Mean grain size fluctuations of the siliciclastic component in the Aizpute-41 core: implication for end-Ordovician glaciation

Enli Kiipli, Sven Siir, Toivo Kallaste and Tarmo Kiipli

Institute of Geology at Tallinn University of Technology, Ehitajate tee 5, 19086 Tallinn, Estonia; enli.kiipli@ttu.ee

Received 21 May 2014, accepted 6 October 2014

Abstract. The article deals with grain size distribution of the insoluble residue of Upper Ordovician carbonate rocks of the Baltoscandian Basin in the West Latvian Aizpute-41 core. Great fluctuations in mean grain size in the sections of the Pirgu (uppermost Katian) and Porkuni (Hirnantian) stages are considered as indications of eustatic sea level fluctuations, pointing to the glaciation in the Hirnantian and its prelude in Pirgu time. An alternative cause of grain size fluctuations might be the up-and-down tectonic movements. Nevertheless, the synchronicity of cessation of fluctuations with the end of the Hirnantian glaciation supports the glaciation-related reasons.

Key words: Ordovician, Katian, grain size, Baltoscandian Basin.

INTRODUCTION

The start of the end-Ordovician glaciation at the South Pole is usually related to the beginning of the Hirnantian at 445.2 Ma (www.stratigraphy.org). This time exhibits the greatest faunal changes, disappearance of many taxa and spreading of cosmopolitan Hirnantian fauna. The $\delta^{18}O$ measured from marine fossils increases, indicating a rapid decrease in temperature at the beginning of the Hirnantian (Trotter et al. 2008). The $\delta^{18}O$ excursion coincides with the positive excursion of carbon isotopes (Brenchley et al. 1994; Kaljo et al. 2007; Bergström et al. 2010, 2014). Many researchers have studied the history of glaciations in Africa and distinguished several glaciation events during the Upper Ordovician (Loi et al. 2010; Videt et al. 2010). The Hirnantian glaciation lowered the sea level about 150 m compared to the Middle Katian, whereas several eustatic fluctuations preceded the Hirnantian culmination.

The present study is based on the grain size of the siliciclastic component of sedimentary rock of the Pirgu (Katian) and Porkuni (Hirnantian) stages in the West Latvian Aizpute-41 core. We discuss the factors controlling the grain size distribution in this section. The variability of grain size may reflect transgressions and regressions of the sea related to the waxing and waning of ice sheets. One reason for grain size variability may be tectonic movements, as intense tectonic events occurred at the western borders of the Baltica Plate during the Upper Ordovician.

THE GEOLOGICAL BACKGROUND

The Aizpute-41 (further referred to as Aizpute) borehole is located in western Latvia, in the deeper shelf part of the Eastern Baltoscandian Basin, within the Jelgava Depression or 'Livonian Tongue' (Fig. 1). The Baltoscandian Basin was open to the Iapetus and Tornquist oceans during the Ordovician. The streams and rivers from the low mainland of the Fennoscandian and Ukrainian shields carried terrigenous material to the adjacent sedimentary basin. The shallowest facies are very likely eroded away, as sand fraction is scarce in coastal zones in the northeastern part of the Baltoscandian Basin in Estonia. An exception is the Hirnantian where fine sand is common. The shoreward facies are mainly represented by limestones and marlstones, which are replaced by more clayey rocks in deeper-water areas. In the late Sandbian (457 Ma) the first phases of the Baltica–Avalonia collision brought along large amounts of volcanic material and caused tectonic movements in the Baltoscandian Basin and adjacent regions. Currents from the Rügen area delivered chromium to the Eastern Baltoscandian Basin (Kiipli et al. 2009), derived from the erosion of emerged greywackes. Old shear zones in the eastern part of the basin revived, causing downward movement of the Jelgava Depression and uplift of the shallow shelf areas (Ulst et al. 1982; Nestor & Einasto 1997). The Middle Lithuanian Depression formed during the Ordovician and expanded westwards in the Silurian (Ulst et al. 1982; Paškevičius 1997). The connection

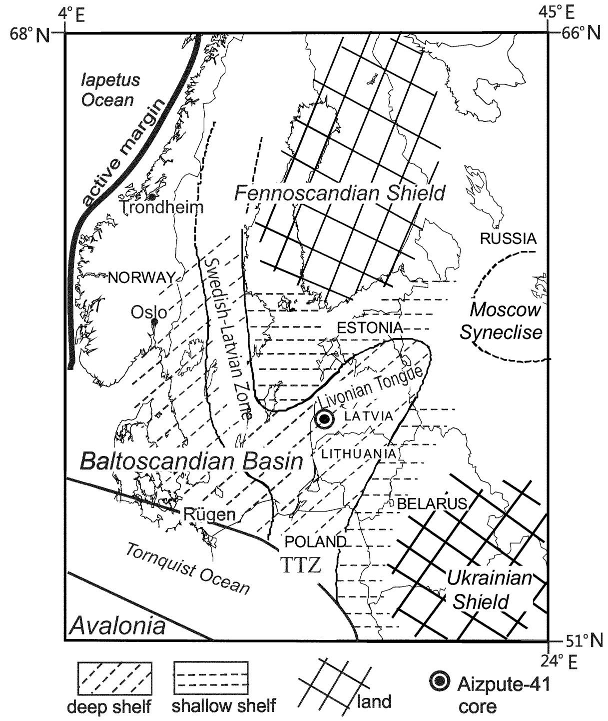

Fig. 1. Location of the Aizpute-41 drill core and schematic Late Ordovician palaeogeography. TTZ, Teisseyre–Tornquist Zone.

between the Baltoscandian and Moscow basins obviously broke off in the early Katian corresponding to the Nabala Stage, because the lithology of the sediments overlying the widespread cryptocrystalline limestones of the Rakvere Stage differs from that in the neighbouring Russian areas. Collisional movements at the Baltica–Avalonia borders temporarily decreased in the late Katian. A Geniai Tuff at the Aeronian–Telychian boundary (Silurian), found in drill cores of Latvia and Lithuania, probably originating from carbonatite source magma (Kiipli et al. 2012, 2014b) gives evidence of the extensional tectonics between Baltica and Avalonia. Rapid subsidence of the southern part of the Baltoscandian Basin started in the Wenlock (Poprawa et al. 1999) due to the subduction of the Baltica Plate under Avalonia. Thrusting and mountain-building at the Caledonian Deformation Front (Katzung et al. 1993; Beier et al. 2000) supplied large amounts of sediments to the southern part of the Baltoscandian Basin. In the Scandinavian side, as well, the tectonic processes were active during the Ordovician–Silurian transition. The emergence of granitic plutons indicates the subduction of the oceanic crust beneath the continent. During this time interval the sea-floor spreading in one and ophiolite obduction in the other area occurred (Andersen et al. 1998; Fossen et al. 2008). Metabentonite layers in the Estonian geological sections of Pirgu age refer to volcanism and tectonic activity in the west (Kiipli et al. 2014a, 2014b).

MATERIAL AND METHODS

The sedimentary succession comprising the Katian, Hirnantian and lower Silurian strata is relatively complete in the Aizpute core compared to the shallow shelf successions containing a number of gaps. We studied in detail the grain size distribution in the Pirgu and Porkuni stages, including the material from the under- and overlying sections. The Pirgu Stage starts with 18 m thick red-coloured dolomitic marlstone of the Jonstorp Formation. The content of the siliciclastic component in the marlstone, calculated according to the contents of main chemical elements in the whole rock, varies from 42% to 75%, being mostly 60%. The marlstone is overlain by 3 m thick grey limestone of the Paroveja Formation containing 80–90% carbonate, and 4 m thick red dolomitic claystone of the Kuili Formation containing 12–25% carbonate. The Porkuni Stage consists of light grey calcareous marlstone of the Kuldiga and limestone of the Saldus formations, respectively 14 and 2.3 m in thickness (Fig. 2A). The Ordovician–Silurian boundary reveals a sharp change in lithology – the clayey red and greenish-grey claystone of the Silurian Juuru Stage overlies the oolithic limestone of the Hirnantian Saldus Formation of the Porkuni Stage. Desiccation cracks and ripple marks, found in the upper Saldus Formation of western Latvia, point to a temporary retreat of the sea and likely gap in sedimentation at the Ordovician–Silurian transition (Ulst et al. 1982).

Grain size analysis was carried out using the sedigraph Horiba LA-950. The carbonate component of the samples was dissolved in 1N HCl solution, the insoluble residue was centrifuged, cleaned with distilled water and put into the analyser. The automatic procedure provided the data on grain size composition in volume % and statistical parameters. The mean grain size (MGS) applied in the present study was calculated using the formula $MGS = \Sigma\, q \cdot ø/100$, where q is the percentage of a particular grain fraction and ø is the diameter of grains (in µm) in this fraction. The ‘depth vs MGS’ plot gives the most reliable picture of grain size variation (Fig. 2A). The grain size composition of samples is also presented as a bar chart to visualize the distribution of fractions and compare different parts of the section (Fig. 2C). Mean grain size and chemical analyses were compared with the same aim as done for the Silurian (Kiipli et al. 2010), where the coarse grain corresponds to higher Si/Al + K/Al values and indicates a decrease in sea depth. Data on the Si/(Si + Al) ratio used in the present

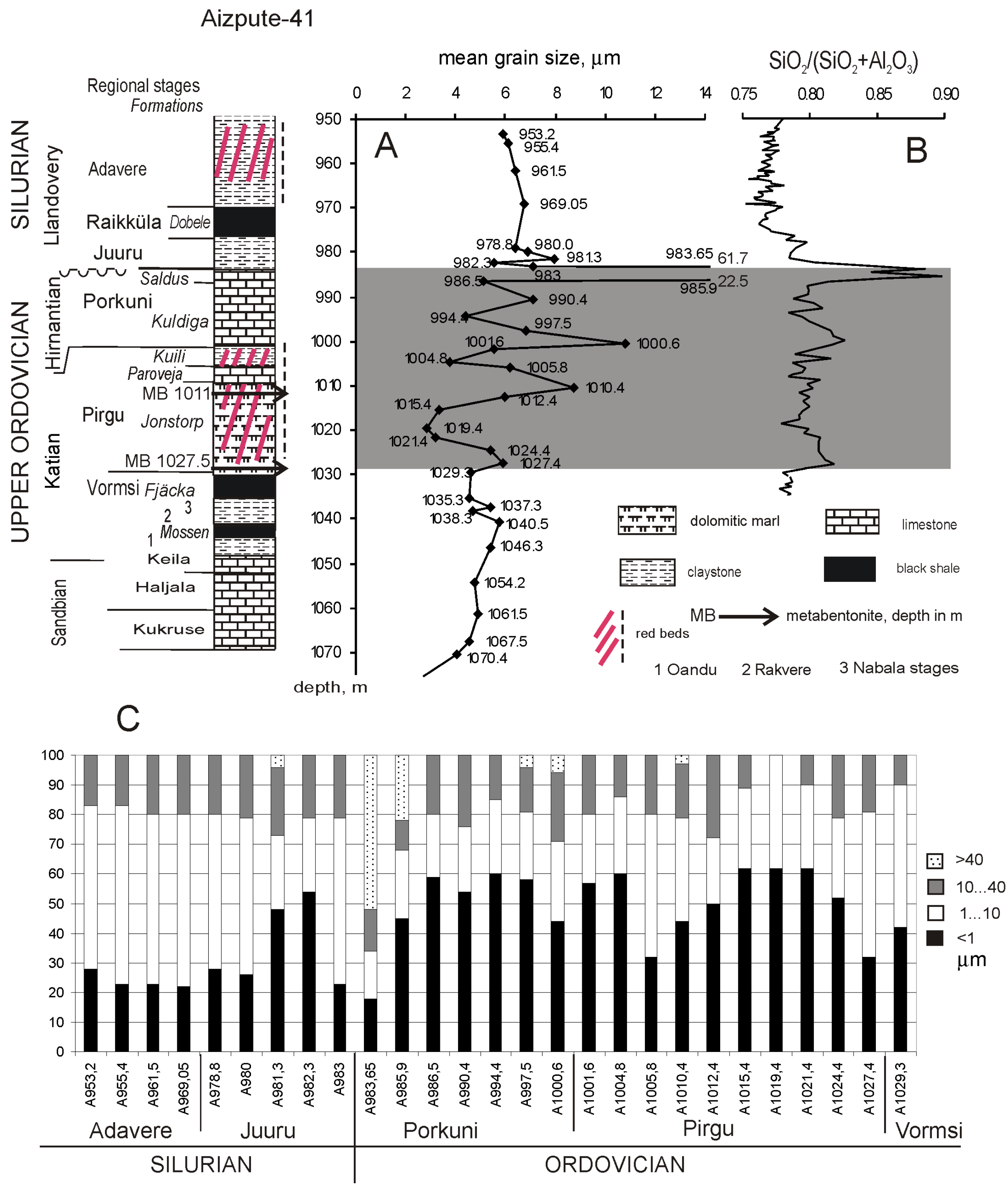

Fig. 2. Stratigraphy and lithology of the Aizpute-41 core and (A) mean grain size (MGS) of the insoluble residue of carbonate rock; (B) $SiO_2/(SiO_2 + Al_2O_3)$, from Kiipli & Kiipli (2006); (C) grain size composition of the insoluble residue of carbonate rock of selected samples (in %), calculated from the sedigraph data.

study were taken from Kiipli & Kiipli (2006) (Fig. 2B). The minerals in the 10–40 μm fraction were determined by X-ray diffractometry (Fig. 3).

RESULTS

As the carbonate component was removed before grain size analysis, our results are based on the insoluble residue. It is mainly a siliciclastic component with some addition of authigenic iron oxides/hydroxides and minor pyrite. Mean grain size reveals larger fluctuations starting with the Pirgu Stage. The peaks shift rapidly towards higher values, achieving a maximum in the Saldus Formation of the Porkuni Stage (Fig. 2A). The minima of MGS increase constantly as well. The spectrum of grain fractions is variable in the Pirgu Stage (Fig. 2C). The content of clay fraction varies from 30% to 60%, of fine silt (1–10 μm) from 20% to 50% and of coarse silt (10–40 μm) mainly from 10% to 20%. In the case of fine sand admixture even less than 5%, both MGS and the Si/(Si + Al) ratio increase. The Porkuni Stage, too, shows variable grain size and the content of clay fraction very often reaches 60%. In samples containing fine sand, particularly those from the Saldus Formation (Figs 2C, 4B), the MGS values and Si/(Si + Al) rise considerably (Fig. 2A, B). At the beginning of the Silurian, the MGS values decrease again to 6–7 μm, being somewhat higher than in pre-Pirgu time, 5 μm. The Llandovery reveals an increase in the very fine silt fraction (1–10 μm), resulting in the decrease in clay (Fig. 2C). In the coarser fraction (Fig. 3), the muscovite and K-feldspar contents increase and quartz decreases in the Llandovery compared to the end-Ordovician. The Si/(Si + Al) ratio is higher in the Pirgu–Porkuni section and decreases in the Silurian (Fig. 2B) due to reappearance of kaolinite and diminishing of quartz content in the siliciclastic part of rock (Kiipli et al. 2009). Kaolinite, the mineral of high aluminium content, was present in the Middle Ordovician and disappeared in the lower Sandbian in the Aizpute section (Kiipli et al. 2008). Kaolinite disappearance was a major reason for the background increase in the Si/(Si + Al) ratio in the Upper Ordovician (Fig. 2B).

The grain size frequency diagrams show the sorting of the sediment (Fig. 4). Bi-modal distribution is prevailing in most samples, whereas multi-modal distribution is characteristic of the Porkuni Stage. The MGS value does not differentiate between sorting, except in the Porkuni samples where high MGS shows the poorest sorting (Fig. 4B). The samples with the lowest MGS recorded in the red-coloured Pirgu Stage (Fig. 4D) contain abundantly material with the grain size <0.1 μm. Fine-dispersed hematite and goethite were formed from amorphous iron oxides and hydroxides carried to the basin as coatings on clay particles. Low MGS values in the middle of the Jonstorp Formation of the Pirgu Stage may be related to these diagenetic minerals.

DISCUSSION

Currents, weathering, diagenesis and petrology of the provenance influence the mineral and chemical composition of the siliciclastic part of the sedimentary rock. Grain size distribution depends mainly on eustatic and tectonics-related sea level changes. The highest MGS values of deep shelf correspond to gaps in shallow shelf sections. The Saldus Formation, Porkuni Stage (Hirnantian), has the highest MGS values in the deep shelf Aizpute core (Fig. 2A), whereas in the shallow

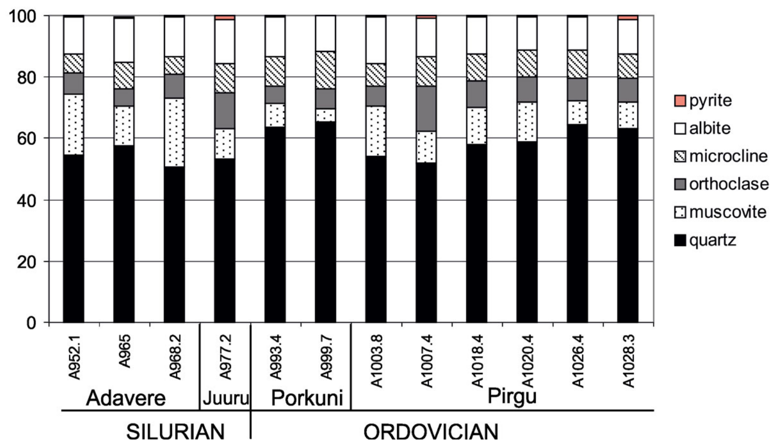

Fig. 3. Mineral composition (in %) of the silt (10–40 μm) fraction of selected samples of the Aizpute-41 core.

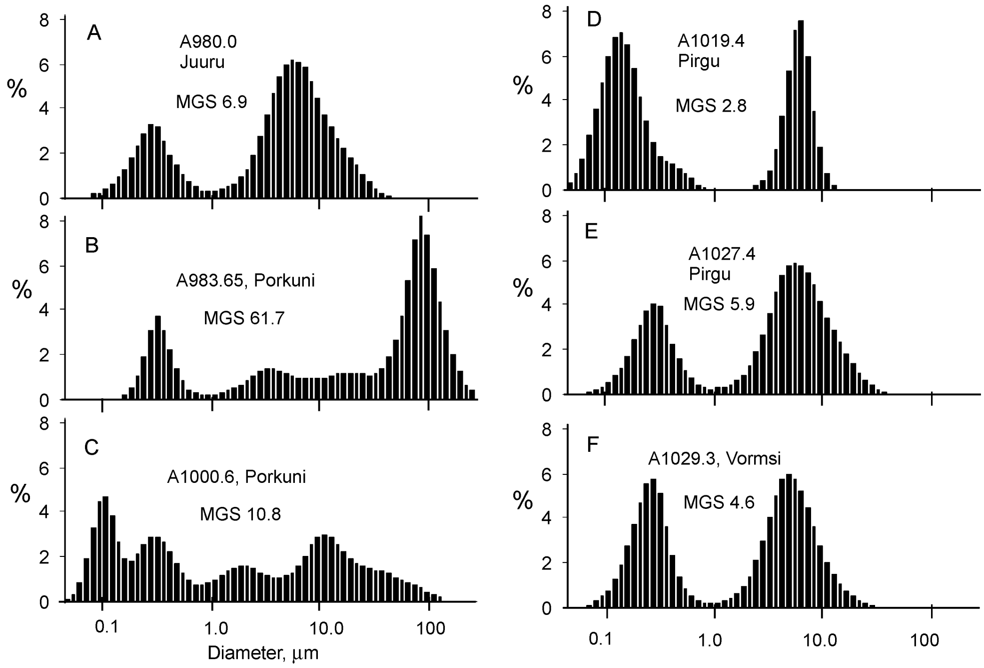

Fig. 4. Grain size frequency (in %) diagrams and mean grain size (MGS) of the siliciclastic part of rock of selected samples of the Aizpute-41 core.

Estonian shelf the correlative sediments are missing (Kaljo et al. 2008). The Pirgu–Porkuni transition, corresponding to the boundary of the Kuili and Kuldiga formations in the Aizpute core (Fig. 2A), is marked by a high MGS value as well. The sediments contemporaneous with the upper Kuili Formation are absent in the Estonian shallow shelf (Nõlvak 1997). Down in the section, the next peak of high MGS in the upper Jonstorp Formation has synchronous sediments in central Estonia – the upper Halliku Formation, but does not have correlative layers in the shallowest part of the basin in northern Estonia, as shown by bentonite stratigraphy (Kiipli et al. 2014a). However, opinions concerning the correlations differ (Hints et al. 2005). The earliest sea level lowering and MGS rise of Pirgu age was of smaller extent and correspondingly it has contemporary sediments in the whole of the Estonian shelf, indicated by a correlative bentonite layer in shallow shelf in the Moe Formation. The lithological change, nevertheless, supports the idea about regression, because cryptocrystalline limestone of the Moe Formation indicates shallower seawater than the overlying Adila Formation. The named agreements between MGS and sedimentation show that sea level lowering is the main factor in grain size increase. The increasing trend of MGS values, in peaks as well as in 'lows', allows us to consider the succession from Pirgu to end-Porkuni times as a joint sea level lowering trend.

However, the MGS built up by the deepening and shallowing of the sea does not discriminate eustatic or tectonic movements as a cause of fluctuations. As said above, tectonic activity was high in the Late Ordovician and Silurian, causing structural changes in the Balto-scandian Basin and adjacent areas. Still, none of the known tectonic events or succession of events in the southeastern margin of Baltica falls between early Pirgu and late Porkuni times. If tectonics were the main factor, the MGS fluctuations that started in the Ordovician might have continued in the Lower Silurian, but they did not. A better concordance is seen between MGS and glaciation dynamics. The Hirnantian ice age ends with lower $\delta^{18}O$ values (Brenchley et al. 1994; Heath et al. 1998). The MGS fluctuation also ends in the latest Ordovician sedimentary layers, i.e. it does not continue into the Silurian. A common cause of the entire trend of increasing MGS pointing to falling sea level can be the waning and waxing of ice sheets culminating in the Hirnantian glaciation. The global eustatic sea level curve might give evidence about the relationship between MGS fluctuations and glaciation dynamics. The third-order sea level changes established in Morocco (Loi et al. 2010, fig. 14) can be tentatively correlated with the MGS of the Aizpute core and inferred sea level fluctuations in Baltica. In Morocco the boundary of the *Acanthochitina barbata/Tanuchitina fistulosa–Armoricochitina nigerica* chitinozoan biozones shows regression and probably correlates with the Vormsi–Pirgu stage boundary and increase in MGS in the Aizpute core. The rise in sea level comprises the following part of the Katian of Morocco, corresponding, probably, to the low MGS interval of the middle Jonstorp Formation in the Aizpute core. Thereafter the sea level in Morocco falls, turns into a new smaller highstand in the latest Katian and decreases constantly through the Katian–Hirnantian boundary. The latest Hirnantian sea level is interrupted by sudden fluctuations. One can find some common features for the late Katian and Hirnantian between such distant regions as Morocco and Baltica, although the exact correlation is hard to achieve.

CONCLUSIONS

Comparing the possible tectonics- and glaciation-related reasons for grain size fluctuation in the Late Ordovician Pirgu and Porkuni times in the Aizpute section, the glaciation-related change in sea level seems to be more plausible. No single tectonic event or succession of events starting in Pirgu time and ending in Porkuni time is known. Suggesting that the glaciation dynamics was the main factor affecting grain size and inferred sea level changes, one can say that cyclic growth of ice sheets at the South Pole started already in Pirgu time.

Acknowledgements. This study was financed by the Estonian Ministry of Education and Research target-financing project SF0140016s09. The article is a contribution to IGCP 591. S. Peetermann is thanked for correcting the English. The anonymous referees are thanked for constructive reviews of the manuscript.

REFERENCES

Andersen, T. B., Berry IV, H. N., Lux, D. R. & Andresen, A. 1998. The tectonic significance of pre-Scandian $^{40}Ar/^{39}Ar$ phengite cooling ages in the Caledonides of western Norway. *Journal of the Geological Society, London*, **155**, 297–309.

Beier, H., Maletz, J. & Böhnke, A. 2000. Development of an Early Palaeozoic foreland basin at the SW margin of Baltica. *Neues Jahrbuch für Geologie und Paläontologie – Abhandlungen*, **218**, 129–152.

Bergström, S. M., Young, S. & Schmitz, B. 2010. Katian (Upper Ordovician) $\delta^{13}C$ chemostratigraphy and sequence stratigraphy in the United States and Baltoscandia: a regional comparison. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **296**, 217–234.

Bergström, S. M., Eriksson, M. E., Young, S. A., Ahlberg, P. & Schmitz, B. 2014. Hirnantian (latest Ordovician) $\delta^{13}C$ chemostratigraphy in southern Sweden and globally: a refined integration with the graptolite and conodont zone successions. *GFF*, **136**, 355–386.

Brenchley, P. J., Marshall, J. D., Carden, G. A. F., Robertson, D. B. R., Long, D. G. F., Meidla, T., Hints, L. & Anderson, T. F. 1994. Bathymetric and isotopic evidence for a short-lived Late Ordovician glaciation in a greenhouse period. *Geology*, **22**, 295–298.

Fossen, H., Pedersen, R.-B., Bergh, S. & Andresen, A. 2008. Creation of a mountain chain. The building up of the Caledonides; about 500–405 Ma. Iapetus – an ancient (Proto-) Atlantic Ocean. In *The Making of a Land – Geology of Norway* (Ramberg, I. B., Bryhni, I., Nøttvedt, A. & Rangnes, K., eds), pp. 182–195. Norsk Geologisk Forening, Trondheim.

Heath, R. J., Brenchley, P. J. & Marshall, J. D. 1998. Early Silurian carbon and oxygen stable-isotope stratigraphy of Estonia: implications for climate change. *New York State Museum Bulletin*, **491**, 313–326.

Hints, L., Oraspõld, A. & Nõlvak, J. 2005. The Pirgu Regional Stage (Upper Ordovician) in the East Baltic: lithostratigraphy, biozonation, and correlation. *Proceedings of the Estonian Academy of Sciences, Geology*, **54**, 225–259.

Kaljo, D., Martma, T. & Saadre, T. 2007. Post-Hunnebergian Ordovician carbon isotope trend in Baltoscandia, its environmental implications and some similarities with that of Nevada. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **245**, 138–155.

Kaljo, D., Hints, L., Männik, P. & Nõlvak, J. 2008. The succession of Hirnantian events based on data from Baltica: brachiopods, chitinozoans, conodonts, and carbon isotopes. *Estonian Journal of Earth Sciences*, **57**, 197–218.

Katzung, G., Giese, U., Walter, R. & von Winterfeld, C. 1993. The Rügen Caledonides, northeast Germany. *Geological Magazine*, **130**, 725–730.

Kiipli, E. & Kiipli, T. 2006. Carbonate distribution in the East Baltic deep shelf in the late Ordovician–early Silurian. *GFF*, **128**, 147–152.

Kiipli, E., Kallaste, T. & Kiipli, T. 2008. Hydrodynamic control of sedimentation in the Ordovician (Arenig–Caradoc) Baltic Basin. *Lethaia*, **41**, 127–137.

Kiipli, E., Kiipli, T. & Kallaste, T. 2009. Reconstruction of currents in the Mid-Ordovician–Early Silurian central Baltic Basin using geochemical and mineralogical indicators. *Geology*, **37**, 271–274.

Kiipli, T., Kiipli, E. & Kaljo, D. 2010. Silurian sea level variations estimated using SiO_2/Al_2O_3 and K_2O/Al_2O_3 ratios in the Priekule drill core section, Latvia. *Bolletino della Societa Paleontologica Italiana*, **49**, 55–63.

Kiipli, T., Radzievičius, S., Kallaste, T., Kiipli, E., Siir, S., Soesoo, A. & Voolma, M. 2012. The Geniai tuff in the southern East Baltic area – a new correlation tool near the Aeronian/Telychian stage boundary, Llandovery, Silurian. *Bulletin of Geosciences*, **87**, 695–704.

Kiipli, T., Dahlquist, P., Kallaste, T., Kiipli, E. & Nõlvak, J. 2014a. Late Katian (Ordovician) bentonites in the East Baltic, Scandinavia and Scotland: geochemical correlation and volcanic source interpretation. *Geological Magazine*, doi:10.1017/S001675681400051X

Kiipli, T., Soesoo, A. & Kallaste, T. 2014b. Geochemical evolution of Caledonian volcanism recorded in the sedimentary rocks of the eastern Baltic region. In *New Perspectives on the Caledonides of Scandinavia and Related Areas* (Corfu, F., Gasser, D. & Chew, D. M., eds), *Geological Society of London Special Publications*, **390**, 177–192.

Loi, A., Ghienne, J.-F., Dabard, M. P., Paris, F., Botquelen, A., Christ, N., Elaouad-Debbaj, Z., Gorini, A., Vidal, M., Videt, B. & Destombes, J. 2010. The Late Ordovician glacio-eustatic record from a high-latitude storm-dominated shelf succession: the Bou Ingarf section (Anti-Atlas, Southern Morocco). *Palaeogeography, Palaeoclimatology, Palaeoecology*, **296**, 332–358.

Nestor, H. & Einasto, R. 1997. Ordovician and Silurian carbonate sedimentation basin. In *Geology and Mineral Resources of Estonia* (Raukas, A. & Teedumäe, A., eds), pp. 192–204. Estonian Academy Publishers, Tallinn.

Nõlvak, J. 1997. Table 7. The Ordovician of Estonia. In *Geology and Mineral Resources of Estonia* (Raukas, A. & Teedumäe, A., eds), pp. 54–55. Estonian Academy Publishers, Tallinn.

Paškevičius, J. 1997. *The Geology of the Baltic Republics*. Vilnius University, Geological Survey of Lithuania, Vilnius, 387 pp.

Poprawa, P., Šliaupa, S., Stephenson, R. & Lazauskiene, J. 1999. Late Vendian–Early Palaeozoic tectonic evolution of the Baltic Basin: regional tectonic implications from subsidence analysis. *Tectonophysics*, **314**, 219–239.

Trotter, J. A., Williams, I. S., Barnes, C. R., Lécuyer, C. & Nicoll, R. S. 2008. Did cooling oceans trigger Ordovician biodiversification? Evidence from conodont thermometry. *Science*, **321**, 550–554.

Ulst, R. Zh., Gailite, L. K. & Yakovleva, V. I. 1982. *Ordovik Latvii* [*Ordovician of Latvia*]. Zinatne, Riga, 293 pp. [in Russian].

Videt, B., Paris, F., Rubino, J. L., Boumendjel, K., Dabard, M. P., Loi, A., Ghienne, J. F., Marante, A. & Gorini, A. 2010. Biostratigraphical calibration of third order Ordovician sequences on the northern Gondwana platform. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **296**, 359–375.