, porous and relatively fragile varieties. The storm ripped up cohesive fragments of such microbial mats (e.g. Schieber 1999) could have been the source of the convoluted organic-rich fragments that were commonly observed in the matrix of the Saka and the Pakri samples.

The results of this research demonstrate that vertical sections of the Türisalu Fm. are lithologically heterogeneous, even in intervals dominated by well-laminated beds. We suggest that the observed fabric variability with elements such as ripple and high-angle cross-lamination, grading, common microbial laminations, lenticular intercalations of siliceous sponges, submarine erosional surfaces, silty massive fabrics with marine detritus and traces of bioturbation indicate a shallow-water surface-wave-controlled sedimentary environment of primary mud accumulation. The interpretation of a shallow-water origin is consistent with the conclusion that was previously made by numerous studies (e.g. Scupin 1922; Heinsalu 1990). However, accumulation pathways of primary mud in those settings were obviously much more variable than the commonly assumed “slow suspension settling in stagnant water column inferred by rather infrequent storm events” (e.g. Heinsalu 1990). In their landmark paper, Rine & Ginsburg (1985) demonstrated, based on studies of modern equatorial Atlantic mud shore faces, that siliciclastic mud deposits can form in high-energy dynamic shallow-water environment. Furthermore, their study hinted that actual mud- or sand-dominated facies distribution in shallow-water settings can be rather different from traditional sandy near-shore–muddy offshore facies zonation.

The well-documented occurrence of typical marine fauna in the Türisalu Fm. such as early planktic graptolites Rhabdinopora sp. (Kaljo et al. 1986) designates that inner-shelf organic-rich muds deposited under normal marine conditions with non-restricted surface circulation. The documented fabric successions of the Pakri black shale shows general change from the laminated fabrics-dominated lower part to massive varieties-dominated upper part. This could possibly reflect a major shift in the character of sediment-laden flows during the accumulation of studied black shale section, from diluted turbulent flows to more dense fluid mud flows. According to Baltoscandian sea-level reconstruction of Nielsen (2004), the initial Early Ordovician transgression, which reached to its maximum in Rhabdinopora spp. interval (lower part of the Pakerort Stage), was followed by shallowing at the base of the Adelographus hunnebergensis graptolite zone and then by more moderate sea-level rise, which culminated during the Kiaerographus Drowning Event (lower part of the Varangu Stage). Thus, the shift from more laminated to massive fabrics observed in the Pakri section could be related to eustatic sea-level fall. A limited occurrence of massive fabrics and widespread biogenic fabrics in the stratigraphically younger Saka section suggests that, besides water depth control, different sediment accumulation patterns and related hydrodynamic and sediment supply regimes were dominant in the two studied localities. The Saka section most likely represented a more sheltered shallow-marine setting, protected from storm waves by submerged sand bars or ridges between the Vihula and Toolse
areas as proposed by Heinsalu et al. (1994). Such sheltered, but not stagnant environments favoured an increase in benthic biogenic factors, including the development of benthic microbial mats and abundant shallow-water sponges.

6. Discussion

6.1 Sedimentary framework of organic-rich mud accumulation

In the early Palaeozoic, the considered marginal area of the Baltic palaeobasin was situated in the interior of the palaeocontinent, hundreds of kilometres away from deep water settings, facing the Iapetus Ocean and the Tornquist Sea, and hosting the Alum Shale Fm. For Alum Shale, which was deposited from the Mid-Cambrian to the early Tremadocian, the average net accumulation rate of 1–10 mm/1000 years has been suggested (Thickpenny 1987; Schovsbo 2001). Based on the available biostratigraphic framework and the latest time-scale calibration, black shales of the Türisalu Fm. deposited within a maximum time frame of \( \sim 5 \text{ My} \) (Cooper & Sadler 2012). Thus, the average net accumulation rates stayed very low both in the deeper basin and in the marginal settings. The very low level of terrestrial input into the primary sedimentary environment was controlled by the peneplaned nature of the main input area – low-altitude Proterozoic hard rock terrain of the Fennoscandian Shield in the present day north and northeast (Utsal et al. 1982; Artyushkov et al. 2000). Furthermore, a drop in fluvial particulate input into more distal settings at the start of the organic-rich mud accumulation was apparently supported by the sea-level rise and trapping riverine fluxes in back-stepping estuarine-coastal systems (e.g. Wignall 1991; Nielsen & Schovsbo 2011). At the time of high sea level (Nielsen 2004; Dronov et al. 2011) in early Tremadocian, the Finland–Russian part of the Fennoscandian Shield (adjacent to the accumulation area of the Türisalu Fm.) likely remained the main terrestrial source area of siliciclastic input for this part of the palaeobasin, as indicated by the occurrence of relatively immature siliciclastic deposits in Estonian settings (e.g. Heinsalu et al. 2003). The encounter of regular small-scale erosional features and thebedded character of the studied black shale successions indicate that the Türisalu Fm. is not a condensed deposit *sensu stricto* but presents evidence of intermittent dynamic sedimentation and reworking.

Formation of cohesive sediment-laden flows (as well as sediment storm clouds) in the accumulation environment of the Türisalu Fm. could have either been connected with the reactivation of muds that were trapped in coastal/estuarine settings, with the resuspension of seabed muds or alternatively with “fresh” fine sediment load into the basin from extensive flooding events (e.g. Arthur & Sageman 2005). The rivers of the pre-vegetational era were likely far more prone to the generation of sediment surges during flooding events compared with modern rivers (Davies & Gibling 2010). On other hand, the storm wave activity at dynamic estuaries (supposedly rather typical for pre-Devonian rivers according to Davies & Gibling (2010)) or in related coastal systems most likely had a higher potential for triggering the formation of long-travelling sediment-laden flows and for causing the dispersal of fine sediments.

In the early Palaeozoic, the study area was characterised by high tectonic and sedimentary facies zone stability (Männil 1966; Jaanusson 1976). In settings with very flat seabed, additional wave energy was needed to allow the progression of sediment-laden flows over long distances (e.g. Plint et al. 2012). Such seabed topography was not probably favourable for the formation and progression of sediment-laden density currents in water depth below storm wave base. Furthermore, the innermost shelf position also meant that the Estonian area was situated far from strong currents and upwelling systems at the continental margins, which thus had likely minor influence on sediment dispersal. The flow deposition features observed in the Türisalu Fm. together with palaeogeographic position therefore favour shallow-water storm-wave-controlled deposition rather than a deeper water origin of primary muds. Several general features in the architecture of the Türisalu Fm. indicate a tight supply–transport–accommodation space-controlled nature of the black shale distribution: (1) the belt of the Estonian–Russian Tremadocian black shales (e.g. Heinsalu 1986) along the supposed terrestrial areas, (2) diachronous accumulation in different localities, (3) the gradual thinning towards the most distal (southern) part with respect to supposed terrestrial sources and (4) the gradual thinning and decrease in age towards more shallow-water settings in the NW Estonia (Fig. 9). The intimate association of black shales with the peritidal shell phosphorite-containing Kallavere Fm. has been commonly considered as a strong evidence for a shallow-water origin of the Türisalu Fm. (e.g. Scupin 1922; Heinsalu 1990). Furthermore, the Türisalu Fm. is set within the limits of shallow-water North Estonian facies belt in terms of post-Tremadocian Ordovician carbonate sedimentary basin being absent in the deeper water settings of the Livonian Tongue facies belt (Jaanusson 1976). Thus, based on the thickness distribution of the Kallavere and Türisalu formations (and the absence of evidence on major tectonic movements in the considered setting in the Tremadocian), the migration of the sedimentation locus towards near-shore settings during sea-level rise and diminished clastic input is suggested. Alternatively, however, the absence of organic-rich Tremadocian sediments in presumably deeper water settings in southern Estonia could be related to post-Tremadocian erosion of mudbeds (Mens & Pirrus 1997). Nevertheless, the rather irregular thickness of the Kallavere Fm., juxtaposed with the established litho- and bio-stratigraphy of the Türisalu Fm., suggest that the sedimentary architecture of the primary organic-rich mud was strongly influenced by inherited seafloor topography, i.e. drowning of complex sets of sand–silt bed forms formed during the previous stages of transgression (cf. Heinsalu et al. 1994).

Previous studies by Heinsalu (1990) and Artyushkov et al. (2000) have suggested that the black shales of the Türisalu Fm. should have been deposited at a depth near storm-wave base (40–60 m). The results of this research, however, indicate that the accumulation of primary mud could also probably occur in shallower depths depending on the local physiography, material supply and patterns of wind-forced storm waves. Thus, spatial and stratigraphic changes in the lithology within the Türisalu Fm. cannot be directly interpreted in terms of water depth, but reflect an interlinked effect of proximity to hinterlands, the volume and type of distributed sediment, seafloor gradients, seafloor morphology and variegated hydrodynamic energy patterns (e.g. Macquaker et al. 2010a). We suggest that storm-induced sediment dispersal and sedimentation characteristic of the later Early Ordovician sedimentary record in the north Estonian shelf (Dronov et al. 2002), dominated also in the Tremadocian and storm-wave-
aided near-bed flows, acted as major agents of mud reworking, dispersal and accumulation in the studied black shale localities.

6.2 Sequestration of OM and trace metals in the context of dynamic deposition

Evidence of physical and biogenic mixing of precursor muds of the Türisalu Fm. suggests a shallow-water hydrodynamically variegated marine environments and makes permanent anoxia (euxinia) in the lower water column questionable. However, an O₂ deficit has been shown to be a critical factor for the preservation of labile marine OM and trace metal enrichment in black shales (e.g. Algeo & Maynard 2004). Both studied sections presented a high content of redox-sensitive elements such as V, Mo and U (recorded maximum content: V = 1500 ppm, Mo = 1800 ppm, U = 800 ppm; Voolma et al.

Fig. 9. Thickness of the Türisalu and Kallavere Fm. A. Location of drill cores used for thickness calculations and representative thicknesses of the Türisalu Fm. Data of Geological Survey of Estonia (Niin et al. 2008). B. Scheme of interpolated thicknesses of Türisalu Fm. C. Scheme of interpolated thicknesses of the Kallavere Fm. Note that only thicknesses within the distribution area of the Türisalu Fm. are provided on the scheme.
The average concentration of those metals was detected to be considerably higher in the Saka section (enrichment factor $V = 1.2$, $U = 2.95$, $Mo = 3.9$ respective to the average content in the Pakri section; Voolma et al. 2013). Widely used geochemical palaeoredox proxies, such as $V/(V + Ni)$ and $V/Cr$ (Fig. 2; Hatch & Leventhal 1992; Jones & Manning 1994), suggest that the studied organic-rich mud deposit is formed under anoxic (euxinic) conditions. Thus, lithologically more heterogeneous and an average more metalliferous, the Saka section yielded results varying from anoxic to euxinic conditions. Somewhat less anoxic conditions were deduced for the Pakri section. The few element-based indices might have, however, limited value for interpreting the palaeoredox situation without a detailed knowledge of the local geological situation (e.g. Tribovillard et al. 2006). Schovsbo (2001) calibrated the combined $V/(V + Ni)$ and sulphur values in the Alum Shale Fm. against triolobite and brachiopod occurrence data. According to this classification, most of the Tûrisalu Fm. belong to an upper dysoxic zone, where $V$ enrichment was favoured by advective transport of the trace elements (Schovsbo 2001). The latter author also suggested crucial role of advective transport by $U$ enrichment of the near-shore Cambrian Alum Shale Fm. and Tremadocian black shales.

Global-scale processes, such as the development of a strongly stratified ocean with anoxic deep waters, are commonly seen as the triggers of widespread contemporary black shale development (Schlanger & Jenkyns 1976). The Upper Cambrian part of the metalliferous Alum Shale Fm. in deeper basinal settings of the Baltic palaeobasin could have been linked to one such ocean anoxic event in the Late Cambrian (Gill et al. 2011). Wilde et al. (1989) suggested a build-up of strong upwelling at the western margin of Baltica in the Tremadocian and a transgression of deep anoxic nutrient-rich ocean waters to the shelf. However, Schovsbo (2001) argued that at the beginning of the Ordovician, less oxygen-depleted conditions and better circulation had been restored in the Baltic palaeobasin compared with the Upper Cambrian marine environments. Despite the uncertainty about deep water redox conditions, it is evident that the primary muds of the Tûrisalu Fm. accumulated well within the photic zone (e.g. Chester 2003). In present-day seas, photic zone anoxia can be found under specific conditions that are related to strongly stratified water column limiting the $O_2$ supply and/or high bioproductivity—decomposition rates and is confined to closed or barred marine to brackish water bodies (e.g. Yao & Millero 1995) and/or to environments with high anthropogenic nutrient input fuelling eutrophication (e.g. Rabalais et al. 2002). In mid-latitude epicontinental shallow seas, such as the Baltic palaeobasin in the Tremadocian, strong thermohaline stratification could possibly develop because of a combined effect of high freshwater fluxes and seasonal temperature variations. However, modern and ancient analogues suggest that such stratification most likely had temporal character because large seasonal climate variation at mid-latitudes also supports perturbation and regular mixing of the water column, thus favouring oscillatory redox conditions (cf. Murphy et al. 2000). Another critical factor of black shale development is bioproductivity. The formation of rich skeletal phosphorite complexes during the initial stage of the Late Cambrian—early Tremadocian transgression suggests enhanced bioproductivity in considered marginal settings of the Baltic palaeobasin (Ilyin & Heinsalu 1990). The primary OM of the Tûrisalu Fm. was likely produced by cyanobacteria and possibly by green sulphur bacteria (Klesment & Urov 1980; Lille 2003). Both those groups contain species capable of fixing $N_2$. The dominance of nitrogen-fixing primary production pathways during the accumulation of Tremadocian black shales in Estonia has been lately proposed by Kiipli & Kiipli (2013) based on low $\delta^{15}N$ values. Blumenberg & Wiese (2012) suggested that high bioavailable $P$ loading versus bioavailable $N$ could have been the main trigger of black shale formation in shallow seas during late phases of Cenomanian/Turonian ocean anoxic event. The rather low $P$ content (average $P_2O_5$ concentration of the studied section remains less than 0.5 wt%) in the studied black shale sections versus the high OM content (Voolma et al. 2013) could indicate the effective recycling of this element in a primary marine environment. This process was likely supported by the anoxic conditions in the sediment column, seasonal mixing of water masses, but possibly also by constant reworking and lateral transport of sediments (e.g. Emelis et al. 2006). Consequently, the deposition of primary organic-rich muds of the Tûrisalu Fm. might have been controlled by a feedback loop to the supply of biolimiting elements (most importantly bioavailable $P$) to the marginal photic settings, enhanced bioproductivity and build-up of strong $P$ bioproduction–regeneration cycling (e.g. Tribovillard et al. 2006; Blumenberg & Wiese 2012).

The role of bioproductivity and the OM incorporation into primary mudbeds of the Tûrisalu Fm. are nevertheless rather poorly understood. The herein documented occurrence of microbial mats is the first direct evidence of the existence of microbial consortia at the sediment—water interface of primary organic-rich muds and suggests that microbial mats could have been major primary producers of OM of the Tûrisalu Fm. (cf. Gorin et al. 2009). Buchardt et al. (1997) proposed that widespread thick algal mats could have been the source of OM in the Alum Shale Fm. The oxygen production by benthic photosynthesising microbes in the photic zone and the degradation of the OM below mat surface could support the formation of steep redox gradients at sediment–water interface (e.g. Kazmierczak et al. 2012). On the other hand, several recent studies have implied a crucial role of the formation of organomineral aggregates in the water column (e.g. during phytoplankton blooms) and the related quick sequestration of OM into sediments (Macquaker et al. 2010b). Inside such aggregates, and also in benthic microbial mats, the OM could be protected by EPS (Pacton et al. 2007) or by physicochemical interactions with mineral particles (Salmon et al. 2000), thus supporting selective OM preservation in generally oxygenated environments. Consequently, the aggregation of organic and mineral matter might explain the preservation of the organic fraction in dynamic sedimentary processes in shallow-wateroxic settings. Event deposition could also promote the preservation of OM by increasing episodic burial rates and limiting the residence time of OM at sediment–water interface (Macquaker et al. 2010b; Ghadeer & Macquaker 2012). Studies of microfabrics in the Saka section hinted that rather different physicochemical (biological) conditions of primary mud layers (including permeability, diffusion and microbially mediated processes) possibly developed in those settings compared with the Pakri section. Higher porosity and simultaneous supposedly steep redox gradients at the sediment–water interface brace fluxes of redox-sensitive elements between mudbeds and marine water (cf. Schovsbo 2001). The development of high trace metal heterogeneity in the Tûrisalu Fm. (Voolma et al. 2013) has thus been partly forced by variegated fabric characteristics of the
primary mud. We suggest that during the accumulation of primary mud of the Türisalu Fm., the lower water column was characterised by oscillating redox systems with H$_2$S-rich conditions mostly confined below the sediment–water interface. The OM supply, intermittent deposition, contact time of mud with seawater and heterogeneity of mud fabrics and porosity likely had a profound influence on trace metal enrichment processes in the examined settings. Not less importantly, advective transport and redeposition of particulate and colloidal matter most likely acted as major controllers of element cycling, including P recycling and trace element supply.

7. Conclusions

The results of this research are consistent with previous studies on the shallow-water origin of the Türisalu Fm., further suggesting that the water depth remained above the storm wave base within the photic zone throughout the deposition of the studied proximal complexes. The observed lithological characteristics provide evidence that the sedimentary dynamics of the Türisalu Fm. varied spatially and temporally, whereas intermittent accumulation with rapid short-term sedimentary fluxes prevailed. The cohesive sediment dispersal and deposition were mainly controlled by the near-bed storm-induced flows, which, besides causing the dynamic deposition of mud, also acted as eroding and reworking agents on muddy seafloor. The rather shallow-water organic-rich mud settings in NE Estonia were protected from storm wave action by a complex set of drowned transgressive sand bodies that favoured the formation and preservation of more mosaic fabric patterns in primary mud successions, including common biogenic fabrics. This study is the first to report the occurrence of fossilised microbial mats in these settings of the Türisalu Fm.

Some geochemical indices, enrichment of redox-sensitive elements and high OM content seems to favour the idea that the primary mud formed in anoxic environment. In contrast, the observed traces of bioturbation and dynamic sedimentation features suggest oscillating redox conditions in the lower water column during primary mud accumulation. Metal sequestration in such environments could have been favoured by steep redox gradients at sediment–water interfaces covered by microbial mats. This work suggests that a thorough understanding of syngenetic metal sequestration pathways in the Türisalu Fm. requires further studies on sedimentary environments. In particular, we need to learn more about (1) variability of accumulation rates, (2) proximity to fluvial sources, (3) sediment transport routes within the basin, (4) element cycling because of the formation and preservation of more mosaic fabric patterns in primary mud successions, including common biogenic fabrics. This study is the first to report the occurrence of fossilised microbial mats in these settings of the Türisalu Fm.

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