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Lithology and diagenesis of the poorly consolidated Cambrian siliciclastic sediments in the northern Baltic Sedimentary Basin

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The present study discusses lithology and diagenetic characteristics of the siliciclastic Cambrian and the enclosing Ediacaran and Ordovician deposits in the northern Baltic Sedimentary Basin (BSB). The Neoproterozoic and Lower Palaeozoic sediments are despite their age unconsolidated with primary porosity of 20–25% for both shales and sandstones. The sparse Fe-dolomite cementation of arenitic and subarenitic sandstones and siltstones occurs mainly at lithological contacts with the massive Ediacaran and Lower Cambrian claystones and is probably related to ions released during illitization. In contrast to weak mechanical and chemical compaction of sandstone, the clay mineral diagenesis of Cambrian deposits is well advanced. The highly illitic (80–90%) nature of illite-smectite (I-S) suggests evolved diagenetic grade of sediments which conflicts with shallow maximum burial and low compaction. Smectite-to-illite transformation has resulted in formation of diagenetic Fe-rich chlorite in claystones. Some porosity reduction of sandstones is due to formation of authigenic kaolinite at the expense of detrital mica or K-feldspar.

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Key words: Cambrian, Baltic Sedimentary Basin, siliclastic sediments, diagenesis, clay minerals, compaction.

INTRODUCTION

The modifications of old sedimentary rocks, which remained at shallow burial conditions throughout the burial history of the basin, are still poorly understood, as besides to chemical and physical parameters, the time factor becomes essential. The Ediacaran and Cambrian deposits at the northern margin of the East European Platform and in particular within the Baltic Sedimentary Basin are examples of such sediments. The Cambrian sediments are exposed along the southern coast of the Gulf of Finland, and are increasingly buried under younger Palaeozoic, Mesozoic and Cenozoic sediments in the south and west, reaching depths of up to 2–4 km in the southwestern part of the Baltic Basin (Fig. 1). The Cambrian succession, comprising alternating claystone-sandstone sequences was deposited in a shallow-marine shelf environment in the passive continental margin setting. The Middle Cambrian reservoir of the BSB contains oil fields in the deeper part of the basin, e.g. in West Lithuania and Latvia and offshore area (Górecki *et al.*, 1992). The Cambrian succession is also an aquifer, which is extensively used for drinking water supply in shallow periphery of basin in Northern Estonia.

Various stratigraphical, lithological and mineralogical aspects of the Cambrian clastic sediments of the BSB have been studied during the past five decades and the summary of the present knowledge is given by Laškova (1979), Brangulis (1985), Rozanov and Łydka (1987), Jankauskas (1994) and Mens and Pirrus (1997*a*, *b*). However, data on the diagenetic features of the deposits are limited and the diagenetic history of the basin is poorly understood.

The sediments of Baltoscandia have undergone variable burial and diagenetic history. As the result, despite of generally similar detrital composition and facies distribution of the sediments, the diagenetic processes in the basin show contrasting features varying both vertically and laterally. The variations are particularly distinct in the lowermost Ordovician-Cambrian sandstone lithologies of the northern shallowly buried part of the basin.

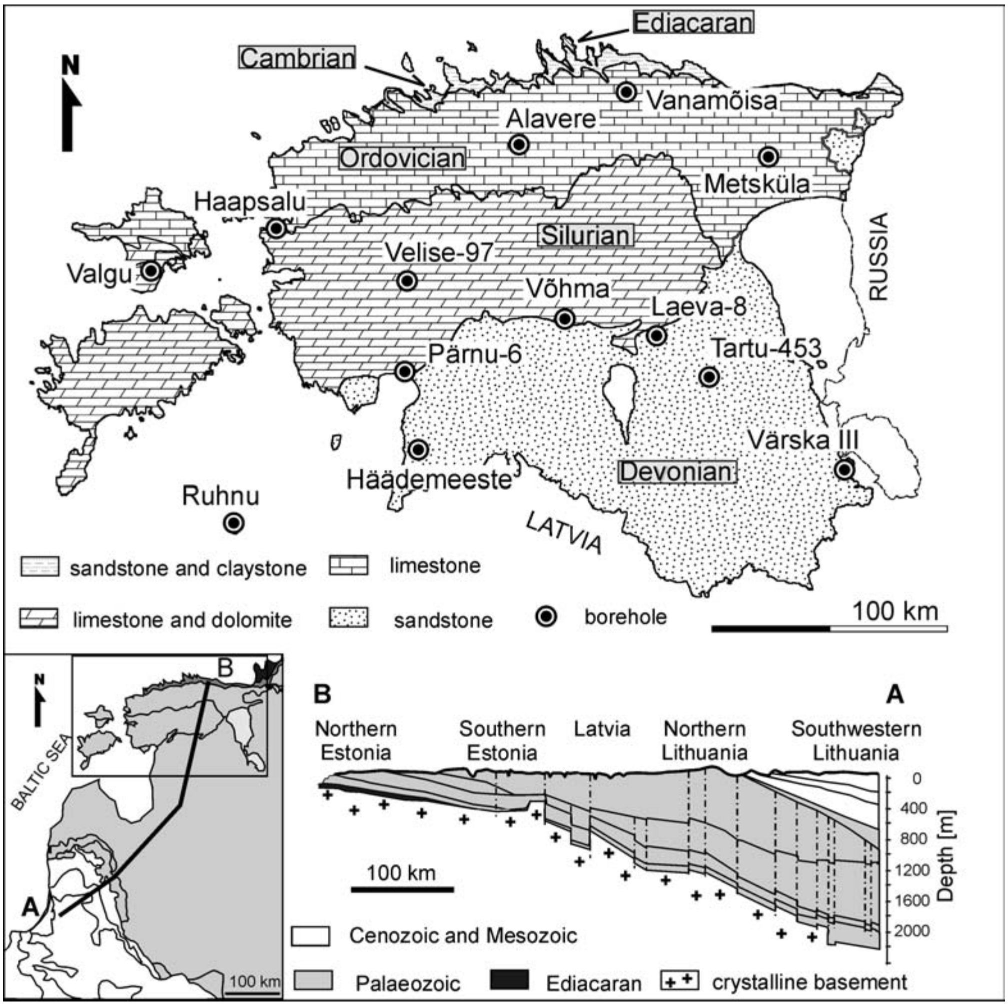

Fig. 1. Geological setting and location of studied boreholes in Estonia

Lines on inset map and cross-section show boundaries between systems

The present study focuses on the lithology and diagenetic characteristics of the Cambrian and the enclosing (Upper Ediacaran and Lower Ordovician) clastic deposits of the northern BSB, which, despite their old age (>500 Myr) remained unconsolidated and show only slight diagenetic modification of their mineral composition, except for clay minerals.

GEOLOGY AND STRATIGRAPHY

The succession of the oldest detrital deposits of the BSB is composed of Neoproterozoic Ediacaran (Vendian Complex), and Lower, Middle and, to a lesser extent, of Furongian sediments (Fig. 2). Crystalline basement of the Palaeoproterozoic age is gradually sloping 2–4 m/km towards the south (Fig. 1). The Neoproterozoic Ediacaran deposits are on average 60 m thick (maximum 123 m). In Estonia these deposits are represented by light grey to reddish, mica-rich, quartz-feldspar sandstones and siltstones alternating with clay in the lower part of the succession (Gdov Formation), passing up the section into 80 m thick, laminated grey claystones alternating with light-coloured very fine-grained sand- or siltstones assigned to the Kotlin Formation. The upper portion of the Ediacaran Complex is composed of multicoloured siltstones and clays that form the regressive part of the sedimentation cycle, represented by Voronka Formation (Mens and Pirrus, 1997*a*).

The lowermost part of the Cambrian, attributed to Rovno and Lontova stages, rests unconformably on the Ediacaran in the eastern part of the basin and the crystalline basement in the west. Deposits of the Rovno and Lontova stages represent respectively two transgressive-regressive cycles of normal marine sediments composed in the lower parts of sandstones with gravel inter-layers, grading upwards into clay, slightly coarsening in the uppermost parts of the succession (Rozanov and Łydka, 1987). The uppermost part of both stages are truncated and regressive sediments are only partly preserved (Mens and Pirrus, 1997*a*).

Similarly to the Ediacaran, the lowermost Cambrian was deposited in the western periphery of the Moscow Palaeobasin (Jankauskas, 1994). Sediments of the Rovno Stage are present only in East Latvia and East Lithuania. Lontova Clays (Lontova Formation) and shallow-water sandstone-siltstone equivalents

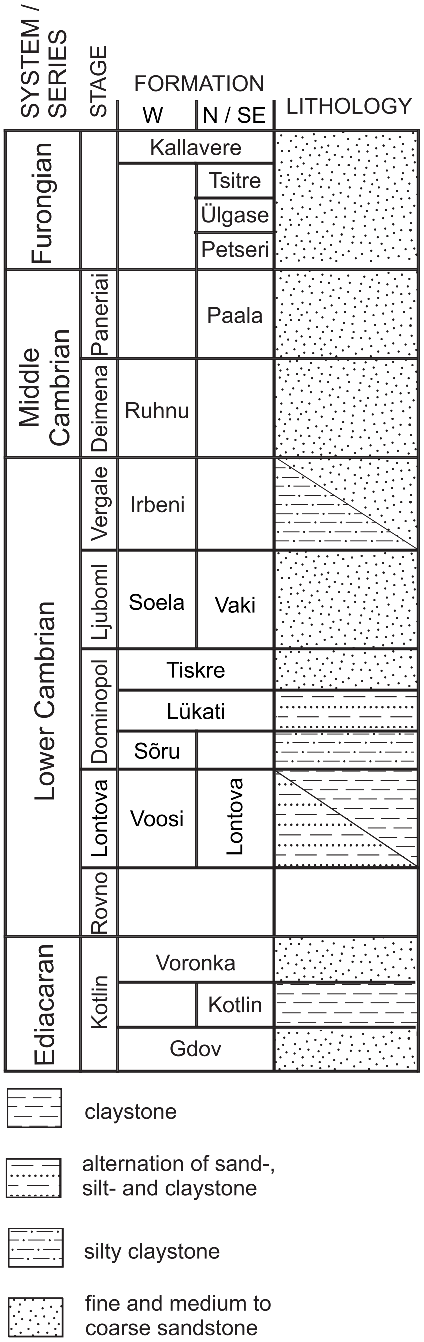

Fig. 2. Stratigraphy and lithology of the Cambrian and Ediacaran in western and northern/southeastern Estonia, northern Baltic Sedimentary Basin (Mens and Pirrus, 1997*a*, modified)

(Voosi Formation) of up to 90 m thickness are more widely distributed, reflecting the transgression in the basin.

The Dominopol Stage marks a significant rearrangement of the sedimentation pattern that was controlled by invasion of the new marine basin from the west in the middle Lower Cambrian. The Dominopol Stage sediments are distributed in the central part of the Baltic Sea and extend to West Estonia and north-west Latvia. They are composed of alternating arenaceous and argillaceous sediments (Sõru, Lükati and Tiskre formations), usually 10–20 m thick (Rozanov and Łydka, 1987). Sediments of the Ljuboml, Vergale and Rausve stages of the late Early Cambrian, and Kybartai, Deimena and Paneriai stages of the Middle Cambrian mark the maximum transgression of the Cambrian basin. In the northern BSB these stages are composed of interbedded silty sandstones and claystones attributed to the Soela and Irbeni formations. Middle Cambrian deposits are represented by 10–40 m thick well-sorted quartz-arenaceous sandstones in the eastern part of Estonia (Paala Formation) and by silty sandstones with clayey inter-layers in the west (Ruhnu Formation). Quartz sandstones of Late Cambrian age, defined as Petseri, Ülgase, Tsitre and lower portion of Kallavere formations, are only occasionally distributed in the northern and southeastern part of the basin, where their thickness is commonly 2–3 m. Furongian sediments are also mapped in the southwestern part of the BSB.

The Baltica continent was located in high to intermediate southerly latitudes (50–30°) during Vendian and Cambrian times; it was surrounded by the Tornquist Sea and the Iapetus Ocean to the west (Torsvik *et al*., 1992). Weathering and erosion of the Ediacaran sediments as well as the igneous and metamorphic rocks of the craton have been considered as the source of material for the uppermost Ediacaran and Cambrian deposits (Pirrus, 1970; Mens, 1981; Jankauskas, 1994).

Towards south, Ediacaran and Cambrian sediments are increasingly buried under younger sediments (Nikishin *et al*., 1996). The subsidence of the basin was most intense during Silurian and Devonian times (McCann, 1998; Poprawa *et al*., 1999). In the northern part of the basin the sediments of post-Silurian/post-Devonian age are missing and the reconstruction of the basin history is based on the thermal maturity of the organic matter (e.g. Hagenfeldt, 1996), apatite fission track analysis (e.g. Zeck *et al*., 1988; Larson *et al*., 1999), tectonic modelling (Samuelsson and Middleton, 1998) and the clay mineral diagenetic transformations (Kirsimäe and Jørgensen, 2000). According to these reconstructions, the burial of the northern periphery of the basin has never exceeded 2 km, whereas reaching 2 km in the basin centre (West Lithuania) and 4–6 km close the Teisseyre-Tornquist Zone in the south-west.

MATERIAL AND METHODS

Mineral, chemical, and grain-size composition of Cambrian, Ediacaran, and Lower Ordovician deposits was investigated in 153 samples collected from 13 boreholes representing different lithofacies of the northern periphery of the BSB (Fig. 1).

The mineralogical composition of sediments was determined by means of X-ray powder diffractometry in whole rock and in the clay (<1 μm) fraction. The X-ray diffractograms were obtained using a *DRON 3M* diffractometer with Ni-filtered Cu$K\alpha$ radiation. Quantitative mineral content in whole rock powders was determined using the Rietveld technique by means of *SIROQUANT-2.5™* (Taylor, 1991) code. The oriented Sr^{2+} exchanged clay preparations were obtained by smearing of clay on a glass slide. Conventional treatments with solvation in ethylene glycol (EG) vapour (60°C, 48 h) and occasionally a heat treatment (525°C, 2 h) were used to verify the mineral identification and estimate their semi-quantitative proportions. Clay mineral identification criteria were based on Moore and Reynolds (1989). The air-dried (AD) and ethylene glycol EG XRD curves of <1 μm subfractions were decomposed in the 5–14°2θ region into elementary XRD bands according to the criteria given by Lanson (1997) with AXES code (Mändar *et al*., 1996). The smectite layers content in mixed-layer illite-smectite was estimated from peak position in 33–35°θ region after EG solvation according to Środoń (1984) and from low-angle peak position of illite-smectite mineral on AD patterns according to Lanson (1997). The results from both methods agree within ±5% of smectite layers. In order to estimate the semi-quantitative mineral composition, peak integral intensities of chlorite (14 Å), mixed-layered illite-smectite (10.5–14 Å), illite (10–10.5 Å) and kaolinite (7 Å peak after decomposition into chlorite and kaolinite elementary peaks), were multiplied by factors of 1, 0.35, 2, 1.4 (Kalm *et al*., 1997), respectively. Illite content was found as the sum of poorly crystalline and well crystalline diffraction bands integral intensities. The estimated accuracy for major clay mineral phases in clay fraction is not better than ±20% and probably much less for minor components. Selected samples were observed under a scanning electron microscope using *Zeiss 940D SEM*.

The trace and major elements of 151 rock samples were determined by X-ray fluorescence spectroscopy in All-Russian Geological Institute, St.-Petersburg (Russia), following standard procedures. The rock powders were analysed in Li-tetraborate homogenized pellets. The loss on ignition (LOI) was estimated by heating the pre-dried samples (1h at 105°C) for 2 h at 920°C. The grain-size of selected sandstone and claystone lithologies was determined by using standard sedimentation and sieve analysis. The samples were dispersed in distilled water with sodium hexametaphosphate with help of short ultrasonic treatment (70 W, 2–5 min) for partly cemented sandstones. Petrophysical properties (effective porosity, wet, dry and grain densities) were measured on samples cut as cubes 24 mm. Due to generally loose and uncemented nature of rocks, only 51 samples were measured for the porosity by weighing in water and air (after drying at 105°C). The water-saturation was achieved by soaking under vacuum.

RESULTS AND DISCUSSION

GRAIN-SIZE

The grain-size of Cambrian rocks ranges from clays and very fine-grained siltstones to fine grained sandstone lithologies. The Lontova and Lükati formations are dominated by clays (Fig. 3A) with fine-to-medium silt grain-size siltstone intercalations. The succession has a bimodal grain-size distribution with two maxima in the clay and medium silt fractions, which has been interpreted as modes representing suspension load material and clay mineral flocs/aggregates, respectively (Kirsimäe *et al*., 1999*b*). Sandstones are predominantly clean quartz arenites (subarkoses) with no or little clay admixture (<5%) (Fig. 3B, D). The sandstone grain-size is predominantly fine-to-medium sand, but occasionally beds with coarse sand to gravel-size grains are distributed in the lower part of the section. The sorting of sandstones is moderate-to-(very) high with bimodal pattern in alternating clayey siltstone sections; detrital quartz grains are subrounded-to-rounded. Abundance of sandstones increases to the west.

POROSITY

Porosity of sandy lithologies varies from 20–25% in northernmost part of the basin to less than 5% and in deeply buried sections in West Lithuania (Fig. 4). The shallow reservoirs in the northern periphery of BSB show the most considerable

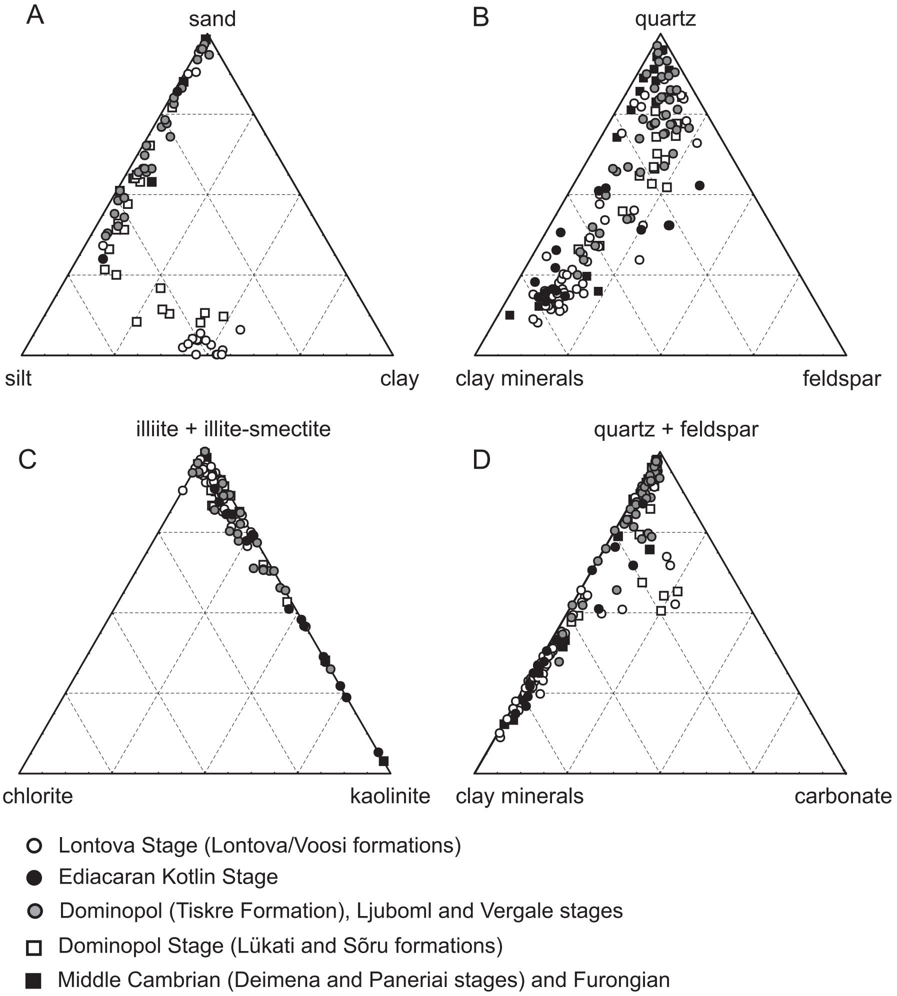

Fig. 3. Grain-size (A) and mineralogical (B and D), composition of whole rock and clay mineral composition of <1 μm fraction (C)

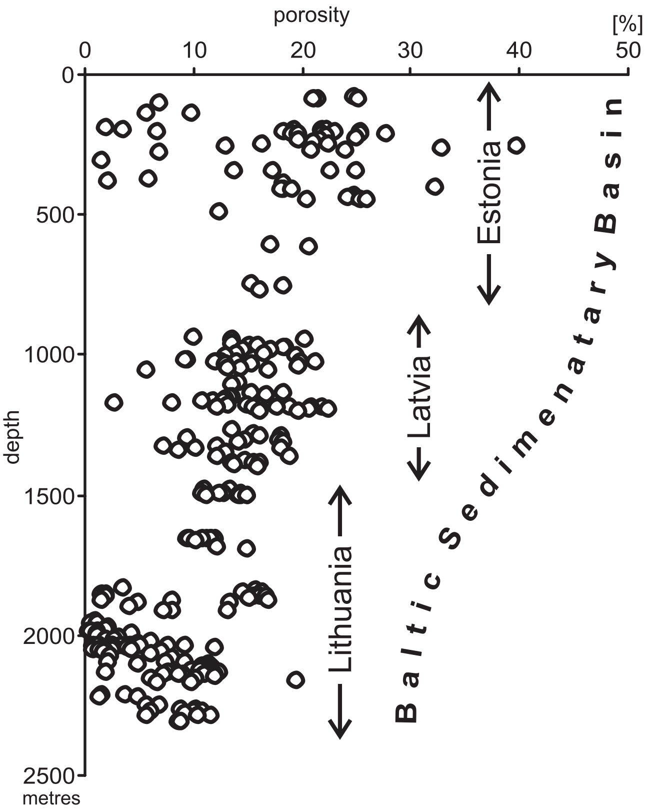

Fig. 4. Porosity of Cambrian terrigenous sediments in Baltic Sedimentary Basin

Note a considerable variation in shallowly buried Estonian part of the basin; the data for Latvia and Lithuania from Šliaupa *et al*. (2001) and Jõeleht *et al*. (2002)

variations in porosity that is accounted for mainly by uneven calcite and dolomite cementation (18–26% of rock), which locally leads to decrease of the porosity to less than 5%. The minimum values were reported from sandstones and siltstones cemented by calcite and phosphate, where the pore space is reduced to 2%. The porosity of clay and mudstone lithologies in the northern part of the basin is commonly in the range of 20–25(30)%.

At greater depths (e.g. Latvia and Lithuania) porosity of sandstones and siltstones systematically decreases to 10–20% at 1–1.8 km and 2–5% at the depths of 2–2.3 km, which is explained by the intense chemical compaction and occurrence of secondary quartz (Šliaupa *et al*., 2001; Jõeleht *et al*., 2002). The bulk porosity of claystones changes from 16–20% at the depths of 0.6–0.8 km to 4–12% in West Lithuania (Šliaupa *et al*., 2001).

WHOLE-ROCK MINERAL COMPOSITION

The whole-rock composition of the Cambrian deposits in northern BPB (Fig. 3B, D) shows distinct age and lithology controls. The greenish-gray claystones of the Lontova and Lükati formations are composed of illite, illite-smectite, and, in smaller quantities, also chlorite and kaolinite; clay minerals compose 45–70% of the rock. The illite and mixed-layer mineral illite-smectite are the predominant clay minerals comprising up to 45 and 25% of a rock volume. The amount of clay minerals defined as the sum of measured clay minerals decreases to <20% in Tiskre Formations and in western facies (Voosi Formation), though locally increases up to 35–50% in clay-rich interlayers within silt- and sandstone dominated facies. The illite and illite-smectite are the most abundant clay minerals (Fig. 3C), although in sandstones, where the clay mineral content is less than 10%, the kaolinite may dominate over illite and illite-smectite (e.g. Paala Formation).

Sandstones of the Cambrian and lowermost Ordovician are dominantly quartz arenites and subarkoses. The quartz content in Tiskre and Paala sandstones attains >90%, with an average of 47% for all samples studied (including claystone lithologies). The feldspars are almost exclusively K-feldspars (1–34%, on average 12%), with subordinate (<5%, usually close to 1%) amounts of albite. Content of mainly authigenic apatite (shell detritus of phosphatic brachiopods) and pyrite and/or hematite is on average close to 1% or less. The lithic fragments have not been found in the sediment.

The authigenic carbonate minerals are represented mostly by Fe-rich dolomite, which is found in most samples. Its content is in the range of 0–29% with average about 3%. Also, calcite and siderite cements are occasionally reported (up to 19 and 8% of rock, respectively). Siderite is present only in Ruhnu borehole (southwestern Estonia). Calcite is more abundant than siderite, but its content only occasionally exceeds 1%. The highest dolomite content (10–20%) is identified in silty sandstones at contacts with clays of the Lontova Formation and in sandy-silty interlayers within the claystones and also close to the overlying Ordovician carbonates. Petrographic observations indicate mainly poikilotopic type of the patchily or uniformly distributed cements. Paragenetic relationships suggest dolomite formation during latest phases of diagenesis although in some cases simultaneous precipitation with authigenic clay minerals cannot be excluded.

Whole rock composition of Ediacaran deposits is similar to Cambrian lithological equivalents. The sandstone-dominated Gdov and particularly Voronka formations are rich in quartz (>30%) and feldspar (in average 4–10%). The composition of clay minerals of the Kotlin Formation is dominated by illite and illite-smectite, whereas clay minerals of Gdov and Voronka formations are considerably richer in kaolinite.

WHOLE ROCK CHEMICAL COMPOSITION

The chemical composition of main oxides of the whole rock (Fig. 5) agrees with the mineral composition. The amount of SiO_2 varies from 48–98%, with the average 77%; its content correlates closely with the quartz content. Al_2O_3 variations are controlled by abundance of clay minerals, and in lesser amount, by K-feldspar. In clayey layers the amount of Al_2O_3 varies between 17 and 27%, whereas layers richer in quartz tend to have less than 5% of Al_2O_3. Similar distribution is obtained for K_2O, abundance of which is <1% in the quartz arenitic sandstones of the Tiskre Formation and up to 7% in homogenous clays (average 4%). TiO_2 is also more abundant in the clayey rocks (about 1%). Of Fe-oxides the Fe_2O_3 predominates (0.1–8.5%), whereas FeO amounts to 0.1–6.5%. Similarly to Al_2O_3 and

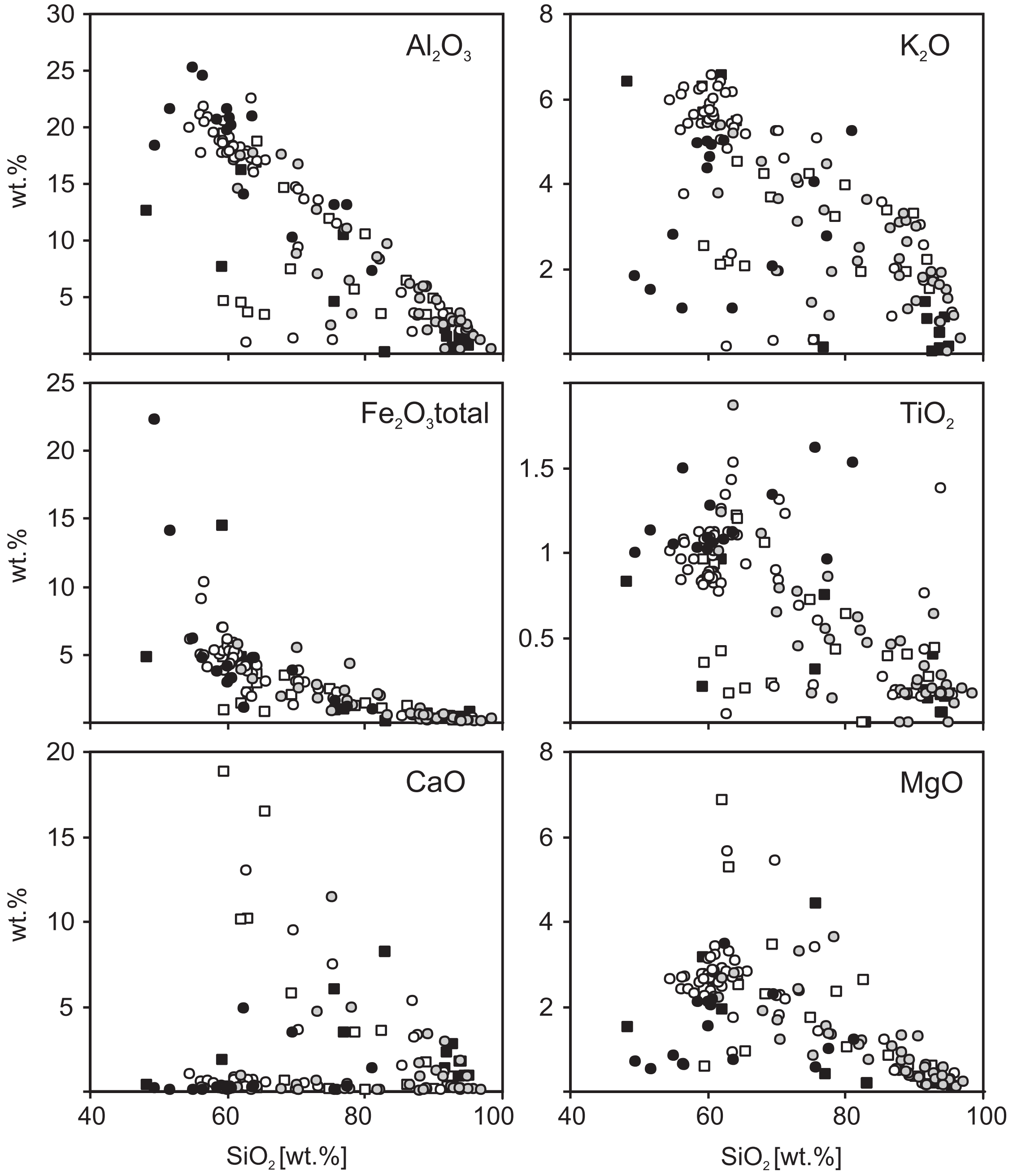

Fig. 5. Harker variation diagrams for studied samples

For explanations see Figure 3

K_2O, the Fe-oxides are more abundant in clayey rocks. Amounts of CaO and MgO are commonly less than 0.5% and 2.5%, respectively. CaO and MgO concentrations are considerably higher in the quartz-rich inter-layers comprised by clays (essentially in the Lontova Formation), which is related to the occurrence of a carbonate cement, mainly dolomite.

There is between 0.79 and 2.56% of organic matter in the Cambrian clays. In addition to the Lontova Formation it has been found in the Petseri and Paala formations (also in samples rich in quartz), and in the Ediacaran Gdov Formation. The $\delta^{13}C$-values of the organic matter are about –31‰ VPDB (Bityukova *et al.*, 2000), which is quite characteristic for organic matter of the Cambrian origin (Schidlowski, 1988), and typical for dispersed organic matter of sapropelitic type of Cambrian sedimentary rocks (Sidorenko and Sidorenko, 1975).

CLAY MINERALOGY

The clay minerals found in the studied rocks include illite, chlorite, kaolinite and illite-smectite mixed layered minerals. Figure 6 shows the typical XRD diffraction curves for the oriented samples of clay (<1 μm) fraction of the Cambrian rocks. The illite, with its strong 10.5 and 3.3 Å peaks is aluminous and dioctahedral. The low-angle slope of the 10 Å peak shows the presence of an ordered I-S phase. Treatment with EG caused a

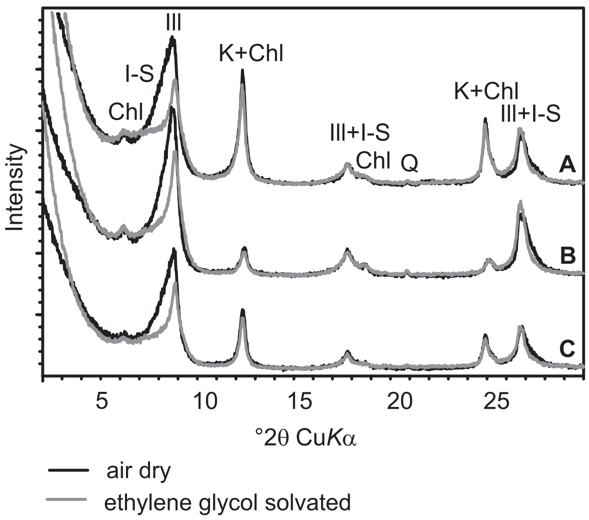

Fig. 6. Representative XRD patterns of the oriented clay fraction (<1 µm) of Cambrian rocks

A — Soela Formation, sample R-06, Ruhnu core; B — Lükati Formation, sample Vh-03, Vthma borehole; C — Lontova Formation, sample F270-09, F270 (Vaemla) borehole; Chl — chlorite, I-S — illite-smectite, Ill — illite, K — kaolinite, Q — quartz

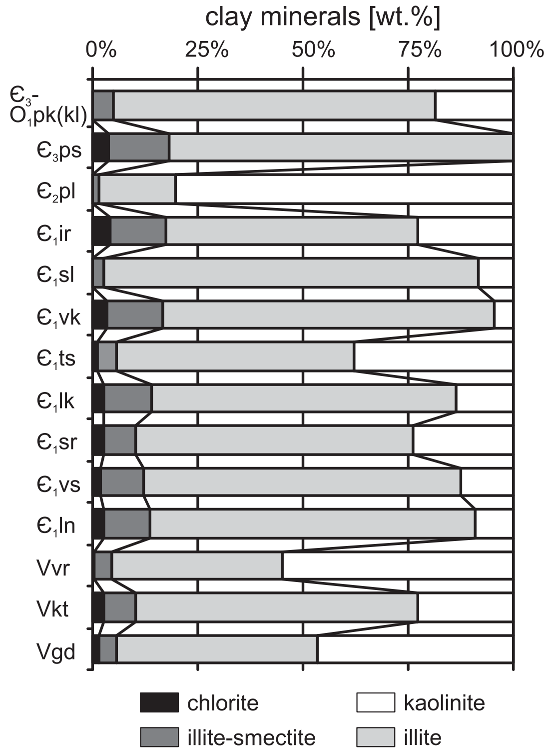

Fig. 7. Average clay mineral composition in <1 µm fraction of the sections studied

Vgd — Gdov Fm., Vkt — Kotlin Fm., Vvr — Voronka Fm., ∈ ln — Lontova Fm., ∈$_1$vs — Voosi Fm., ∈$_1$sr — Stru Fm., ∈$_1$lk — Lükati Fm., ∈$_1$ts — Tiskre Fm., ∈$_1$vk — Vaki Fm., ∈$_1$sl — Soela Fm., ∈$_1$ir — Irbeni Fm., ∈$_2$pl — Paala Fm., ∈$_3$ps — Petseri Fm., ∈$_3$-O$_1$pk(kl) — Kallavere Fm. (see Fig. 2 for stratigraphy)

clear reduction in intensity of the 10 Å peak and the highly illitic I-S phases show weak and broad reflection in 12–13 Å region. Smectite layer percentages in illite-smectite are in the range of 10–25%. The ordering type of I-S is on the transition from R1 to R2 type. Chlorite in the Cambrian sediments was found to be Fe-rich, which is indicated by *d00l* peak intensity ratios on decomposed patterns. The kaolin mineral is rather well crystallized and is recognized in unoriented preparations as the kaolinite polytype. In addition to clay minerals the clay fractions contain quartz, K-feldspar, albite, hematite and traces of anatase and dolomite.

The semi-quantitative clay mineral composition of the studied rocks is shown in Figures 3C and 7. Sediments are composed of illite(I-S)-kaolinite-chlorite or kaolinite-illite(I-S)-(chlorite) clay-mineral assemblages. The clay assemblages of Ediacaran Gdov and Kotlin Formation clay-, silt- and sandstones are dominated by illitic minerals (illite and I-S in average 52 and 75%, respectively) with kaolinite (in average 47 and 23%, respectively) (Fig. 7). The Ediacaran Voronka Formation is significantly richer in kaolinite, which comprises 55% of clay fractionin in average.

The clay mineral composition of Lontova/Voosi formations, as well as of the overlying Lükati Formation of Estonia is characterized by an illite-kaolinite-chlorite assemblage. Illite and I-S are the most abundant clay minerals, whereas the content of kaolinite and chlorite is usually less than 30%. The average content of illitic minerals in all three formations ranges from 84 and 86% in Lükati and Voosi formations up to 89% in the Lontova Formation. The higher kaolinite content is in the upper and lower parts of the section reaching maximum 26% of the clay minerals in Lontova/Voosi formations and up to 33% in the Lükati Formation (Fig. 3C). However, the average kaolinite content in Lontova/Voosi and Lükati formations is 9 and 13, and 12%, respectively (Fig. 7). The highest kaolinite value (54%) in Lontova/Voosi sediments was found in a sample of the weathering crust of the Lontovan clays in Värska core. In comparison to the Lontova/Voosi and Lükati formations, clayey silt- and sandstones of the Sõru Formations contain more kaolinite, whose average content is 24%, but it can vary greatly. The increase in kaolinite content is characteristic also for the remaining sediments of upper part of the Lower and Middle Cambrian that generally are dominated by sandy lithologies (Fig. 7). The maximum kaolinite content (65–96%) was found in medium- to coarse-grained sandstones of the Middle Cambrian Paala Formation. The Furongian and the overlying Lower Ordovician sediments are dominated by illitic clay mineral association (>80%) with small amount of chlorite and kaolinite.

Some lateral trends are identified in clay mineral composition. The kaolinite content is higher in western and southwestern sections in all three major stratigraphic units studied. The clay-rich silt- and sandstones and clays of East and Central Estonia are dominantly illitic, whereas the quartzose siltstones and sandstones, which are more frequent in Western Estonia, are more rich in kaolinite. The similar tendency is recognized up the section. The ratio of illitic minerals to kaolinite within particular formation varies greatly depending on a lithological composition as illustrated by the well Metsküla (Fig. 8), where the upper and central parts of the Lontova section are rich in clay and illitic, whereas the lower part dominated by siltstones and sandstones contains relatively more kaolinite.

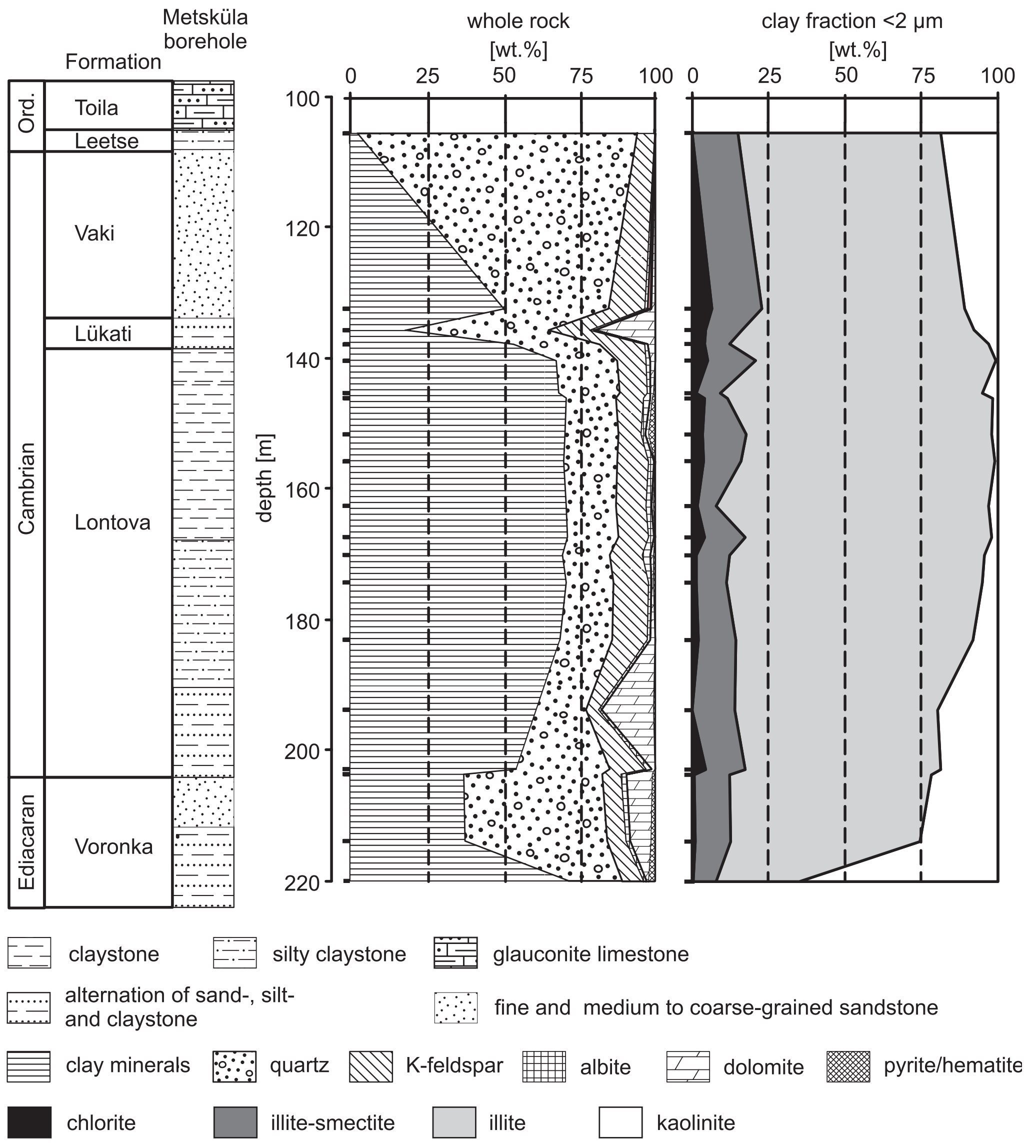

Fig. 8. Whole-rock and clay fraction mineralogy in Metsküla borehole

Similarly to Estonian sections, Lontova clayey layers of East Lithuania are dominated by illite (60%) with the second major mineral kaolinite, content of which decreases up the section (Cyziene *et al*., 2005). Smectite content in illite-smectite does not exceed 10%. In this part of the basin, illite dominates both in clayey and sandy lithologies with some admixture of kaolinite and chlorite.

DIAGENETIC TRANSFORMATION OF THE SEDIMENTS

COMPACTION AND CARBONATE CEMENTATION

The extent of a compaction in the BSB depends on the burial history of the sediments. The average porosity of well-sorted sandstones and siltstones in the northern part of the BSB, where the estimated maximum burial depth is on the order of 1–1.5 km (Kirsimäe and Jõrgensen, 2000), is commonly in the range of 18–25%. The porosity decreases with the burial depth to 3–8% in southwestern part of the basin (SW Lithuania) at present burial depth of >2 km, which is mainly attributed to chemical compaction (e.g. Kilda and Friis, 2002). The porosity of an average (standard) sandstone at the depths of 1.5–2.5 km is reduced by mechanical compaction to about 25% (Einsele, 1992). The mechanical compaction dominates in Cambrian and enclosing clastic deposits of the northern periphery of the basin. Sediments are very loosely cemented and only scarce secondary carbonate cementation with rare occurrences of quartz cementation (Kaisa Mens, 2004, pers. comm.) occurs. The carbonate cementation is most abundant in the fine-grained sandstone and siltstone lithologies and it is spatially related to the lithological contacts with the mud(clay)stones and/or overlying Ordovician carbonates. Cements are usually represented by Fe-rich dolomite, in a few cases also by siderite and calcite. Interestingly, the dolomite cementation is typical only in rocks with a quartz/clay mineral ratio of about 2 to 3. Dolomite content is lower both in more clay-rich samples (claystones) and in quartz-rich samples (clean sandstones) (Fig. 3D).

Carbonate cementation of siliciclastic rocks may commence at very early stages of diagenesis influenced by marine or mixed marine-meteoric waters, or anoxic pore-waters in which the dissolved sulphate ions were removed by bacterial reduction (Baker and Kastner, 1981). The marine water environment, related to compaction fluid flow, was established for carbonate cement precipitation from stable carbon isotope studies in the southern periphery of the BSB (Schleicher, 1994). At the later stages of diagenesis the carbonate precipitation could have occurred in pore-waters where pH was buffered by alumosilicate equilibrium or by organic acids and the excess CO_2 derived from thermal oxidation of organic matter was eliminated by simultaneous carbonate precipitation (Smith and Ehrenberg, 1989). However, in northern part of the basin the dispersed organic material in Cambrian sediments is in an immature state (Talyzina, 1998) and we suggest that dolomite cementation results from ions released during the illitization. This process has enhanced the secondary dolomite precipitation preferentially close to the claystone-silt/sandstone interfaces, although also the early diagenetic marine-fresh water mixing and/or sulphate reduction could have contributed to a formation of carbonate minerals at earlier stages of diagenesis.

The carbonate cementation and also the growth of secondary quartz is more important in the southern and southwestern part of the basin, where the present burial depths of the Cambrian sediments considerably exceeds 1000 m (Kilda and Friis, 2001; Shogenova *et al*., 2001). Widespread secondary quartzose cementation in southwestern Latvia and West Lithuania is attributed to local silica sourcing induced by quartz dissolution and precipitation under deep burial conditions (Laškova, 1994; Vosylius, 1997). The occurrence of quartz cement is associated with decrease in carbonate cement content in Cambrian sandstones.

FORMATION OF KAOLINITE

Kaolinite content in the clay fraction of Cambrian sediments varies from traces up to 80–90% of clay minerals volume. In homogenous claystones-shales the kaolinite is probably of clastic origin, whereas in permeable sandstones and coarse-grained mudstones the kaolinite can be mostly authigenic (Bjørlykke, 1998). The latter is suggested by a higher proportion of the kaolinite in the clay fraction of the northern BSB in sand- and siltstone dominated bodies of both Early-Middle Cambrian, and Ediacaran age. High crystallinity and well-defined sharp-edge hexagonal morphology of crystallites and, specifically, the vermiform occurrence of kaolinite aggregates, suggests its authigenic origin (Fig. 9). The same features are reported from the Lower and Middle Cambrian section of Latvian (Brangulis, 1985). The authigenic kaolinite may form at the expense of detrital mica and/or K-feldspar (Bjørlykke and Brendstal, 1986) at the very early diagenesis stage at temperatures as low as 25–50°C (Osborne *et al*., 1994) and mostly at depths shallower than 100 m (Bjørkum *et al*., 1990). In this case, the kaolinitization is preferential in permeable sandstones, where the process is controlled by H^+ supply and the K^+/H^+ activity ratio, whereas relatively high water fluxes are required for the sediment pore-water to remain in the stability field of the kaolinite (Bjørlykke, 1998). Considering the present state of knowledge, it is difficult to estimate the time for kaolinite formation. Reconstructions of the palaeohydrogeological conditions in the BSB (Mokrik, 1997) show at least three major episodes of meteoric fresh-water infiltration, which could account for kaolinitization: late Middle Cambrian and Late Cambrian, Early Devonian and Permian-Cenozoic. The last was the period of the most prominent uplift and erosion.

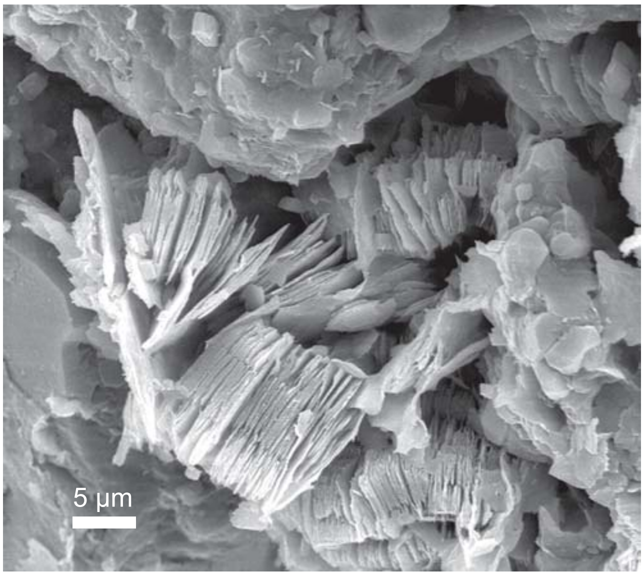

Fig. 9. SEM image of vermiform kaolinite aggregates in clayey sandstone, Lower Cambrian, Lontova Formation

SMECTITE-TO-ILLITE TRANSFORMATION AND DIAGENETIC CHLORITES

The Cambrian clays of the northern part of the BSB are typically soft (non-unlithified) sediments. The well-preserved pale-transparent acritarch palynomorphs show negligible thermal alteration (Talyzina, 1998) indicating the maximum palaeotemperatures less than 50°C in the northern part of the basin. Low palaeotemperatures and present burial depths within first hundred metres are in conflict with the high illitic layers content in illite-smectite amounting about 80–90%, which suggests high diagenetic grade of sediments.

Progressive smectite-to-illite reaction has been widely used in diagenesis studies as a geothermometer showing the diagenetic grade of the sediments (e.g. Pollastro, 1993). The illitization onset temperature is commonly estimated in the range 60–110°C at burial depths over 2–3 km (Hoffman and Hower, 1979), which does not agree with either estimated palaeotemperatures nor burial depths in northern BSB. However, in Central and Eastern Latvia the illite-smectite of Lontova clays contains ~90% of illitic layers, and ~95% of illitic layers in southwestern Lithuania (Kirsimäe, unpubl. data). This is consistent with the increasing burial depth up to >2000 m and high thermal maturity of organic material (R_0 >0.7, Zdanavièiûte, 1997) in the centre of the basin. The question on driving mechanisms of illitization of Cambrian clays in shallowly buried and unlithified claystones in the northern periphery of the basin is up to present unclear. Gorokhov *et al.* (1994) proposed a multistage illite evolution owing to retrograde diagenesis of the sediments. Kirsimäe *et al.* (1999*a*) and Kirsimäe and Jørgensen (2000) suggested a low-temperature slow-rate illitization, whereas Chaudhuri *et al.* (1999) and more recently Clauer *et al.* (2003) associate smectite-to-illite transformation of Cambrian clay of the northern BSB with intrusion of high temperature and/or alkaline K-rich hydrothermal brines at some stage of the basin evolution. K-Ar and Rb-Sr isotope analyses of illite-smectite fractions of Cambrian clays and Ordovician–Silurian K-bentonites from BSB and Pomerania, Northern Poland, show large scatter of diagenetic ages from Late Silurian to Permian (Chaudhuri *et al*., 1999; Kirsimäe and Jørgensen, 2000; Środoń and Clauer, 2001), which does not point to any specific period of transformation. Large scatter of isotope ages of Cambrian clays points in our opinion to a geologically prolonged conversion of smectite to illite-smectite at relatively low diagenetic temperatures or alternatively to multiple diagenetic events, which have not been recognized yet. Irrespective of the smectite-to-illite transformation mechanism the illitization of clayey Ediacaran and Cambrian sediments has probably played an important role in carbonate cementation by releasing Ca, Mg and Fe to adjacent coarser grained sediments, where they have precipitated as carbonate cements (e.g. Wintsch and Kvale, 1994).

Also, the Fe-rich chlorite, which is present in Cambrian clays, is probably related to the smectite-to-illite transformation and it could have been formed as a reaction by product using iron and magnesium released during the illitization. Chlorite content is the highest in homogenous clayey sequences and it appears in two forms: Fe-rich chlorite and traces of Mg-chlorite (Kirsimäe *et al.* 1999*b*). Fe-rich chlorite is typically a diagenetic chlorite (Curtis *et al*., 1985), whereas Mg-chlorite is characteristic for metamorphic environments (Laird, 1988). Chlorite precipitates usually within the precursor smectite or I-S by forming mixed layered chlorite-smectite type mineral (Ahn and Peacor, 1985). The formation of chlorite during illitization is accompanied also by precipitation of secondary microcrystalline quartz, which is characteristic of Cambrian clays in Latvia (Apinite, 1971) and Estonia (Kirsimäe *et al*., 1999*b*). In Cambrian sequences of the southwestern part of the basin specific type of Fe-chlorite-chamosite- is found (Pirrus, 1973, 1986; Laškova, 1979). Chamosite occurs in massive pelitic (clayey) siltstone and is believed to have been formed diagenetically at the expense of kaolinite by intense inflow of iron in the basin (Pirrus, 1973). However, chamosite could have been formed also by the transformation of sedimentary or very early diagenetic berthierine. Berthierine, which may have formed in Cambrian shallow-marine siliciclastic facies together with smectitic glauconite, starts to transform into chamosite at temperatures of ~70°C (Jahren and Aagaard, 1989).

CONCLUSIONS

The siliciclastic Cambrian and enclosing terrigenous Ediacaran and Ordovician sediments in northern BSB are practically unconsolidated and/or weakly cemented. The porosity of Cambrian sediments in the northern part of the basin is about 20–25%. High porosity of the sediment suggests dominating mechanical compaction with only subordinate chemical compaction. The sparse carbonate cement is composed of Fe-rich dolomite and rarely of siderite and calcite. The dolomite cementation of arenitic and subarenitic sand-/siltstones is spatially related to the fine-grained sandstones and siltstones at contacts with the mud(clay)stone lithologies. This suggests that the dolomite cementation has resulted from ion-release during mudstone illitization. Well-advanced smectite-to-illite transformation of Cambrian mudstones has also caused formation of Fe-rich chlorite in homogenous clayey sequences. The sandstone sequences became considerably enriched in authigenic kaolinite, which formed at the expense of detrital mica or K-feldspar, already during the early diagenetic stages.

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REFERENCES

AHN J. H. and PEACOR D. R. (1985) — Transmission electron microscopic study of diagenetic chlorite in Gulf Coast argillaceous sediments. Clays and Clay Miner., **33**: 228–236.

APINITE I. (1971) — Clay material in Cambrian rocks of Latvia. Proceedings of Estonian Academy of Sciences. Geology, **20** (3): 232–238 (in Russian).

BAKER P. A. and KASTNER M. (1981) — Constraints on the formation of sedimentary dolomite. Science, **213**: 214–216.

BITYUKOVA L., BITYUKOV M., SHOGENOVA A., RASTENIENE V., ŠLIAUPA S., ZABELE A., LASHKOVA L., EIHMANIS E., KIRSIMÄE K., JØELEHT A. and HUENGES E. (2000) — Organic matter distribution and variations of isotopic composition of organic carbon in Cambrian siliciclastic rocks in Baltic region. Sediment 2000. 20–23 June, 2000, Leoben, Austria. Mitteilungen der Gesellschaft der Geologie and Bergbauaustudenten in Österreich. Sediment 2000. Kurzfassungen/Abstracts: 27–28.

BJØRKUM P. A., MJRS R., WALDERHAUG O. and HURST A. (1990) — The role of the late Cimmerian unconformity for the distribution of kaolinite in the Gullfaks Field, northern North Sea. Sedimentology, **37**: 396–406.

BJØRLYKKE K. (1998) — Clay mineral diagenesis in sedimentary basins – a key to the prediction of rock properties. Examples from the North Sea Basin. Clay Miner., **33**: 15–34.

BJØRLYKKE K. and BRENDSTAL A. (1986) — Diagenesis of the Brent sandstone in the Statfjord field. In: Roles of Organic Matter in Sedimentary Diagenesis (ed. D. L. Gaultier). SEPM Spec. Publ., **38**: 157–168.

BRANGULIS A. (1985) — Vend i Kembrij Latvij. Zinatne. Riga.

CHAUDHURI S., ŚRODOŃ J. and CLAUER N. (1999) — K-Ar dating of illitic fractions of Estonian "Blue Clay" treated with alkylammonium cations. Clays Clay Miner., **47**: 96–102.

CLAUER N., ZWINGMANN H. and GOROKHOV I. M. (2003) — Postdepositional evolution of platform claystones based on a simulation of thermally induced diffusion of radiogenic Ar-40 from diagenetic illite. J. Sediment. Res., **73**: 58–63.

CURTIS P. M., HUGHES C. R., WHITEMAN J. A. and WHITTLE C. K. (1985) — Compositional variation within some sedimentary chlorites and some comments on their origin. Mineral. Magaz., **49**: 375–386.

CYZIENE J., ŠLIAUPA S., LAZAUSKIENE J., BALIUKEVICIUS A. and SATKUNAS J. (2005) — Characterization of the Lower Cambrian Blue Clays for deep geological disposal of radioactive waste in Lithuania. Geologija, **52**: 11–21.

EINSELE G. (1992) — Sedimentary Basins. Springer-Verlag, New York.

GÓRECKI W., LAPINSKAS P., LASHKOVA L., LASHKOV E., REICHER B., SAKALAUSKAS K. and STRZETELSKI W. (1992) — Petroleum perspectives of the Baltic Syneclise. Pol. J. Miner. Resourc., **1**: 65–88.

GOROKHOV I. M., CLAUER N., TURCHENCO T. L., MELNIKOV N. N., KUTYAVIN E. P., PIRRUS E. and BASKAKOV A. V. (1994) — Rb-Sr systematics of Vendian-Cambrian claystones from the East European Platform: implications for a multi-stage illite evolution. Chem. Geol., **112**: 71–89.

HAGENFELDT S. (1996) — Lower Palaeozoic acritarchs as indicators of heat flow and burial depth of sedimentary sequences in Scandinavia. Acta Universitatis Carolinae. Geologica, **40**: 413–424.

HOFFMAN J. and HOWER J. (1979) — Clay minerals assemblages as low grade metamorphic geothermometers: application to the thrust faulted disturbed belt of Montana, USA. USA SEPM Spec. Publ., **26**: 55–79

JAHREN J. S. and AAGAARD P. (1989) — Compositional variations in diagenetic chlorites and illites and relationships with formation-water chemistry. Clay Miner., **24**: 157–170.

JANKAUSKAS T. (1994) — Vendas. Kambras. Lietuvos Geologija. Mokslo ir enciklopediju ledykla. Vilnius: 30–46.

JØELEHT A., KIRSIMÄE K., SHOGENOVA A., ŠLIAUPA S., KUKKONEN I. T., RASTENIENE V. and ZABELE A. (2002) — Thermal conductivity of Cambrian siliciclastic rocks from Baltic paleobasin. Proceedings of Estonian Academy of Sciences. Geology, **51**: 5–15.

KALM K., KRIISKA A. and ARUVÄLI J. (1997) — Mineralogical analysis applied in provenance studies of Estonian Neolithic pottery. Proceedings of the Estonian Academy of Sciences. Geology, **46**: 16–34.

KILDA L. and FRIIS H. (2002) — The key factors controlling reservoir quality of the Middle Cambrian Deimena group sandstone in West Lithuania. Bull. Geol. Soc. Denmark. Copenhagen, **49**: 25–39.

KIRSIMÄE K., JØRGENSEN P. and KALM V. (1999*a*) — Low temperature illite-smectite in Lower Cambrian clays, North Estonia. Clay Miner., **34**: 151–163.

KIRSIMÄE K., KALM V. and JØRGENSEN P. (1999*b*) — Clay mineral diagenetic transformation in Lower Cambrian argillaceous sediments of norther Estonia. Proceedings of Estonian Academy of Sciences. Geology, **48**: 15–34.

KIRSIMÄE K. and JØRGENSEN P. (2000) — Mineralogical and Rb-Sr isotope studies of low-temperature diagenesis of Lower Cambrian clays of the Baltic Paleobasin of north Estonia. Clays Clay Mineral., **48**: 95–105.

LAIRD J. (1988) — Chlorites: metamorphic petrology. In: Hydrous phyllosilicates (Exclusive of Micas) (ed. S. W. Bailey). Miner. Soc. America, Washington DC. Review. Mineral., **19**: 405–447.

LANSON B. (1997) — Decomposition of experimental X-ray diffraction profile (profile fitting): a convenient way to study clay minerals. Clays Clay Miner., **45**: 132–146.

LARSON S.-C., TULLBORG E.-L., CEDERBROM C. and STIBERG J.-P. (1999) — Sveconorwegian and Caledonian foreland basins in the Baltic Shield revealed by fission-track thermochronology. Terra Nova, **11**: 210–215.

LAŠKOVA L. (1979) — Litologiya, fatsij i kollektorskie svoistva kembrijskih otlozhenij yuzhnoi Pribaltiki. Nedra. Moskva.

LAŠKOVA L. (1994) — Reconstruction of paleotemperatures in Cambrian rocks of the Baltic Syneclise. Geologija, **16**: 43–50.

McCANN T. (1998) — Lower Palaeozoic evolution of the NE German Basin/Baltica borderland. Geol. Magaz., **135**: 129–142.

MENS K. (1981) — Ob ehtapnosti osagkonakopleniya v rannem Kembrij Pribaltiki. Izvestiya Akademij Nauk SSSR. Geologija. **30:** 82–90.

MENS K. and PIRRUS E. (1997*a*) — Cambrian. In: Geology and Mineral resources of Estonia (eds. A. Raukas and A. Teedumäe): 39–48. Estonian Acad. Publ.

MENS K. and PIRRUS E. (1997*b*) — Vendian-Tremadoc clastogenic sedimentation basins. In: Geology and Mineral Resources of Estonia (eds. A. Raukas and A. Teedumäe): 184–191. Estonian Acad. Publ.

MOKRIK R. (1997) — The palaeohydrogeology of the Baltic Basin: Vendian and Cambrian. Tartu University Press, Tartu.

MOORE D. M. and REYNOLDS R.C. (1989) — X-Ray diffraction and the identification and analysis of clay minerals. Oxford University Press. New York.

MÄNDAR H., VAJAKAS T., FELCHE J. and DINNEBIER R. (1996) — AXES — a program for preparation of parameter input files for FULLPROF. J. App. Crystal., **29**.

NIKISHIN A. M., ZIEGLER P. A., STEPHENSON R. A., CLOETINGH S., FURNE A. V., FOKIN P. A., ERSHOV A. V., BOLOTOV S. N., KOROTAEV M. V., ALEKSEEV A. S., GORBACHEV V. I., SHIPILOV E. V., LANKREIJER A., BEMBINOVA E. Y. and SHALIMOV I. V. (1996) — Late Precambrian to Triassic history of the East European Craton — dynamics of sedimentary basin evolution. Tectonophysics, **268**: 23–63.

OSBORNE M., HASZELDINE R. S. and FALLICK A. E. (1994) — Variation in kaolinite morphology with growth temperature isotopically mixed pore-fluids, Brent Group, UK North Sea. Clay Miner., **29**: 591–608.

PIRRUS E. (1970) — The distribution of clay minerals of Vendian and Cambrian Deposits in East Estonia. Proceedings of Estonian Academy of Sciences. Chemistry, Geology, **19**: 322–333.

PIRRUS E. (1973) — Chamosite in Late-Vendian sediments of the Leningrad region. Proceedings of Estonian Academy of Sciences. Chemistry, Geology **22** (1): 58–64.

PIRRUS E. (1986) — The facial peculiarities of the Vergale-Rausve iron ore horizon in the Baltic Syneclise. In: Vendian and Cambrian Facies and Stratigraphy of the Western Part of East-European Platform. Acad. Sc. Estonian S.S.R.: 99–109.

POLLASTRO R. (1993) — Considerations and applications of the illite/smectite geothermometer in hydrocarbon-bearing rocks of Miocene to Mississippian age. Clays Clay Miner., **41**: 119–133.

POPRAWA P., ŠLIAUPA S., STEPHENSON R. and LAZAUSKIENE J. (1999) — Late Vendian-Early Palaeozoic tectonic evolution of the Baltic Basin: regional tectonic implications from subsidence analysis. Tectonophysics, **314**: 219–239.

ROZANOV A.Y. and ŁYDKA K. eds. (1987) — Palaeography and lithology of the Vendian and Cambrian of the western East-European Platform. Warsaw: Wyd. Geol.

SAMUELSSON J. and MIDDLETON M. F. (1998) — The Caledonian foreland basin in Scandinavia: constrained by the thermal maturation of the Alum Shale. GFF, **120**: 307–314.

SCHIDLOWSKI M. (1988) — A 3800-million-year isotopic record of life from carbon in sedimentary rocks. Nature, **333**: 313–318.

SCHLEICHER M. (1994) — Sedimentologie, Diagenese und Muttergesteinsbewertung der kambrischen Siliziklastika in Nord- und Südostpolen.- Clausthaler Geowissenschaftliche Dissertationen, Clausthal-Zellerfeld, **43**.

SHOGENOVA A., KIRSIMÄE K., BITYUKOVA L., JØELEHT A. and MENS K. (2001) — Physical properties and composition of cemented siliciclastic Cambrian rocks, Estonia. Res. Petrol. Technol., **5**: 123–148.

SIDORENKO S. A. and SIDORENKO A. V. (1975) — Organitseskoe vetsestvo v osadotsno-metamorfitseskih porodah dokembriya. Nauka, Moskva.

SMITH J. T. and EHRENBERG S. N. (1989) — Correlation of carbon dioxide abundances with temperature in clastic hydrocarbon reservoirs: relationships to inorganic chemical equilibrium. Mar. Petrol. Geol., **6**: 129–135.

ŚRODOŃ J. (1984) — X-Ray Powder Diffraction Identification of Illitic Materials. Clays Clay Miner., **32**: 337–349.

ŠLIAUPA S., RASTENIENŹ V., LAŠKOVA L. and SHOGENOVA A. (2001) — Factors controlling petrophysical properties of Cambrian siliciclastic deposits of central and western Lithuania. Res. Petrol. Technol., **5**: 157–180.

TAYLOR J. C. (1991) — Computer programs for standardless quantitative analysis of mineralsls using the full powder diffraction profile. Powder Diffraction, **6**: 2–9.

TALYZINA N. M. (1998) — Fluorescence intensity in Early Cambrian acritarchs from Estonia. Rev. Paleobot. Palynol., **100**: 99–108.

TORSVIK T., SAMETHURST M., VAN DER VOO R., TRENCH A., ABRAHAMSEN N. and HALVORSEN E. (1992) — Baltica. A synopsis of Vendian-Permian palaeomagnetic data and their palaeotectonic implications. Earth-Science Rev., **33**: 133–152.

VOSYLIUS G. (1997) — Silicification of Middle Cambrian rocks and geothermal anomaly (in Lithuanian with English summary). Lithosphere, **1**: 73–75.

WINTSCH R. P. and KVALE C. M. (1994) — Differential mobility of elements in burial diagenesis of siliciclastic rocks. J. Sediment. Res., **A64**: 349–361.

ZDANAVIÈIÛTE O. (1997) — New data on thermal maturity of organic matter in source rocks. Lithosphere, **1**: 76–79.

ZECK H. P., ANDRIESSEN P. A. M., HANSEN K., JENSEN P. K. and RASMUSSEN B. L. (1988) — Paleozoic paleo-cover of the southern part of the Fennoscandian Shield — Fission track constraints. Tectonophysics, **149**: 61–66.