

Silurian sea level variations estimated using $\text{SiO}_2/\text{Al}_2\text{O}_3$ and $\text{K}_2\text{O}/\text{Al}_2\text{O}_3$ ratios in the Priekule drill core section, Latvia

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ABSTRACT - The $\text{SiO}_2/\text{Al}_2\text{O}_3$ and $\text{K}_2\text{O}/\text{Al}_2\text{O}_3$ ratios are used as proxies for grain size and sea depth changes in a more than 400 m thick succession of Telychian to Ludfordian shale and marlstone of the Priekule core. Good correlation of the increased $\text{SiO}_2/\text{Al}_2\text{O}_3$ and $\text{K}_2\text{O}/\text{Al}_2\text{O}_3$ values in the Priekule section with positive $\delta^{13}\text{C}$ excursions recognized worldwide suggests that these sea depth changes correspond to global sea level changes. The curves composed indicate a moderate long-range sea level low stand from the Sheinwoodian to the middle Ludfordian, superimposed with larger sea level falls in the lower Sheinwoodian, upper Homerian and middle Ludfordian. The Telychian and upper Ludfordian are characterized by sea level high stands. Higher sulphur contents over 1% and higher contents of carbonates occur close to the intervals interpreted as sea level low stands.

RIASSUNTO - [Variazioni del livello marino nel Siluriano ricavate dall'analisi del rapporto $\text{SiO}_2/\text{Al}_2\text{O}_3$ e $\text{K}_2\text{O}/\text{Al}_2\text{O}_3$ nella perforazione di Priekule, Latvia] - Vengono qui utilizzati i rapporti $\text{SiO}_2/\text{Al}_2\text{O}_3$ e $\text{K}_2\text{O}/\text{Al}_2\text{O}_3$ come indici di variazione del livello del mare e di granulometria in una successione di oltre 400 m di spessore di scisti e marne del Telychiano-Ludfordiano dalla perforazione di Priekule. La buona correlazione riscontrata tra l'aumento dei valori di $\text{SiO}_2/\text{Al}_2\text{O}_3$ e $\text{K}_2\text{O}/\text{Al}_2\text{O}_3$ nella sezione di Priekule con le escursioni positive di $\delta^{13}\text{C}$ riconosciute globalmente suggerisce che questi cambiamenti di profondità del mare corrispondano a variazioni globali del livello del mare. Le curve ottenute indicano una prolungata fase di moderato stazionamento basso del livello del mare dal Sheinwoodiano al Ludfordiano medio, associata a più ampi abbassamenti del livello del mare nel Sheinwoodiano inferiore, Homeriano superiore e Ludfordiano medio. Durante il Telychiano e Ludfordiano superiore si verificarono fasi di stazionamento alto del livello marino. L'analisi di spesse lenti di sedimenti provenienti da una scarpata tra la piattaforma poco profonda e quella profonda, le variazioni di facies e il confronto con l'attuale piattaforma di Bering indicherebbero cambiamenti del livello del mare superiori a 200 m. Contenuti di zolfo superiori a 1% e valori più alti nel contenuto di carbonati si registrano in prossimità degli intervalli interpretati come fasi di stazionamento basso del livello del mare.

INTRODUCTION

Eustatic sea level variations respond sensitively to climatic changes due to the growth and retreat of continental ice sheets at high latitudes (McKerrow, 1979). Long-range variations in global sea level may be caused by plate tectonic processes and global distribution of continents (Haq & Shutter, 2008). Sea level falls and rises can be observed in the lithology, facies movements, breaks in sedimentation and changes in faunal communities in sedimentary sections on stable platforms (Johnson, 1996; Loydell, 1998). In this paper we use an approach based on grain size proxies such as the $\text{SiO}_2/\text{Al}_2\text{O}_3$ and $\text{K}_2\text{O}/\text{Al}_2\text{O}_3$ ratios for establishing sea level high and low stands. Secular trends in sulphur and CaO contents and the carbon isotope ratio are compared to get integrated information about environmental changes at times of sea level variations.

MATERIAL AND METHODS

A total of 126 Silurian deep shelf rock samples were collected for this study from the West Latvian Priekule drill core section (Fig. 1). The samples are stored at the Institute of Geology, Tallinn University of Technology. Pressed powders were analysed by the standard X-ray fluorescence method. The precision of element

determination was better than $\pm 5\%$ of the concentration. The correlation of the section is based on finds of zonal graptolites and the published $\delta^{13}\text{C}$ curve (Kaljo et al., 1997). The $\text{SiO}_2/\text{Al}_2\text{O}_3$ and $\text{K}_2\text{O}/\text{Al}_2\text{O}_3$ ratios were used as indicators of grain size because aluminium concentrates preferably in clay minerals forming the major part of the fine-grained pelitic fraction of terrigenous material. Silicon and potassium, on the contrary, concentrate in coarser fractions. Silicon is mainly found in quartz, increasing in abundance from the 2 μm fraction towards coarser grain sizes (Kiipli et al., 2008a). The $\text{K}_2\text{O}/\text{Al}_2\text{O}_3$ ratio complements the $\text{SiO}_2/\text{Al}_2\text{O}_3$ data. Potassium occurs in the clay fraction in illite and in coarser silt bound in muscovite and K-feldspar. As the $\text{K}_2\text{O}/\text{Al}_2\text{O}_3$ ratio of illite, the main clay mineral in Silurian sections of the East Baltic Basin (Jürgenson, 1988), is stable, the increase in the $\text{K}_2\text{O}/\text{Al}_2\text{O}_3$ ratio in the whole-rock samples points to the addition of K-feldspar characteristic of coarser grain fractions (Kiipli et al., 2008a). Therefore, positive correlation of these ratios with coarse silt (Fig. 2) and their similar increasing-decreasing trends in the Priekule section (Fig. 3) warrant the use of these ratios as grain size proxies of siliclastic material. Grain size data used for comparison with element ratios (Fig. 2) are taken from an unpublished report by E. Jürgenson (1973), stored at the Institute of Geology, Tallinn University of Technology. As the $\text{SiO}_2/\text{Al}_2\text{O}_3$ and $\text{K}_2\text{O}/\text{Al}_2\text{O}_3$ ratios both depend on the grain size

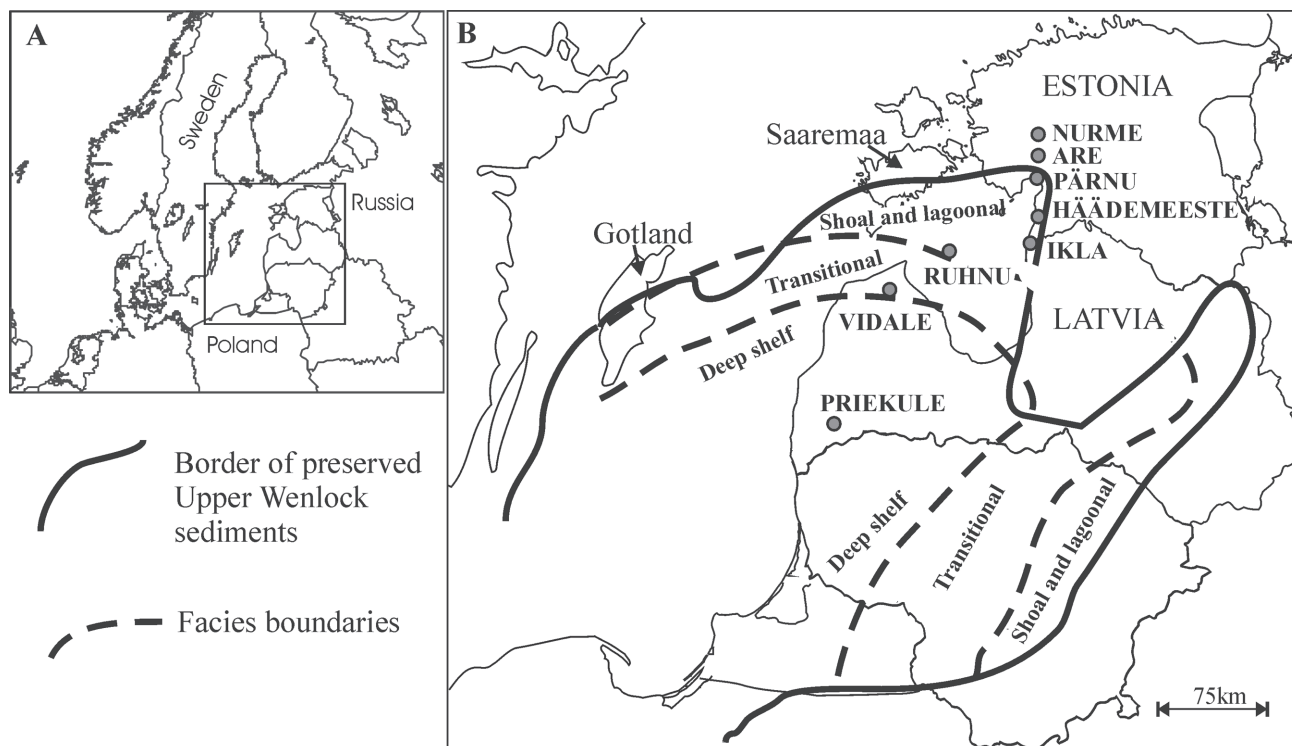


Fig. 1 - Location of the Priekule and other sections in the frame of upper Wenlock facies (Einasto et al., 1986). Lagoonal facies include dolomitic mudstones, shoal facies grainstones and bioherms, transitional facies open shelf nodular limestones and marlstones, and deep shelf includes shales with marlstone interbeds containing graptolites.

of siliclastic material, the respective curves are averaged on the sea depth curve in Fig. 4. In some levels silt consists mostly of quartz having greater impact on the $\text{SiO}_2/\text{Al}_2\text{O}_3$ ratio, in other levels variations in K-feldspar content have more influence on the $\text{K}_2\text{O}/\text{Al}_2\text{O}_3$ ratio. The average of these ratios allows better correlation with grain size than correlating both ratios separately (Fig. 2). To obtain an average of $\text{SiO}_2/\text{Al}_2\text{O}_3$ and $\text{K}_2\text{O}/\text{Al}_2\text{O}_3$ ratios, the ratio in each sample was divided with the average for the whole section: 3.4 and 0.27, respectively. The resulting coefficients vary between 0.80 and 1.35 for both ratios and can be reasonably averaged. This averaging compensates for the long-range opposing trends of these ratios (Fig. 3), probably caused by the rise of the Caledonian Mountains (Gee et al., 2008) supplying less intensely weathered material rich in feldspars for sedimentation later in the Silurian.

GEOLOGICAL BACKGROUND

The Priekule drilling site is located in the central part of the Silurian deep shelf area in the Baltic Basin (Fig. 1). Evidence suggests that the Priekule section represents a deep shelf environment with steady sedimentation and is thus favourable for the study of the sea level changes. In shallow-water sections time intervals with sea level low stands are often hidden in sedimentation breaks and therefore are not suitable for the study of continuous environmental changes. Specifically, in the deep shelf,

compared with shallow-water sections, only great changes in sea level, which are significant with respect to the sea depth at the study site, are recorded.

In the Priekule section Silurian sedimentary rocks of the Rhuddanian to Ludfordian interval (thickness of 436 m) are represented mostly by grey shales and marlstones with minor argillaceous limestone interbeds (Fig. 3). Shales are usually thin-bedded and lack traces of bioturbation indicating low content of oxygen in bottom waters. Some burrowing occurs in the Telychian and in the uppermost Silurian. Sporadic graptolites and brachiopods with thin shells are found throughout the section. Pelitic and fine silt material predominates in the siliclastic material, but some intervals contain up to 50% or more coarse silt (Fig. 2). Clay minerals in the East Baltic Silurian are mainly represented by illite with less chlorite (Jürgenson, 1988). The deposition of more than 400 m of shaly and marly sediments during the Silurian did not substantially change the depositional environment in the deep shelf area, indicating a regional subsidence compensating the accumulation of sediments. The Aeronian is represented by dark brown shales rich in organic matter. We have only a few samples from the Rhuddanian to Aeronian beds (thickness 15.3 m), therefore information about this part of the section is provisional and not discussed hereafter. The thicker, Telychian to Pridoli part of the section is covered by 121 samples, enabling tracing of temporal geochemical trends.

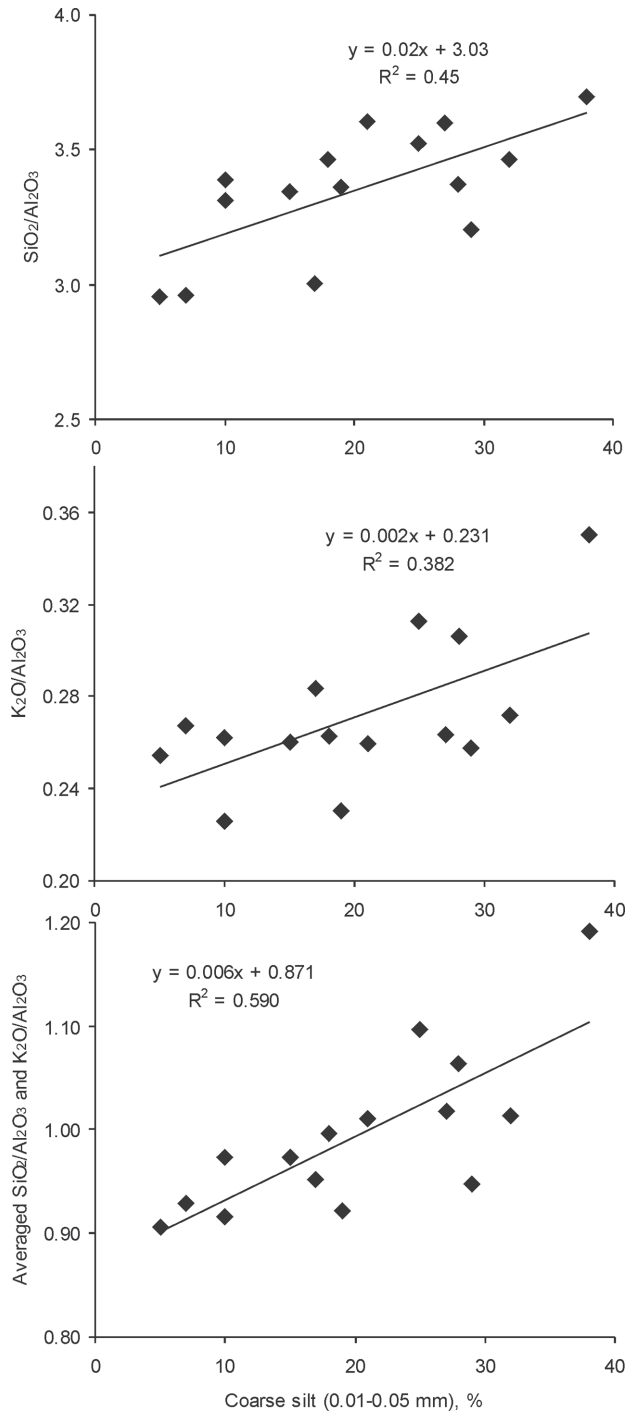


Fig. 2 - Correlation of the coarse silt content with $\text{SiO}_2/\text{Al}_2\text{O}_3$ and $\text{K}_2\text{O}/\text{Al}_2\text{O}_3$ ratios in the Priekule drill core section. Grain size data are from an unpublished report by E. Jürgenson (1973) stored at the Institute of Geology, Tallinn University of Technology.

STRATIGRAPHY

Biostratigraphical dating of several key levels of the Priekule section is based on graptolite occurrences (Figs. 3 and 4) reported by Kaljo et al. (1997) and on some new

supplementary data. Comparison with the $\delta^{13}\text{C}$ positive excursions identified in several other Baltic sections is an important additional criterion for stratigraphical dating of events. The following published correlations of $\delta^{13}\text{C}$ positive excursions with the graptolite zonation have been used herein: the lower Sheinwoodian positive $\delta^{13}\text{C}$ excursion commences clearly within the *Cyrtograptus purchisoni* Biozone and peaks in the *Monograptus riccartonensis* Biozone or slightly higher in the *Streptograptus antennularius* Biozone (Kaljo et al., 1997, 2007; Martma et al., 2005; Kaljo & Martma, 2006); the Homeric positive $\delta^{13}\text{C}$ excursion correlates with the *Pristiograptus parvus*-*Gothograptus nassa* and *Monograptus ludensis* graptolite zones (Martma et al., 2005; Kaljo & Martma, 2006); the mid-Ludfordian positive $\delta^{13}\text{C}$ excursion correlates most probably with *Neocucullograptus kozlowskii*-*Bohemograptus bohemicus tenuis* Zone in the mid-Ludfordian (Martma et al., 2005; Kaljo & Martma, 2006), which is a slightly higher than thought earlier (Kaljo et al., 1997).

In contrast with the common usage (Martinsson et al., 1981), in this paper the Telychian/Sheinwoodian boundary is correlated with the upper part of the *Cyrtograptus purchisoni* Zone. Our approach is based on the correlation of the Ireviken Event Datum 2 with the Llandovery/Wenlock boundary at the GSSP Hughley Brook (Jeppsson, 1997; Männik, 2007) and with the upper part of the *Cyrtograptus purchisoni* Zone using volcanic ash beds as time markers (Kiipli & Kallaste, 2006; Kiipli et al., 2008b).

RESULTS

A general decreasing trend in the $\text{SiO}_2/\text{Al}_2\text{O}_3$ ratio can be traced (Fig. 3) from the start to the end of the Silurian. The $\text{K}_2\text{O}/\text{Al}_2\text{O}_3$ ratio, on the contrary, shows a slightly increasing trend in time. Several contemporaneous excursions are observed against the background of these trends.

On average, the $\text{SiO}_2/\text{Al}_2\text{O}_3$ ratio is 3.4 in the Telychian to Ludfordian. In the lower Sheinwoodian, upper Homeric and Ludfordian the ratio rises to 3.8-4.0. Extrapolating from Fig. 2 suggests that these values correspond to a coarse silt fraction content of 50-60% in siliclastic material. Lower values of the $\text{SiO}_2/\text{Al}_2\text{O}_3$ ratio (2.7-3.3) are characteristic of the Telychian, middle Wenlock, Gorstian and upper Ludfordian, indicating domination of fine-grained pelitic material. In these shorter time intervals the $\text{K}_2\text{O}/\text{Al}_2\text{O}_3$ ratio behaves similarly to the $\text{SiO}_2/\text{Al}_2\text{O}_3$ ratio, confirming changes in grain size of the sedimentary material.

Carbonate contents are higher close to the intervals of higher $\text{SiO}_2/\text{Al}_2\text{O}_3$ and $\text{K}_2\text{O}/\text{Al}_2\text{O}_3$ ratios and coarser grain size of siliclastic material (Fig. 3). The sulphur content exceeds 1% close to the same intervals, although there is no point by point correlation. In the Wenlock higher sulphur contents correspond better to higher $\text{SiO}_2/\text{Al}_2\text{O}_3$ and $\text{K}_2\text{O}/\text{Al}_2\text{O}_3$ ratios, but in the Ludlow the peak of sulphur occurs already in the upper Gorstian, decreasing gradually throughout the Ludfordian. In the middle of the

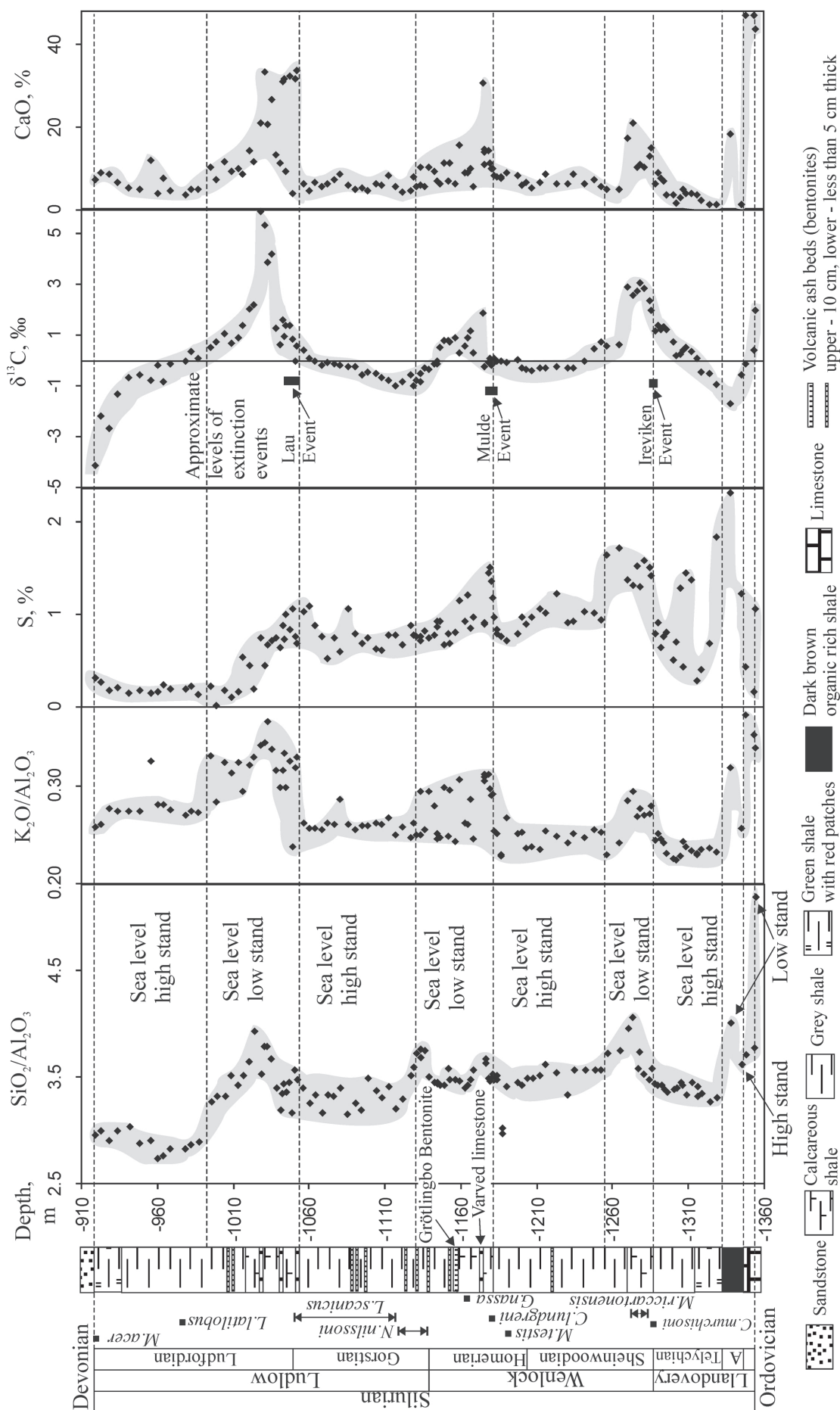


Fig. 3 - Variations in the $\text{SiO}_2/\text{Al}_2\text{O}_3$ and $\text{K}_2\text{O}/\text{Al}_2\text{O}_3$ ratios, S and CaO contents, and $\delta^{13}\text{C}$ in the Prickule drill core section.

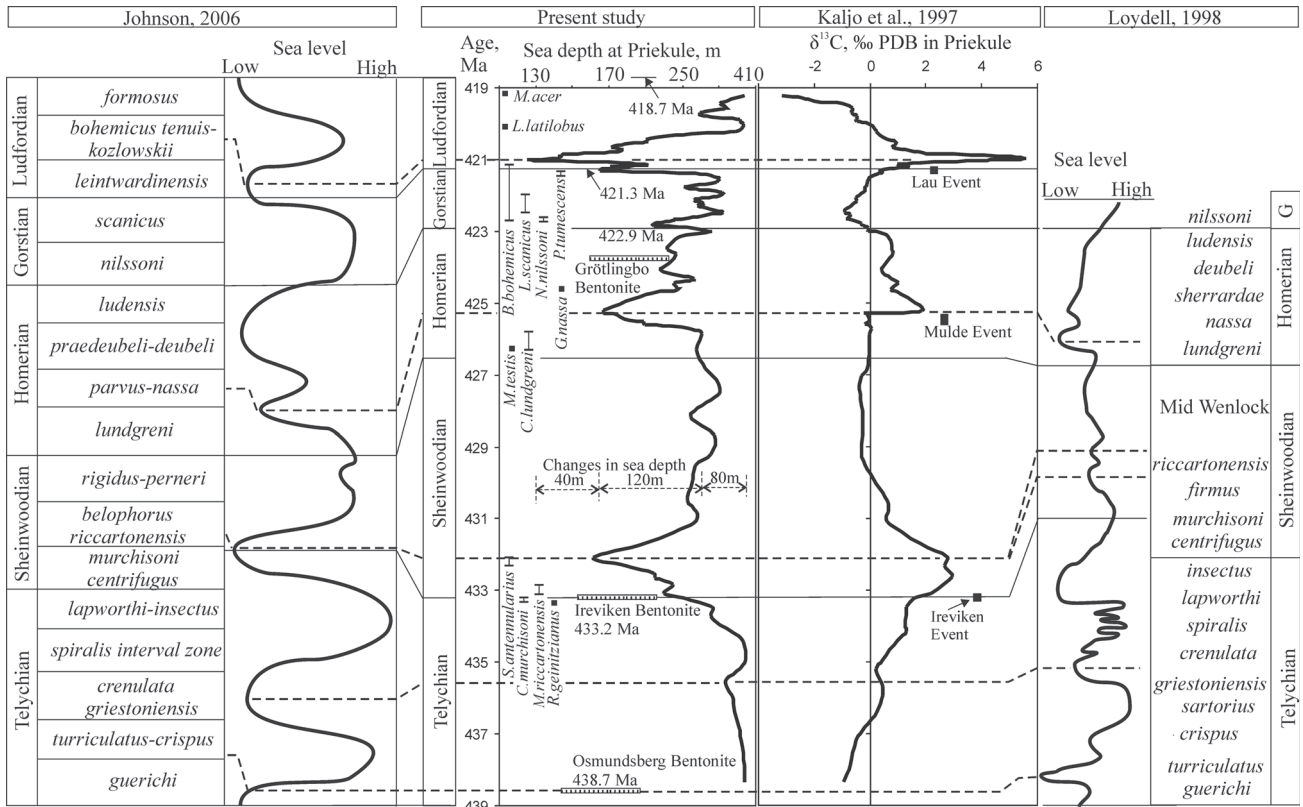


Fig. 4 - Comparison of the sea depth curve at Priekule with the sea level curves by Johnson (2006) and Loydell (1998). According to Kaljo & Martma (2006), the Ludfordian positive carbon isotope peak (and hence the Ludfordian sea level low stand) correlates with the mid-Ludfordian.

Telychian sulphur contents are high without any significant rise in other geochemical parameters.

The $\text{SiO}_2/\text{Al}_2\text{O}_3$ and $\text{K}_2\text{O}/\text{Al}_2\text{O}_3$ ratio curves are similar to the carbon isotope ratio curve (Fig. 3). Carbon isotope positive excursions are recorded within intervals of higher $\text{SiO}_2/\text{Al}_2\text{O}_3$ and $\text{K}_2\text{O}/\text{Al}_2\text{O}_3$ ratios and corresponding coarser grain size of siliclastic material.

DISCUSSION

Interpretation of $\text{SiO}_2/\text{Al}_2\text{O}_3$ and $\text{K}_2\text{O}/\text{Al}_2\text{O}_3$ ratios

The periods that correspond to the rise in $\text{SiO}_2/\text{Al}_2\text{O}_3$ and $\text{K}_2\text{O}/\text{Al}_2\text{O}_3$ ratios in the deep shelf, correlate with gaps or shifts to the most shoreward facies in the shallow shelf, such as the Burgsvik sandstones (Ludfordian) and rocky shore (Homerian) in Gotland. In the Sheinwoodian, shallow-water reefs and associated carbonate grainstones are widespread in Gotland and Saaremaa. Partial or complete absence of positive carbon isotope excursions in the Homerian and Ludfordian in Saaremaa indicates large gaps in sedimentation at these levels (Kaljo et al., 1997, 2003). These sedimentological signatures and correlations suggest that variations in the grain size of siliclastic material in the Priekule section, as reflected in changes in the $\text{SiO}_2/\text{Al}_2\text{O}_3$ and $\text{K}_2\text{O}/\text{Al}_2\text{O}_3$ ratios, are mainly caused by changes in sea depth. Eolian transport and changing river entrance can accompany sea level changes, although are less probable, because the data taken all together support a sea level-related cause.

Timing of the sea depth changes and comparison with earlier sea level studies

In Fig. 4 both the sea depth and the $\delta^{13}\text{C}$ curve are smoothed by a two-point moving average and recalculated from the drilling depth to the time scale. The following dates have been used for the time scale: 418.7 Ma for the Ludlow/Pridoli boundary, 421.3 Ma for the Gorstian/Ludfordian boundary, 422.9 Ma for the Homerian/Gorstian boundary (Ogg, 2004), 433.2 Ma for the Ireviken Bentonite at the Llandovery/Wenlock boundary (Jeppsson et al., 2005) and 438.7 Ma for the Osmundsberg Bentonite in the lower part of the Telychian (Bergström et al., 2008).

The Sheinwoodian to mid-Ludfordian interval in the resulting sea depth curve is characterized by a long-range relatively shallow sea compared with the deep-water in the Telychian and upper Ludfordian. This long range moderate sea level low stand is well recorded also in the Silurian of the Carnic Alps where dominantly limestones occur in this interval (Brett et al., 2009). The shorter-range sea level falls are superimposed in this long-range moderate shallow-water interval. Most, but not all, of these shorter-range changes in the Priekule section can be observed also in the global sea level curves by Johnson (2006) and Loydell (1998):

1. The large sea level fall in the mid-Telychian *Monoclimacis griestoniensis-crenulata* zones (Loydell, 1998; Johnson, 2006) can be tentatively correlated with a weak mid-Telychian excursion in the Priekule core. During the general sea level high stand the sea was relatively deep at Priekule, and the clayey composition

of sediments responded only slightly to a shallowing of up to some tens of metres.

2. The strong sea level fall in the *Cyrtograptus lapworthi-insectus* zones recorded by Loydell (1998) is not observed in the Priekule sea depth curve.

3. The sea level fall in the lower Wenlock can be clearly recognized in all three curves in Fig. 4. In Priekule the peak of this fall is in the end of the *Monograptus riccartonensis* Zone (interval with *Streptograptus antennularius*), corresponding well to the curve by Loydell (1998). According to Johnson (2006), the peak of this excursion is slightly lower, at the *C. murchisoni*/*M. riccartonensis* boundary. This difference may arise from correlation problems, as the sea level curve by Johnson has mainly been composed from shallow-water facies, which are difficult to correlate with deep sea graptolite facies.

4. The sea level fall in the early Homerian is clearly expressed in all three curves. According to the Priekule curve, the fall is clearly smaller in the late Homerian than in the early Homerian.

5. The largest decrease in sea depth in the Priekule section occurs in the Ludfordian. It correlates well with the sea level fall noted by Johnson (2006). However, correlation with the carbon isotope positive excursion indicates that the peak of the sea level fall is in the mid-Ludfordian (Martma et al., 2005; Kaljo & Martma, 2006). This seeming diachroneity can be explained by a significant rise in the sedimentation rate in the mid-upper Ludfordian in the Priekule area and by uncertainties in the correlation of the sea level curve by Johnson with graptolite zonation.

The good correlation of the Priekule sea depth curve compared to the curves by other authors indicates that sea depth changes at Priekule are caused not by regional tectonics but most probably by global changes.

Sea depth in the Silurian at the Priekule locality

During sea level low stands the content of coarse silt in siliclastic material was up to 50-60% in the Priekule core. Among the present-day continental shelves, open to the ocean, the Bering Sea offers the best comparison. A 400 km wide shelf in the eastern part of the Bering Sea, with the outer border at a depth of 200 m, is covered by sandy and silty terrigenous sediments (Smith & McConnaughey, 1999). The predominance of siliclastic material of silt size in the Baltic Silurian deep shelf area at sea level low stands indicates depths similar to those in the deeper part of the Bering shelf, e.g. between 100 and 200 m. During sea level high stands the Baltic Silurian deep shelf was covered by pelitic siliclastic sediments, deposited at clearly greater depths (>200 m) than the Bering shelf today. During the same time intervals the shallow shelf of the Baltic Basin was covered by nodular limestones and marlstones, hinting at depths shallower than those in the deep shelf during sea low stands.

Only in the middle Telychian did the shallow shelf have greater depths than the deep shelf at times of the sea level low stands, which is shown by shale accumulation in the previous shallow shelf area.

An independent estimate of the sea depth in the deep shelf of the East Baltic Basin at times of sea level low

stands can be obtained from the height of the slope in the transitional zone between the shallow and deep shelf (Fig. 5). Sedimentation in the transitional zone took place at a higher rate than in the shallow and deep shelf, forming thick sediment lenses and causing a basinward progradation of the shallow shelf area. The maximum difference in thicknesses has been established in the Aeronian, where up to 177 m of micritic limestones in the transitional zone correlate with 7-10 m of black shales in the deep shelf (Nestor, 1997; Kiipli et al., 2004). Thus the difference in the depths of the deep and shallow shelf was at least 170 m (Fig. 5). The depth differences of 50-100 m can be calculated in the same way from the other stratigraphical levels in the Silurian. These may be minimum estimates, because drill-holes may have not penetrated the maximum thicknesses. Later compaction of sediments also reduces the thickness and shifts slope height estimates to lower values when compaction is comparable in deep and shallow shelf. In contrary smaller compaction of shallow water limestones compared with deep sea shales can shift interpretation of depth difference to the higher values. While sediments of the Aeronian transitional zone are mainly represented by limestones (including also some marlstone intervals) having minimal diagenetic compaction, thick marlstone lenses later in the Silurian (Fig. 5) certainly were subjected to significant compaction decreasing the thickness of sediments. However, the value of the above discussion depends largely on the presumption of stable regional subsidence and lack or subordinate importance of differential vertical movements in the region. This can be inferred from the stability of general facies distribution patterns throughout the Silurian (Kaljo & Jürgenson, 1977). The maximum depth difference of 170 m derived from the Aeronian thick sediment lens corresponds well to the estimate made from the comparison with the Bering shelf, e.g. the sea depth at Priekule could be 100-200 m during low stands and 200-400 m at maximum high stands in the Telychian and upper Ludfordian.

Amplitudes and origin of Silurian sea level variations

The amplitudes of sea level variations can be derived from the estimates of the sea depths in the shallow shelf during sea level high stands. Considering the sea depth in the middle of the Telychian in the shallow shelf comparable with that in the deep shelf at sea level low stands, e.g. around 150-200 m, we get a sea level fall of up to 200 m for the mid-Telychian to lower Sheinwoodian reef and shoal facies. Sea level rise after the Ludfordian low stand can be even a bit larger. These supposed sea level changes are probably close to the possible maximum values. The minimum estimates of the Silurian sea level changes were made by Johnson et al. (1998) and Johnson (2006) from the morphology of rocky shores: 50-53 m in the Telychian, 16 m in the Homerian and 30 m in the Ludfordian. Larger minimum sea level changes (63-70 m) were established for the lower and middle Llandovery.

The sea depth change estimated on the basis of $\text{SiO}_2/\text{Al}_2\text{O}_3$ and $\text{K}_2\text{O}/\text{Al}_2\text{O}_3$ ratios is not linear in the Priekule section, because the grain size is relatively insensitive to water column fluctuations at times of sea level high stands, such as the Telychian and upper Ludfordian. During

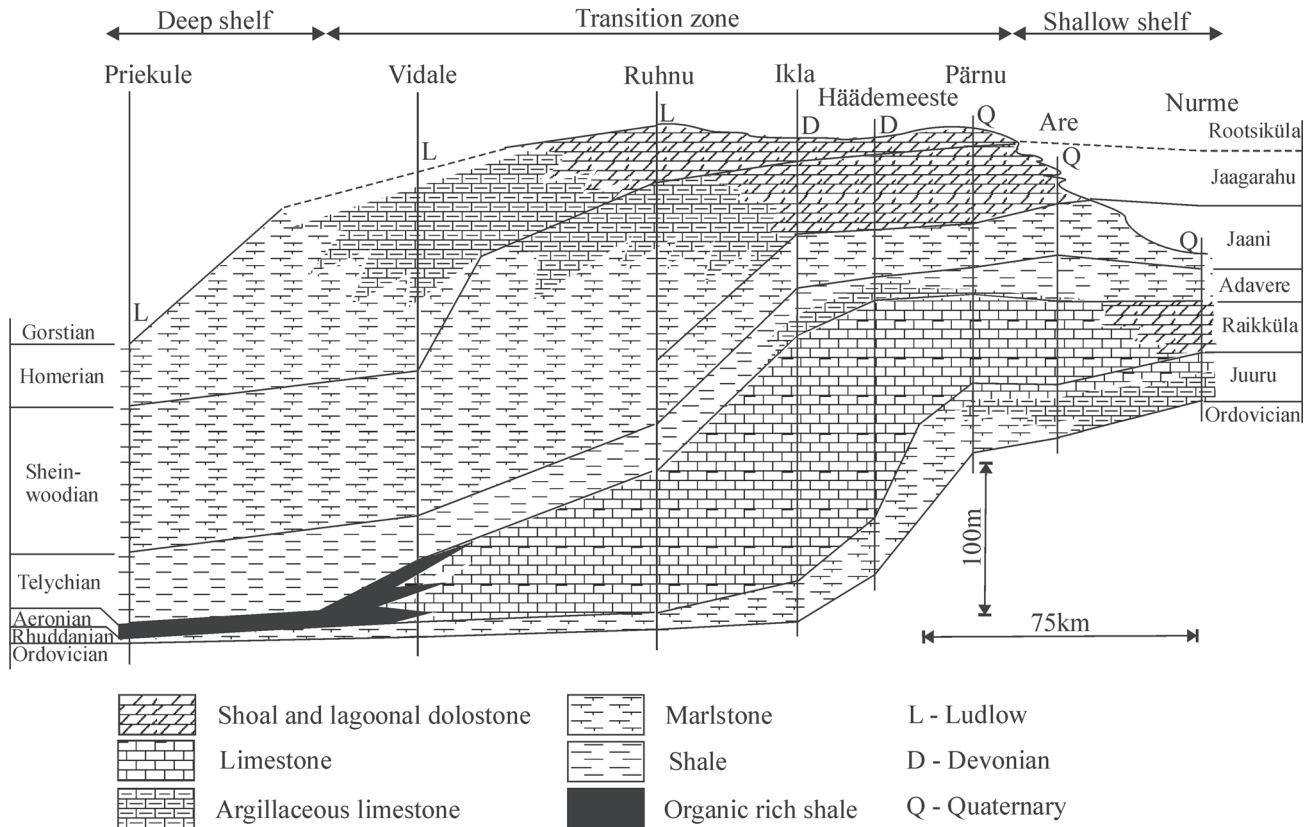


Fig. 5 - The cross section of lower Silurian sediments from shallow to deep shelf in the northern part of the Baltic Basin. The cross section illustrates filling of the slope with sediments in the transitional zone, causing basinward progradation of the shallow shelf. Differences in the thicknesses in the transitional zone and deep shelf hint at the height of the slope. For the cross section from Priekule to Ikla, as a nearly horizontal key-level the Ordovician/Silurian boundary was used, the one from Ikla to Nurme serves the boundary of the Jaani and Jaagarahu stages. Left: international stages, right: regional stages. Sediments above the section are: L=Ludlow, D=Devonian, Q=Quaternary.

sea level low stands these ratios respond more strongly, i.e. they increase or decrease to a greater extent.

The uncertainty of the estimates of sea depths and depth changes in the present discussion and in Fig. 4 is probably around $\pm 30\%$. If we reduce the depth change estimates in Fig. 4 by 30%, we get values quite close to the minimum estimates made by Johnson et al. (1998). This variant can be argued, considering differential subsidence on the Baltic Silurian Shelf and ignoring the Bering Shelf as an appropriate model for comparison. The comparison with the Bering Shelf leaves the maximum depth estimate for silty sediments open, because the shelf does not extend to the depths of stable clay sedimentation.

The average estimates of total sea depth (level) changes are larger in the present discussion (Fig. 4) than those presented by Johnson (1996) and Haq and Shutter (2008), but are comparable with glacioeustatic sea level changes in the Cenozoic.

Carbonate sedimentation and sulphur fixation related to sea level changes

The rise in the concentration of carbonate material at the levels of sea low stands can be caused by shift of shallow shelf sedimentation oceanwards in accord with sea retreat. In the deep shelf carbonate accumulation is hindered by low pH. Low pH of deep waters of the Silurian East Baltic Basin is indicated by the occurrence of

authigenic kaolinite in altered volcanic ash layers in the deep shelf area (Kiipli et al., 2007). Higher carbonate contents at the levels of increased $\text{SiO}_2/\text{Al}_2\text{O}_3$ and $\text{K}_2\text{O}/\text{Al}_2\text{O}_3$ ratios (Fig. 3) support the hypothesis of sea regression in the respective periods.

Sulphur fixation into sediments depends on the reduction of sulphate in pore water, caused by the bacterial degradation of organic matter. Decrease in water depth, i.e. regression, shifts the shallow facies basinwards. In the shallow shelf the higher flux of organic matter and its more rapid burial due to higher sedimentation rate may result in increased sulphur content (Berner, 1971). Alternatively, higher primary bioproductivity can also enhance the flux of organic matter into seafloor. Which case is prevailing in the investigated section is not clear.

Comparison of sea level changes and global $\delta^{13}\text{C}$ variations

Positive $\delta^{13}\text{C}$ excursions, identified in many studies worldwide, reflect global events (Saltzman, 2005). Good correlation of increased $\text{SiO}_2/\text{Al}_2\text{O}_3$ and $\text{K}_2\text{O}/\text{Al}_2\text{O}_3$ ratios in the Priekule section with globally correlated positive $\delta^{13}\text{C}$ excursions indicates that these levels correspond to global regressions (Fig. 4).

By analogy with the end Ordovician glaciation, short-range sea level falls in the Silurian associated with $\delta^{13}\text{C}$ positive excursions can be related to the eustatic changes

caused by the growth of polar ice-sheets (McKerrow, 1979). This corresponds well to the fact noticed by many researchers, that positive carbon isotope excursions coincide with sea level low stands. Melchin & Holmden (2006a, b) proposed a direct causal relationship between positive carbon isotope excursions and sea level low stands.

CONCLUSIONS

Using the $\text{SiO}_2/\text{Al}_2\text{O}_3$ and $\text{K}_2\text{O}/\text{Al}_2\text{O}_3$ ratios in the deep shelf Priekule section the curve of sea depth changes was constructed, which correlates well with the curves of sea level variations provided by other researchers. On the basis of several geological and geochemical data sets a provisional model of sea depth variations at the Priekule locality is presented, showing the maximum amplitude of sea level fall of 200 m ($\pm 30\%$) in the Telychian to Sheinwoodian and rise of 240 m ($\pm 30\%$) in the mid- to upper Ludfordian. The comparison of carbon isotope positive excursions with sea level falls, and increased contents of sulphur and carbonates revealed a good general correlation. The correlation between eustasy and carbon isotope excursions supports the idea of periodical environmental changes in the Silurian, possibly related to glaciations.

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