Silurian sedimentation in East Siberia. Evidence for variations in the rate of tectonic subsidence occurring without any significant sea-level changes

Eugene V. Artyushkov[1] & Peter A. Chekhovich[1,2]

[1] *Institute of Physics of the Earth, 10 B. Gruzinskaya, GSP-5, 123995, Moscow, Russia*

[2] *Institute of the Lithosphere of Marginal Seas, 22 Staromonetny , 119180, Moscow, Russia*

Corresponding author:	Eugene V. Artyushkov
E-mail address of corresponding author:	pchekh@ilran.ru subject <for Artyushkov>
Words of text	10,949
References	89
Tables	3
Figures	25

Abstract: It is widely accepted that major variations of sea level had occurred in the Phanerozoic. Third-order cycles, 1–10 Myr long with amplitudes of 20–100 m, are of special interest for geochronology and petroleum geology. The amplitude of sea-level changes in the Silurian was estimated based on highly detailed data on the East Siberian basin, 2×10^6 km^2 in size. Fischer plots were compiled basing on thickness of 54 chronostratigraphic units — chronozones, each corresponding to time interval ~ 0.5 Myr long. A synchronism of the chronozones ensures reliable comparison of the changes occurring with time in accommodation space in different regions. The occurrence of sub-horizontal Fischer plots in several regions indicates that sea-level changes were very small in the Silurian (≤ 5–10 m). A mathematical analysis of relative sea-level changes, which takes into account a finite rate of crustal subsidence and different possible forms of eustatic fluctuations, shows that at the observed structure of numerous Silurian successions in East Siberia, eustatic sea-level changes of the third order could not have exceed 6–20 m. In several regions of East Siberia,

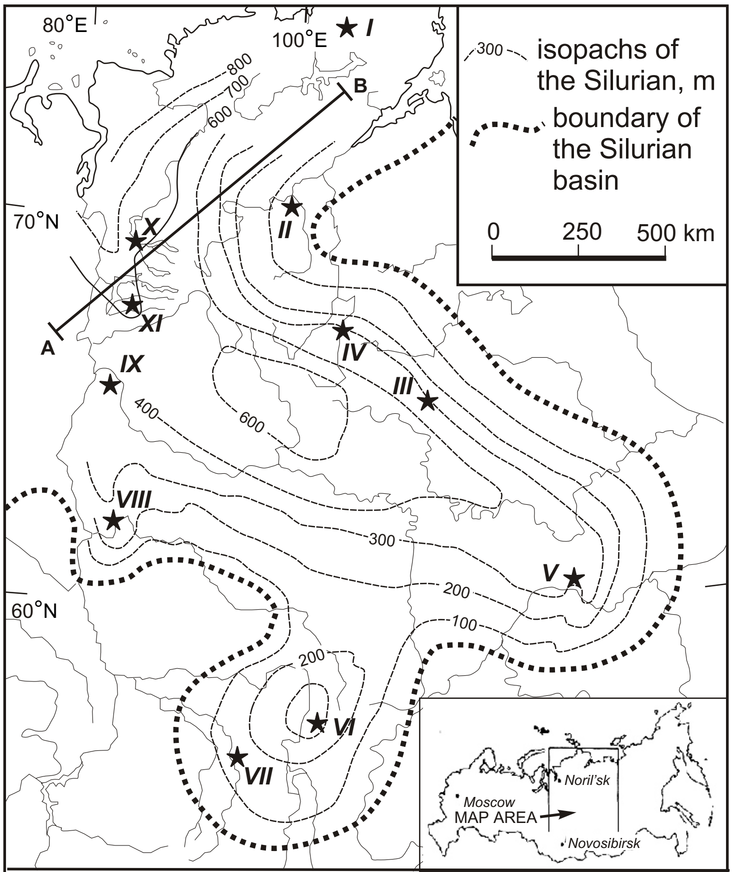
the rate of crustal subsidence varied as strongly as several hundred percent at different times. These variations showed good similarity in form, but their amplitudes were different at different places in the basin. Most probably, they were caused by variations in the rate of phase transformations in mafic rocks in the lower crust. Basing on the example of East Baltic, the absence of large-scale third-order cycles in eustatic changes of sea level has been proven earlier for the Cambrian and earliest Ordovician. Probably, a similar situation was characteristic of many other epochs, when no large glaciations occurred, while many rapid changes of water depth in cratonic areas actually resulted from vertical crustal movements.

A lot of geological and seismic profiling data is available to prove that large-scale changes of water depth took place in the Phanerozoic sedimentation basins. Such variations are commonly attributed to eustatic falls and rises of the sea level (Haq *et al*. 1987; Hallam 1992; Emery & Meyers 1996; de Graciansky *et al*. 1998). Eustatic curves include cycles of different lengths. Third-order cycles, 1–10 Myr long with amplitudes 20–100 m, which are often called "eustatic events", are of special interest for hydrocarbon prospecting (Posamentier & Allen 2000) and geochronology (Cooper & Nowlan 1999). Many authors (e.g., Harris & Laws 1997; Maurer 2000; Cheng *et al*. 2001) have demonstrated the influence of crustal uplift and subsidence on water-depth variations of the third order. Moreover, the very existence of most eustatic events has been doubted since the accuracy of biostratigraphic zonation is usually insufficient to prove a synchronicity of events ~ 1 Myr long on different continents (Miall 1992, 1997, Miall & Miall 2001). A serious problem is also that no physical mechanisms have been proposed to explain the frequent sea-level changes with amplitudes 20–100 m (Harrison 1990). Large-scale and rapid falls and rises of sea level take place due to major glaciations. No large ice sheets existed during many epochs when pronounced and short-term relative sea-level changes took place. For example, a number of sea-level peaks, 1–3 Myr long, are have been proposed for the Late Cretaceous, Paleocene and Eocene (Haq *et al*. 1987) when no large-scale glaciations occurred. However, most authors believe that numerous eustatic events occurred over most of the Phanerozoic (Haq *et al*. 1987; Hallam 1992; de Graciansky *et al*. 1998; Drzewiecki & Simo 2000; Schwarzacher 2000).

Basing on the variations of water depth within six cratonic areas, eight eustatic events, from 1 Myr to several Myr long, have been proposed for the Silurian (Johnson 1996). Using conventional methods of water depth determination from geological data (Brett *et al*. 1993), the amplitude of these events has been estimated as ~ 30–130 m (Artyushkov & Chekhovich 2001). A lot of geological data has been obtained for the Silurian in East Siberia (Tesakov *et al*. 1986, 1998a, 1998b). On this basis, modeling of relative sea-level changes has been done for eustatic events 1–3 Myr long with an abrupt regressive phase, and for events of a harmonic form (ibid.). Maximum possible amplitude of these events has been estimated as 20–30 m. Under such circumstances, large-scale variations of water depth in the Silurian (~ 30–130 m) indicate rapid vertical crustal movements. Highly detailed data have been recently published on the East Siberian basin in the Silurian (Tesakov *et al*. 2000). This allows us to make more accurate estimates of eustatic sea-level fluctuations in the Silurian, and to consider temporal and spatial variations in the rate of crustal subsidence in the basin, and to propose a possible physical mechanism for these variations.

Silurian basin of East Siberia

Silurian deposits occur on the East Siberian Craton over the area of ~ 2×10^6 km^2 (Fig. 1). Their thickness reaches ~ 600 m in the central basin part and increases to ~ 800 m toward the northwest. Practically unmetamorphosed and gently folded Silurian deposits are found along numerous rivers. For example, in the mid-course of the Moyero river, they are found along 70 km in steep banks, up to 50–80 m high, which represents a continuous succession of the



I - Southern Taimyr
II - Ledyanskaya
III - Morkoka River
IV - Moyero River
V - Nyuya River
VI - Ilim River
VII - Balturino
VIII - Kochumdek River
IX - Turukhansk
X - Noril'sk
XI - Igarka

Fig. 1 to the paper by Artyushkov and Chekhovich

Silurian and the lowermost Devonian (Sokolov 1985, 1992; Tesakov *et al*. 2000). In many places, Silurian rocks have been also extensively drilled. Based on a detailed analysis of sedimentary facies and remnants of fauna, a number of continuous stratigraphic successions have been constructed for the Silurian in East Siberia (e.g., Figs. A.1–A.3 in the Appendix) (Tesakov *et al*. 1986, 1998a, 1998b, 2000; Sokolov 1985, 1992). The completeness of data is considerably better than for the other Silurian basins where the successions are commonly constructed using fragments described in regions which are far apart.

Based on lithological and paleontological data, sedimentary successions are subdivided into units of different type and rank (Murphy & Salvador 1999). The smallest standard (globally correlated) chronostratigraphic units are a “stage” and, sometime, “substage”. For the Phanerozoic, the duration of stages is usually several million years, and most substages are 1–2 Myr long. In some regions, for which highly detailed data are available, the smallest chronostratigraphic unit represents virtually a “chronozone” corresponding to a time interval of 0.5–1 Myr. This is characteristic, for example, of the Middle and Upper Devonian of Euroamerica (Johnson *et al*. 1985) and the Mississippian (lower part of the Carboniferous) in the Midcontinent of the North American Craton (Ross & Ross 1987). For the Silurian, 26 Myr long (Gradstein & Ogg 1996), global correlation is based on graptolite and conodont zonations, which include 38 and 12 zones, respectively. Regional correlation is based on the coral, brachiopod, ostracod, and vertebrate zonations, which also include a number of zones. During the Silurian, the East Siberian basin had a good connection to the ocean in the northwest. Subdivision of the Silurian in this area has been done using both global (graptolite and conodont) and regional scales based on hundreds of species (Tesakov *et al*. 1998a,b, 2000). The occurrence of numerous exposures along the rivers allowed to establish reliable correlations between the successions all over the basin. As a result, the Silurian of East

Siberia has been subdivided into 54 chronozones, which are equivalent to the time intervals (chrons), each corresponding to 0.48 Myr on the average (Fig. 2).

The depth of water (h_w, see also Table 1) in paleobasins, in the Silurian in particular, is commonly estimated from benthic associations (fauna and flora) and sedimentary patterns (Brett *et al*. 1993; Scrutton 1998; Watkins *et al*. 2000). According to this approach, marginal basin parts (h_w from 0 to 150–200 m) are subdivided into a number of bathymetric zones with a certain h_w characteristic of each zone. This approach has been used for the East Siberian Basin in the Silurian (Tesakov *et al*. 1986, 1998a, 2000; Sokolov 1992; Johnson *et al*. 1997). Following Wilson (1975), for the basin's shallowest part a more detailed subdivision has been used which includes a carbonate coastal shoal ($h_w \sim$ 0–10 m), lagoon between the shoal and the coast ($h_w \sim$ 0–10 m), and the uppermost shelf above the normal (fair-weather) wave basis ($h_w \sim$ 10–15 m). In the central part of the coastal shoal, composed of coral and algae build-ups and their debris, the depth of water is $h_w \sim$ 0–5 m.

Based on a large amount of sedimentological and paleontological data, it has been determined for a number of places in East Siberia, in which bathymetric zones sea bottom was located at different time levels of the Silurian (Tesakov 1981; Tesakov *et al*. 1986, 2000; Sokolov 1992). Using these data, bathymetric curves have been plotted for several regions of East Siberia (Artyushkov & Chekhovich 2001). Let us briefly describe the evolution of the basin during the standard ages of the Silurian (Gradstein & Ogg 1996) as shown in Table 2. In the Late Ordovician, East Siberia was covered by a shallow epeiric sea. Around the transition from the Ordovician to the Silurian, subaerial exposure of a short duration occurred over most of the basin — in its northern and central parts. Then a rapid transgression followed, and in 1–2 Myr pelagic environment with water depths $h_w \sim$ 100 m had established in these regions (e.g., I–IV, VIII–XI in Fig. 1). On the basin's margins, in the Ilim (VI) and Balturino (VII) regions on the south and in the Nyuya region (V) on the southeast, marine deposition was

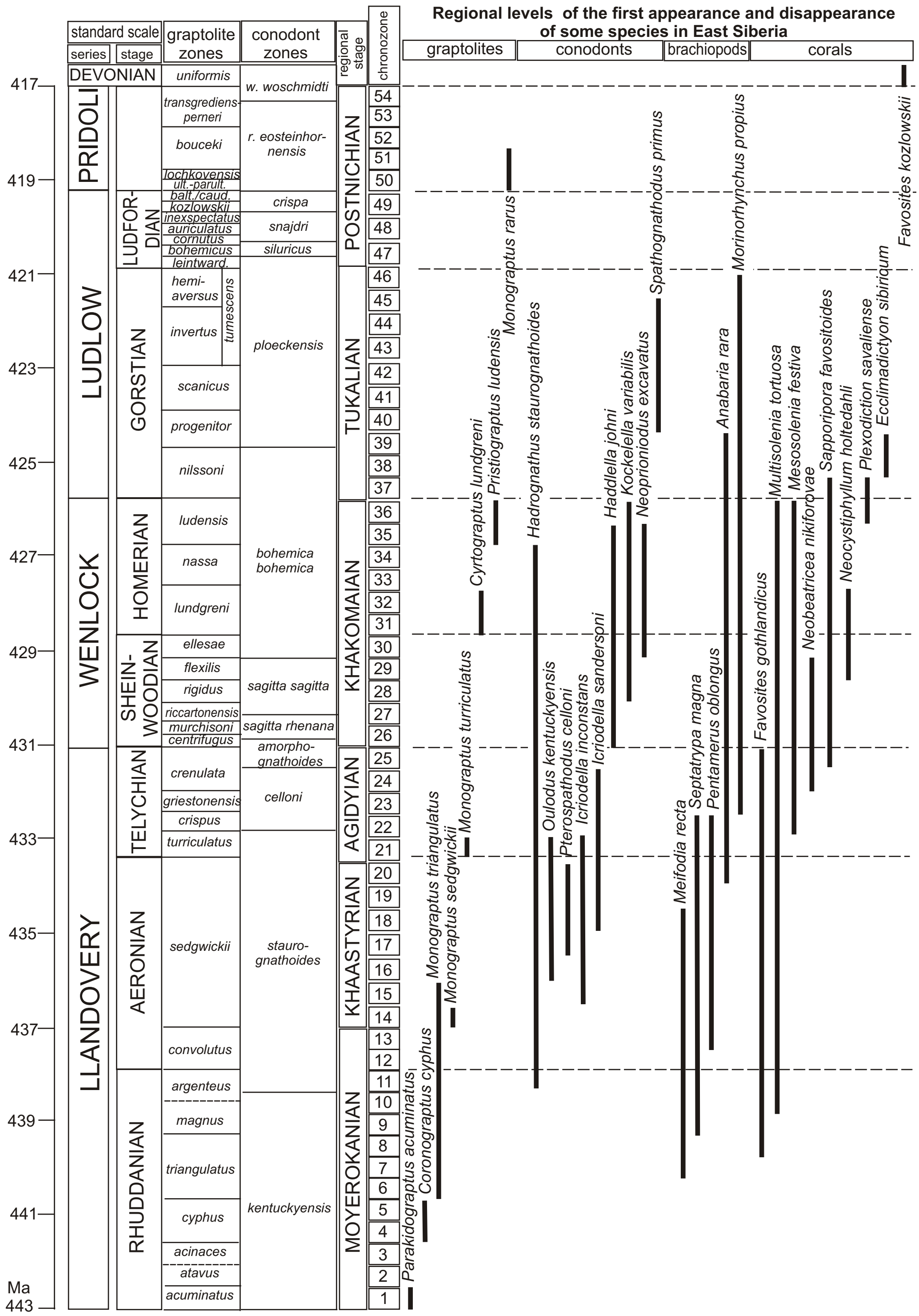


Fig. 2 to the paper by Artyushkov and Chekhovich

Table 1. *List of symbols*

Notation	Description
h_w	Depth of water
h_w^0	Depth of water before eustatic event
d	Thickness of strong part of lithosphere
d_0	Mean value of d
Δd	Lateral variations of d
L	Width of lateral variations of d
ΔF	Change in force acting along lithosphere
c	Vertical displacement of lithosphere
c_0	Amplitude of vertical displacement of lithosphere
ρ_m	Density of mantle — 3350 kg /m^3
ρ_s	Density of sediments
g	Acceleration due to gravity — 9.81 m/s^2
T	Duration of eustatic event
t	Time
τ	Dimensionless time (t/T)
Δt_{cz}	Duration of the interval corresponding to chronozone
Δt_{cz}^0	Initial duration of chronozone
$\delta(\Delta t_{cz})$	Change of chronozone's duration
n	Number of chronozones in certain time interval
Δt	Change of duration of time interval comprising n chronozones due to change in their duration
Δh_{cz}	Thickness of chronozone

Table 1. *(Continued)*

Notation	Description
Δh_s	Change of thickness of sediments of time interval comprising *n* chronozones due to change in their duration
Δh_{cz}^0	Initial thickness of chronozone
Δt_{sa}	Duration of subaerial exposure and non-deposition
z_0	Minimum altitude at which subaerial exposure becomes noticeable
b	Amplitude of eustatic event
b_m	Minimum amplitude of resolvable events
a	Mean rate of crustal subsidence
a_0	Rate of crustal subsidence necessary for compensation of sea-level changes by changes in chronozones duration
a'	Mean rate of crustal subsidence at certain time interval
ζ	Ordinate of crustal surface with respect to sea level
ζ_{eu}	Eustatic signal
$\Delta\zeta_{eu}$	Change of sea level during a chronozone
ζ_{eu}^0	Sea-level change required for subaerial exposure under local isostasy
ξ	Deviation from horizontal axis in Fischer plot
$\Delta\xi$	Change in deviation ξ during certain time interval

Table 2. *Rates of crustal subsidence during the Silurian in the case when chronozone lengths are assumed to be variable*

Standard subdivision	Number of chronozones (n)	Length of standard subdivision, Myr*	Average chronozone length (Δt_{cz}), Myr	Minimum rate of crustal subsidence (a), m/Myr**	Region
Rhuddanian	11	4	0.36	11.2	Nyuya River
Aeronian	9	6.9	0.76	16.5	Nyuya River
Telychian	5	4.1	0.84	6.4	Balturino
Wenlock	11	5	0.45	7.1	Ledyanskaya
Ludlow	13	4	0.31	15	Kochumdek
Pridoli	5	2	0.4	10.6	Kochumdek

*The length of the Llandovery, which comprises the Rhuddanian, Aeronian, and Telychian, Wenlock, Ludlow and Pridoli (Myr), was taken according to Gradstein & Ogg (1996). For this time scale, relative lengths of the Rhuddanian, Aeronian, and Telychian were taken according to Johnson (1996), and Tesakov *et al*. (1998a).

**Rock compaction is taken into account (Artyushkov & Chekhovich 2001).

continuous across the Ordovician-Silurian boundary. At the start of the Silurian, the depth of water in these regions (V–VII) was ≤ 10 m, and slow deposition at such depths continued into the Silurian, but the upper part of the Silurian successions has since been eroded. In the Ilim region (VI), shallow water ($h_w \leq 10$ m) Silurian deposits have preserved from the time interval of ~ 12 Myr — from the initial Silurian and until the lower Telychian. In the Balturino region (VII), the age of such sediments is from the early Rhuddanian and to the early Wenlock (~ 16 Myr). In the Nyuya region (V), Silurian sediments formed at $h_w \leq 10$ m have preserved from the base Silurian and until the lower Ludlow (~ 20 Myr).

The fact that shallow water conditions had preserved on the southern and southeastern basin margins in the early Llandovery indicates that rapid deepening in the central and northern parts of the basin at the start of the Silurian was of a tectonic origin (Artyushkov & Chekhovich 2001). The water filled depression, initially ~ 100 m deep, was shoaling and filling with sediments in the early Llandovery. In the middle of the Llandovery, large areas with water depths $h_w \leq 10$ m, probably up to 15–20 m in some places, existed in the Nyuya, Ilim and Balturino regions on the basin margins (V–VII in Fig. 3). The depth of water gradually increased to ~ 100 m toward the northwest. In the early Wenlock, water depths of ≤ 10 m were characteristic of most of the basin (Fig. 4). The depth of water reached 15–30 m in the basin's narrow axial part. This region was separated from a wide lagoon by a shoal which was several hundred kilometers wide and had water depth of $h_w \sim 0$–5 m. By the end of the Silurian, the depth of water was $h_w \leq 10$ m all over the East Siberian basin (Tesakov *et al*. 2000).

Fischer plots based on elementary cycles

In this paper, we consider temporal and spatial variations in the rate of crustal subsidence in East Siberia and sea-level changes during the Silurian. The study could have been done in

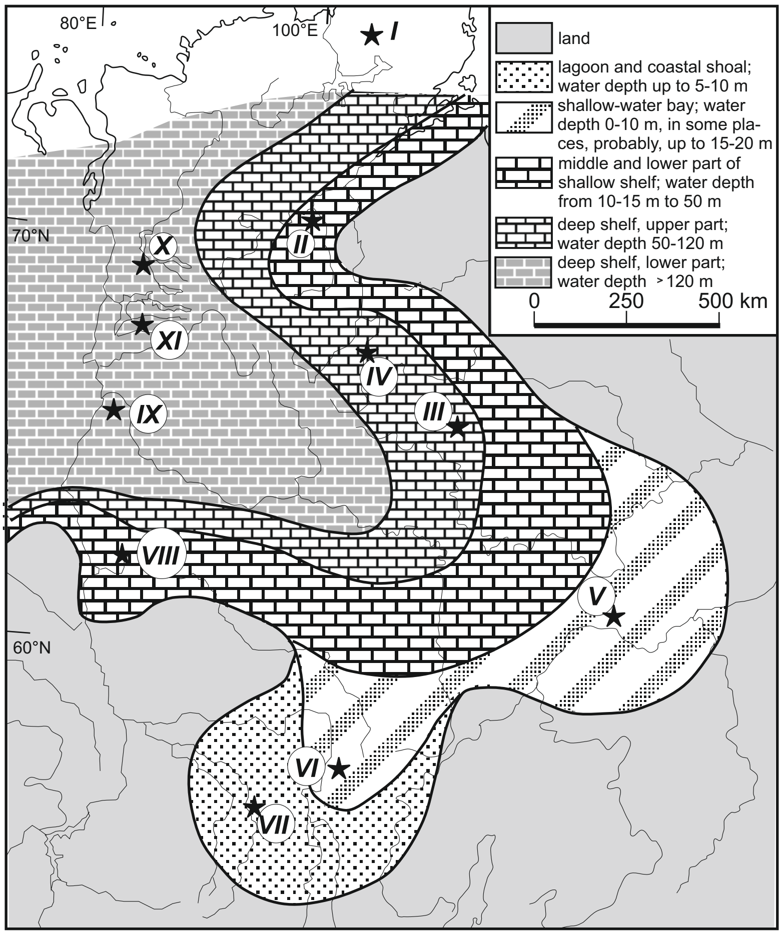


Fig. 3 to the paper by Artyushkov and Chekhovich

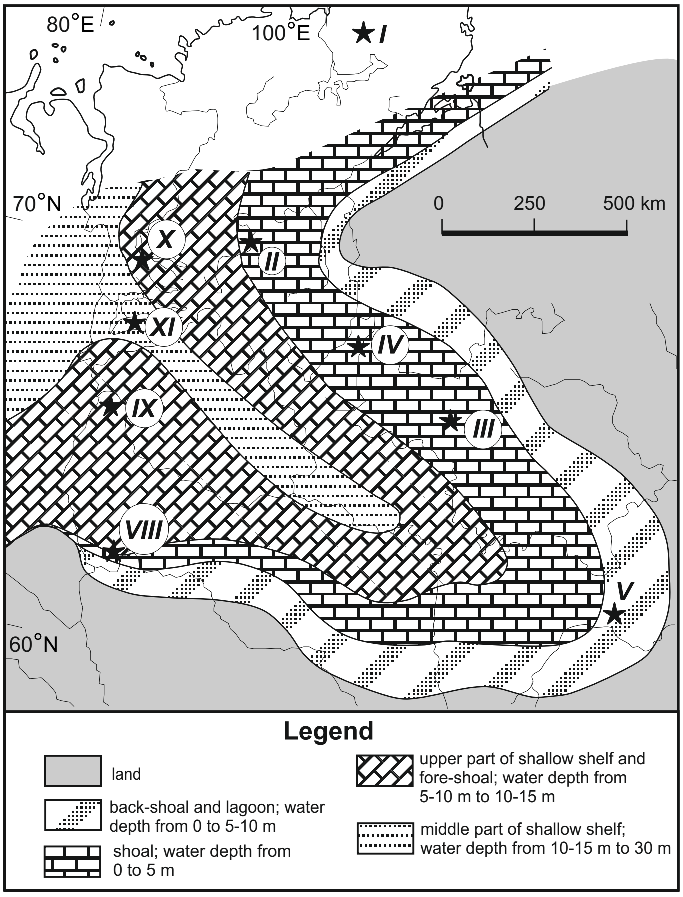


Fig.4 to the paper by Artyushkov and Chekhovich different ways, but we chose the technique of Fischer plots (Fischer 1964) which is well familiar to sedimentologists. Using this approach, many authors have evaluated relative sea-level changes of the third order (Osleger & Read 1991; Goldhammer *et al*. 1993; Elrick 1995; Bosence *et al*. 2000; Cheng *et al*. 2001). Since most scientists specializing in geodynamics are unfamiliar with such plots, we'll provide a brief description of the process of their construction.

Relative changes of sea level produce changes in accommodation space where the deposition of sediments takes place. Under the conditions of continuous deposition in very shallow water, i.e. when sea bottom is close to the surface, relative sea-level rises and falls cause increases and decreases in sediment thickness, respectively; large-scale falls can produce erosion and hiatus. Sedimentary successions of shallow carbonate platforms include upward-shallowing elementary cycles of a meter scale with duration of 0.01-1 Myr. Fischer plots were constructed using large sets of such cycles. In each cycle, sediment thickness was compared with the thickness corresponding to crustal subsidence at a constant rate – line OO* in Fig. 5. Subsidence during one elementary cycle equals AB. If sediment thickness AC is larger than tectonic subsidence AB (Fig. 5a), line OC deflects upwards. If sediment thickness is smaller than crustal subsidence (Fig. 5b), line OC deflects downwards. In a sequence of elementary plots (Figs. A.4 and 6), point C of plot n corresponds to point O of the next plot $n + 1$.

It is often considered that elementary cycles are related to small-scale, quasi-periodic eustatic fluctuations most probably driven by Milankovich orbital forcing, thus the cycles are also quasi-periodic (Goldhammer *et al*. 1991; Read *et al*. 1991; Schwarzacher 2000). Then, under an uniform tectonic subsidence, Fischer plots, which include a large number of elementary cycles, will describe eustatic sea-level changes of the third order — rises and falls in the plots will be equal to sea-level rises and falls, respectively (e.g., Osleger & Read 1991;

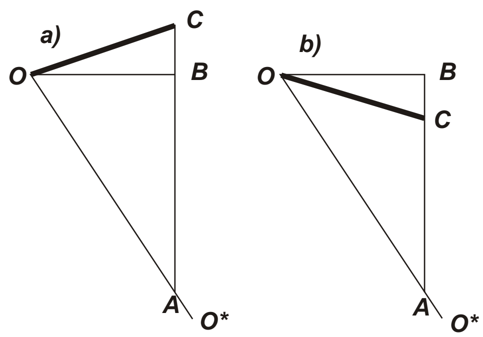


Fig. 5 to the paper by Artyushkov and Chekhovich

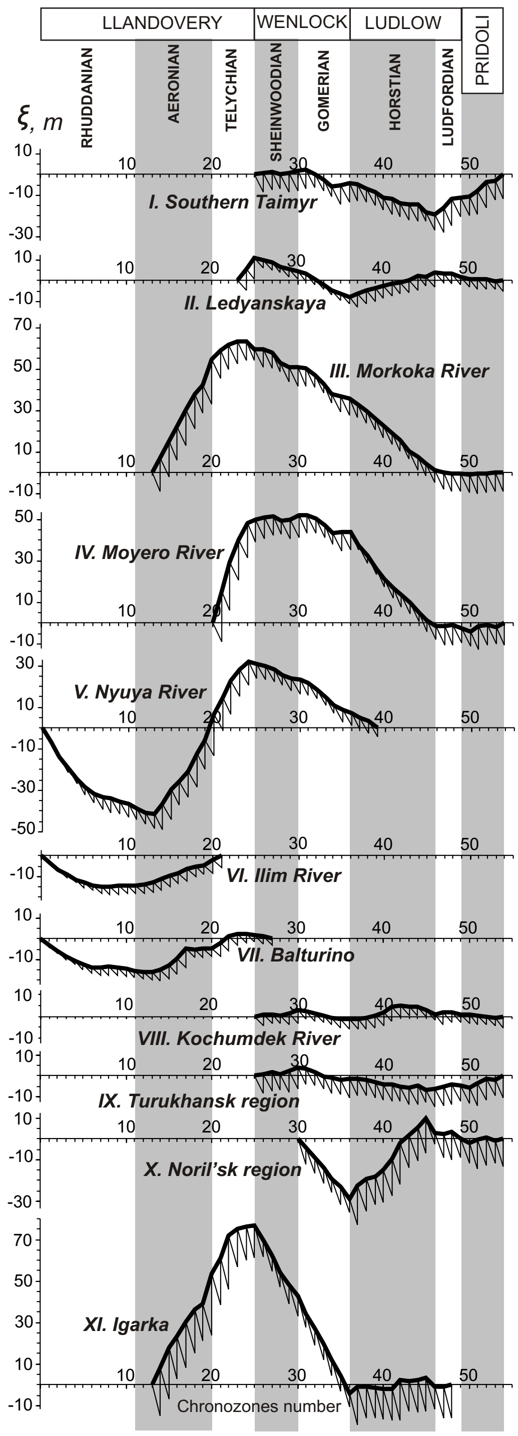


Fig. 6 to the paper by Artyushkov and Chekhovich

Goldhammer *et al*. 1993; Elrick 1995; Bosence *et al*. 2000). As suggested by Ginsburg (1971), elementary cycles can be also produced by a well known process of migration of tidal flats, which is due to a transport of sediments by currents in shallow marginal parts of sedimentary basins. Then lengths of the elementary cycles can change in time randomly with the corresponding random changes in the elementary cycles' thicknesses which is observed in many outcrops (Drummond & Wilkinson 1993 a,b; Wilkinson *et al*. 1997). An increase in cycle length will increase sediment thicknesses, thus producing rises in Fischer plots, even under a stable sea-level and uniform crustal subsidence. A decrease in cycle length will decrease sediment thicknesses resulting in falls in Fischer plots. As follows from numerical modeling (Burgess *et al*. 2001), Fischer plots based on elementary cycles produced by random processes of near-shore deposition cannot be used for estimates of long-term sea-level fluctuations even under a constant rate of crustal subsidence.

Fischer plots based on elementary cycles can describe sea-level changes of the third order, if two basic conditions are fulfilled: (1) elementary cycles are quasi-periodic, and (2) the rate of crustal subsidence is constant. The data on East Siberia can be used to check the validity of these assumption, as well as the applicability of Fischer plots based on elementary cycles for evaluation of sea-level changes. In Fig. A.4, such plots are presented for five regions of East Siberia in the Silurian. They correspond to those epochs when deposition took place at very shallow depths. Eustatic sea-level fluctuations are of a global character and should be similar for all the regions. Plots of Fig. A.4 differ for different regions. Hence they do not describe sea-level changes during the Silurian. As shown in the Appendix, at that epoch, the duration of elementary cycles in East Siberia changed in time, i.e. condition (1) was not fulfilled. Moreover, elementary cycles were not synchronous in different regions which caused large differences in plots for different regions in Fig. A.4. Based on the Figure, it cannot be said was there any influence of changes in the rate of crustal subsidence on the Fischer plots.

However, it is well known that, in most sedimentary basins, the rate of crustal subsidence changed in time (e.g., Beloussov 1980; Sloss 1988). Hence assumption (2) can be also unrealistic, at least for long periods of time. This will be considered below for the case of East Siberia in the Silurian.

Fischer plots based on sediment thicknesses of the Silurian chronozones

Large regions with deposition at very shallow depths $h_w \leq 10$ m existed in East Siberia throughout the Silurian. Deposition usually occurred in the peritidal zone or in the upper part of the subtidal zone (Tesakov *et al*. 2000). Due to the uncertainty of timing of elementary cycles in the Silurian successions, Fischer plots based on such cycles cannot be used for the reconstruction of sea-level changes. Silurian successions of East Siberia are subdivided into chronozones ~ 0.5 Myr each. Their lengths fall within the range of the elementary cycles (0.01–1 Myr) used in Fischer plots. Therefore we can construct Fischer plots, using sediment thicknesses of the chronozones (Δh_{cz}) for those parts of sedimentary successions which correspond to the periods of deposition at $h_w \leq 10$ m. The plots constructed in this way for eleven regions of East Siberia are presented in Fig. 6. Chronozone thicknesses Δh_{cz} are taken from Tesakov *et al*. (1998b, 2000).

In Fischer plots based on elementary cycles, “thin” cycles usually outnumber “thick” cycles two to one (Sadler *at al*. 1993). Then, taking into account the usual scatter of cycle thicknesses, it follows that more than 40 cycles, preferably more than 50 cycles are necessary for obtaining reliable Fischer plots (ibid.). In the case of random distribution of chronozone lengths with a predominance of short chronozones, a large number of chronozones would be required for the construction of reliable plots. Fischer plots presented on Fig. 6 were constructed on the basis of 21–41 chronozones which is insufficient in view of what was said above. However, in Fig. 6, “thin” chronozones are predominant only in three plots (III–V), while the other eight plots comprise comparable numbers of “thin” and “thick” chronozones. Also, it cannot be ruled out that the lengths of the Silurian chronozones (Δt_{cz}) were not as random as those of the elementary cycles. Moreover, in contrast to Fischer plots based on elementary cycles of uncertain timing, plots of Fig. 6 were based on synchronous units. This allows us to compare the plots for different regions which leads to several important conclusions.

Plots on Fig. 6 show cumulative sediment thickness deviations, corrected for compaction (Artyushkov & Chekhovich 2001), from the thickness corresponding to uniform crustal subsidence under the assumption of a constant duration of the chronozones Δt_{cz}. Deviation amplitudes reach 30–75 m, i.e. strongly exceed the deposition depths. Under such conditions, the main factors which can produce such deviations are (1) variations in the duration of the chronozones, (2) eustatic sea-level variations, and (3) variations in the rate of crustal subsidence. Let us discuss possible contributions of these factors.

Fig. 6 includes two types of plots: with large and small deviations from the horizontal axis. In the plots of the first type (III–V and XI) deviations reach 50–75 m, i.e. are within the range commonly associated with third-order cycles (20–100 m). In plots I and X, deviations are 20–30 m which is also within the range. However, the duration of the deviations equals ~ 10–15 Myr which is typical rather of second-order cycles. In plots of the second type (II, VIII, and IX), deviations in the Late Silurian (Wenlock–Pridoli) do not exceed 5–10 m. In plots VI and VII, falls of 15 m occur in the first half of the early Silurian (Llandovery). Very small deviations of ≤ 5 m are also observed in some segments of the plots of the first type: plot I in the Sheinwoodian, plots III, IV, and X in the Ludfordian–Pridoli, and plot XI in the Ludlow. All these values are considerably smaller than eustatic fluctuations of 20–100 m supposed for the third-order cycles of sea-level changes.

Sub-horizontal plots. Indications for relative stability of the sea level

Let's consider the conditions necessary for the formation of subhorizontal segments in plots I–IV and VIII–IX. Suppose that duration of the chronozones Δt_{cz} varied in time, while sea level remained stable and the rate of crustal subsidence was constant. Then, thickness of the sediments corresponding to a chronozone will be as follows:

$$\Delta h_{cz} \approx a\Delta t_{cz}, \tag{1}$$

where a is the rate of crustal subsidence. Assume, for example, that chronozone duration Δt_{cz} increases by $\delta(\Delta t_{cz})$: $\Delta t_{cz} = \Delta t_{cz}^0 + \delta(\Delta t_{cz})$. Then, according to (1), the chronozone thickness increases by $a\delta(\Delta t_{cz})$: $\Delta h_{cz} = \Delta h_{cz}^0 + a\delta(\Delta t_{cz})$ (Fig. 7a). In an elementary Fischer plot, where duration of the chronozones Δt_{cz} is supposed to be constant and equal to Δt_{cz}^0, this will result in a rise of the plot by $a\delta(\Delta t_{cz})$ (Fig. 7b). No rise will occur in the plot if there was a synchronous fall of sea level ($\Delta\zeta_{eu}$) of the same amplitude (Fig. 7c):

$$\Delta\zeta_{eu} = -\, a\delta(\Delta t_{cz}). \tag{2}$$

To explain small deviations in plots I–IV, VIII–IX, it can be supposed that large-scale falls and rises of sea level occurred in the Late Silurian; however, their influence on the plots was almost completely balanced by synchronous increases and decreases in Δt_{cz}. Sea-level changes $\Delta\zeta_{eu}$ are the same in all the regions. In different regions, crustal subsidence occurs at different rates. Condition (2) can be fulfilled only at a certain $a_0 = |\Delta\zeta_{eu}|/|\delta(\Delta t_{cz})|$. In the regions where a is larger ($a > a_0$), sea-level fall $\Delta\zeta_{eu}$ will not completely balance the increase in Δh_{cz}, thus a rise will occur in the Fischer plot (Fig. 7d). In the region with lower a ($a < a_0$), there is a fall on the plot (Fig. 7e). Regions I–IV, VIII–XI of East Siberia are characterized by large variations of *a*: 17.4, 12.8, 20.6, 21.4, 11.7, 21.8, 25.6, and 33 m/Myr. With such variations of *a* from place to place (as large as 200 percent), plots will not show sub-horizontal segments due to the compensation of sea-level changes by variations in chronozone lengths. This indicates a sub-periodicity of the Late Silurian chronozones in East Siberia.

It should be also noted that inverse correlation between the global sea-level changes and the lengths of regional chronozones Δt_{cz} is improbable for an area with a very small depth of water, especially taking into account that the Silurian chronozones are controlled by both regional and global zonations.

Given that chronozone lengths Δt_{cz} are nearly constant, it can be presumed that in the sub-horizontal segments of plots I–IV, and VIII–XI of Fig. 6, an influence of large-scale sea-level falls and rises was almost completely balanced by changes in the rate of crustal subsidence. To provide such balance, similar changes in the rate of crustal subsidence must have occurred in all the regions mentioned above, despite the fact that the average rate of crustal subsidence had varied in them by up to 200 percent. Furthermore, global eustatic fluctuations and regional vertical crustal movements in cratonic areas are independent phenomena. Even in one region, the probability for their balancing each other is very low. Actually, no large deviations synchronously occurred in regions VIII and IX, which are ~ 400 km apart, as well as in region II which is located as far as 1000 km from region VIII. Fischer plot is sub-horizontal for region I in the Sheinwoodian, region XI (650 km from region VIII) in the Wenlock, and regions III and IV (which are 900–1000 km from region VIII) in the Ludfordian and Pridoli. The probability of balancing of large-scale sea-level changes by changes in the rate of crustal subsidence in all the above regions is negligible.

Thus, for the Late Silurian, synchronous existence of three sub-horizontal plots (II, VIII, and IX) and sub-horizontal segments in plots I, III, IV, X, and XI is possible only if the following three conditions are simultaneously fulfilled: (1) eustatic sea-level changes did not exceed 5–10 m; (2) East Siberian chronozones were sub-periodic; and (3) crustal subsidence was nearly uniform in each region during those periods which correspond to sub-horizontal segments of Fischer plots.

In the Early Silurian, falls of about 15 m followed by rises of similar amplitude are seen on plots VI and VII of Fig. 6. Fall and rise on plot V are almost synchronous to those on plots VI and VII, but their amplitudes are by about three times larger. The mean rate of crustal subsidence in region VII (15.8 m/Myr) is about two times larger than in regions VI and VII (7.8 and 8.5 m/Myr, respectively). As shown above, this precludes deviations due to changes in the lengths of the chronozones. A large difference in the amplitude of the deviations indicates a strong influence of the tectonic factor; however, the role of eustatic fluctuations still needs to be considered. Since global eustatic fluctuations and regional changes in the rate of crustal subsidence in cratonic areas are independent phenomena, they cannot be correlated in time and have different lengths and amplitudes. Superposition of such uncorrelated processes with a comparable intensity in plots VI and VII would have destroyed their synchronicity to plot V. Hence eustatic fluctuations could account for only a minor portion of the total deviations of ~ 15 m in plots VI and VII, i.e. sea-level changes during the Early Silurian hardly exceeded ~ 5 m. In the Late Silurian such variations were ≤ 5–10 m. Thus, eustatic fluctuations were small throughout the Silurian Period, which lasted for 26 Myr. They were considerably smaller than sea-level changes of the third order (~ 20-100 m) supposed for the Phanerozoic in general (Haq *et al*. 1987; Hallam 1992; Ross & Ross 1987) and for the Silurian in particular (Johnson 1996).

Plots with large-scale falls and rises. Indications for changes in the rate of crustal subsidence

Shown on Fig. 6 are Fischer plots including both major (II–V, X, and XI) and minor (I, II, VI–IX) deviations. By comparing deviations (ξ) in different plots it is possible to determine factors responsible for the major ones. First, let's once again consider possible influence of changes in chronozone length. Suppose that within a time interval (Δt), which includes n chronozones, their average length changed by $\delta(\Delta t_{cz})$. Then, the interval's length would change by $\Delta t = n\Delta t_{cz}$ as compared to the case when chronozone length was constant. Given that the rate of crustal subsidence and the sea level were constant, this would lead to a change (Δh_s) in the thickness of sediments formed during this time interval by:

$$\Delta h_s = a\Delta t. \qquad (3)$$

Fischer plots were compiled using the assumption of constant chronozone (or elementary cycles) length. Therefore, a Δt change in deposition interval will lead to a Δh_s change in Fischer plot deviation, as determined by (3). Then, for synchronous time intervals, such deviation changes ($\Delta\xi$) will be proportional to the rates of crustal subsidence, a. Consider, for example, the interval of chronozones 21–24 in regions III–V, and VII. For this time interval (see plots III–V, VII on Fig. 6), the values of $\Delta\xi$ are 10, 46, 26, and 7 m, respectively, hence their ratio is 1:4.6:2.6:0.7. The average rates of crustal subsidence a in these regions were 18.8, 18.4, 15.8, and 8.5 m/Myr, respectively, and their ratios are quite different: 1:1.02:0.84:0.45. For the Wenlock (chronozones 26–36; see plots III–V, VIII, IX, and XI), the values of $\Delta\xi$ are 23, 5, 23, 0, 1.4, and 81 m, i.e. the ratios are 1:0.22:1:0:0.02:3.52. The average rates of crustal subsidence in these regions were 18.8, 18.4, 15.8, 9.2, 17.2, and 31.5 m/Myr and the ratios are 1:1.02:0.84:0.49:0.91:1.68, which is again quite different from the ratios of $\Delta\xi$. This confirms that no significant variations took place in chronozone length during the Silurian in East Siberia.

As follows from the above considerations, the existence of subhorizontal segments in plots of Fig. 6 indicates that sea level remained nearly stable during the Silurian, and the East Siberian chronozones were sub-periodical. Then the horizontal scale in Fig. 6 is sub-linear, and the large-scale deviations in the plots approximately reflect changes in the rate of crustal subsidence: the rises correspond to epochs of accelerated subsidence, and the falls took place when subsidence slowed down. In plots III–V, X and XI, changes in the rate of crustal subsidence are quite large. For example, in plot III, the average rate of subsidence a' was 32 m/Myr during the rise in the Aeronian and 12.6 m/Myr during the fall in the Horstian. In plot IV, a' = 33.6 m/Myr for the rise during chronozones 21–24 in the Telychian, and a = 10.9 m/Myr during the fall in the Horstian. In plot V, the rate of subsidence was extremely low during the first five chronozones of the Silurian: a' = 4 m/Myr, while a' = 29.7 m/Myr for the rise during chronozones 14–24 in the Aeronian and Telychian. In plot XI, a' = 44.7 m/Myr for the rise during chronozones 14–22, and a' = 16.2 m/Myr for the fall in the Wenlock.

It has to be noted that the quasi-synchronous existence of large-scale deviations in plots III–V, X, XI, and of sub-horizontal plots II, VI–IX is already sufficient to prove a strong influence of tectonic movements on Fischer plots. These plots are based on synchronous units; hence it is possible to make reliable comparison of changes in accommodation space for a number of regions and time intervals. If such changes are of eustatic origin, they will be same everywhere. Large differences in the plots show that in different regions of East Siberia accommodation space changed in time in different ways. This is a direct indication of existence of considerable changes in the rate of crustal subsidence in time.

The major falls and rises seen on the plots of Fig. 6 have different amplitudes, but in some cases they are nearly synchronous. This is characteristic of the falls seen in plots V, VI and VII in the Rhuddanian, and the rises in plots III–VII and XI in the Aeronian and Telychian. The fall in plot IV in the Horstian, and the fall in plot XI in the Wenlock are asynchronous. However, they both coincide in time with the long fall in plot III in the Wenlock and Horstian. Simultaneously with most of this fall, a fall is also observed on plot V in the Wenlock and earliest Ludlow; however, no younger sediments have been preserved in region V. Thus, accelerations and decelerations of crustal subsidence in East Siberia were, in most cases, roughly synchronous, but different in the amplitude. This suggests that they involved one and the same physical mechanism with the intensity variable in space. Let us discuss the main possibilities.

Thermal relaxation and changes in the forces acting in the lithosphere

Cooling of the lithosphere causes thermoelastic contraction of rocks and hence crustal subsidence (Sleep 1971; McKenzie 1978). Characteristic time of thermal relaxation equals ~ 10^2 Myr. In the Silurian, the Early Proterozoic lithosphere of East Siberia was ≥ 10^3 Myr old (Rosen *et al*. 1994). Therefore, thermal relaxation of the crust and mantle could not have played any significant role in subsidence. Moreover, thermal relaxation is a gradual process, and it could not have produced strong accelerations and decelerations of subsidence during ≤ 10 Myr in regions II–V, X and XI.

Large forces are acting in the lithosphere (Zoback 1992). Considerable lateral variations of lithospheric thickness (*d*) are found in many areas. Under such conditions, to balance the momentum of the forces acting along the lithosphere, in the gravity field, vertical deflections of the lithosphere arise from its isostatically equilibrium position (Fig. 8) (Artyushkov 1974, 1983). It has been proposed that rapid, large-scale changes in the depth of water in sedimentary basins occurred due to lithospheric displacements caused by changes in the forces acting along the lithosphere (Cloetingh *et al*. 1985). Such displacements (c) are proportional to $1/L^2$, where L is the characteristic width of lateral variations in lithospheric thickness (Artyushkov 1974, 1983). Therefore, they are significant only in relatively narrow areas. Suppose, for example, that thickness of the strong part of the lithosphere varies laterally as:

$$d = d_0 + \Delta d \sin(\pi x/L). \tag{4}$$

Assume that force acting along the lithosphere changes by ΔF. Then, vertical displacement of the lithosphere from its initial position is (Artyushkov *et al*. 2000a):

$$c \sim c_0 \sin(\pi x/L), \tag{5}$$

where amplitude of the displacement is:

$$c_0 = \pi^2 \Delta F \Delta d/[2(\rho_m - \rho_s) g L^2]. \tag{6}$$

Here ρ_m = 3350 kg/m^3, ρ_s are densities of the mantle and the sediments, respectively, and g = 9.81 m/s^2 is the gravitational acceleration. It is most probable that in the Silurian the characteristic horizontal dimension of lithospheric thickness variations in East Siberia was approximately equal to that of the basin: L ~ 1200–2000 km. At that time, thickness variations of the strong part of the Early Precambrian lithosphere of East Siberia hardly exceeded $2\Delta d$ ~ 20–30 km, which corresponds to Δd ~ 10–15 km. Suppose that force acting along the lithosphere changes by $\Delta F = 2\times10^{12}$ N m, which is roughly equivalent to the average presentday force caused by the spreading oceanic ridges (ridge push) (Artyushkov 1973, 1983). Taking in (6) ρ_s = 2500 kg/m^3 with the above values of the other parameters, we obtain: c_0 = 3–12 m. This is too small to account for the falls and rises with amplitudes of up to 75 m which are seen in the plots of Fig. 6.

Suppose now that regions with both increased and decreased lithospheric thicknesses existed in East Siberia in the Silurian, and their dimension L was by several times smaller than the basin width. Since $c_0 \sim 1/L^2$, this could increase lithospheric deflections by one order of magnitude and hence make them comparable with the observed ones. In regions with increased and reduced lithospheric thickness $\Delta d > 0$ and $\Delta d < 0$, respectively. Then, as follows from (5) and (6), vertical lithospheric displacements in such regions ought to have had opposite signs, and the basin remained close to regional isostasy. This was not the case for East Siberia in the Silurian where large-scale falls and rises (shown in plots of Fig. 6) were quasi-synchronous. Therefore, changes in forces acting along the lithosphere could have hardly been responsible for the observed changes in the rate of crustal subsidence.

This conclusion refers only to East Siberia in the Silurian. In many regions, the horizontal size L of lateral variations in d does not exceed several hundred kilometres. Changes in the forces acting along the lithosphere occurred from time to time in many regions. Then, as follows from the above estimates, vertical displacements in the lithosphere caused by these changes could have been between ~ 20 m and ~ 100 m, i.e. of the same order of magnitude as those characteristic of the third-order changes in the depth of water in sedimentary basins. Therefore, this mechanism could have been responsible for sea-level changes in some other cases.

Variations of the dynamic topography

Convective flows in the mantle cause lithospheric displacements from the equilibrium, and such displacements are called dynamic topography (Hager & Clayton 1989). In particular, dynamic topography can be generated by flows rising above subducting slabs of the oceanic lithosphere (Gurnis 1992; Burgess & Gurnis 1995; Coakley & Gurnis 1995; Burgess *et al*. 1997). Additional displacements of the lithosphere can be caused by its elastic bending under supracrustal stresses (volcanoes, fold and thrust sheets and clastics). Dynamic topography above the subducting plates can change in time due to changes in the position of subduction zones at the surface, as well as due to changes in the rate and dip angle of subduction. Similarly, elastic displacements of the lithosphere will change with changing supracrustal stresses.

This mechanism has been used to explain transgressive-regressive sequences in North American Phanerozoic cratonic strata, and vertical crustal movements in the Michigan Basin during the Middle Ordovician (ibid.). In the Silurian, the East Siberian basin was part of the Angara Craton (Fig. 9) (Şengör & Natal'in 1996). At that time, subduction took place under this craton along the line ABC, and under the adjacent Khanty-Mansi Ocean along the line DEF. These two subduction lines were separated by a transform fault CD. Therefore, the direction of subduction was approximately parallel to the fault CD, and oceanic slab subducting along line DEF did not reach the mantle beneath the Angara Craton (Fig. 8). Only the plate subducting along line ABC, 1100–1200 km long, penetrated under this craton.

Flows in the mantle have been considered for a certain value of the upper mantle viscosity (Gurnis 1992; Coakley & Gurnis 1996). It is impossible to say for certain if mantle viscosity beneath the Angara Craton in the Silurian was the same as in the model. It is unknown whether any changes in dip angle of subduction and its rate took place in the Silurian. Similarly, changes in supracrustal loads on the active margin of the Angara Craton are difficult to quantify. It is only possible to say that no drastic changes had occurred in the position of subduction zones during the Silurian.

Under such circumstances, we only can compare changes in the rate of crustal subsidence in East Siberia with those expected from the mechanism under considerations. Lithospheric displacements generated in accordance with this mechanism decrease with distance from the subduction line (Coakley & Gurnis 1996; Burgess *et al*. 1997). In the Early Silurian, minor changes in the rate of crustal subsidence occurred in regions VI and VII, which are located 500 km and 800 km from the convergent boundary ABC. Regions III, IV and V were considerably farther from this line: 1500 km, 1800 km, and 1300 km, respectively. However, synchronous changes in the rate of crustal subsidence were several times larger in them (see Fig. 6). In the Late Silurian, almost no changes in the rate of crustal subsidence occurred in the Kochumdek and Turukhansk regions, 1100 and 1400 km from the convergent boundary, while major changes in the rate of subsidence took place in regions III, IV, V, X, and XI, which are 1500 km, 1800 km, 1300 km, 1800, and 1600 km from the line ABC, respectively. Furthermore, dynamic topography is reversible which produces hiatuses in stratigraphic successions (Burgess *et al*. 1997). No significant erosion occurred in the shallow water Silurian successions of East Siberia. This is evidenced by the presence of all the chronozones which, in many cases, are only several meters thick. Therefore, it is very improbable that large-scale variations in the rate of crustal subsidence in East Siberia were caused by changes in dynamic topography or by elastic lithospheric displacements generated by changes in the subduction regime and supracrustal loads.

Changes in the rate of metamorphism in the lower crust

The absence of any significant hiatuses in the Silurian shallow water successions in East Siberia indicates that no crustal uplifts occurred in the area; only subsidence took place at different rates which varied in time and space. An important feature of the plots (Fig. 6) is a correlation, in most cases, between the amplitude of the deviations and the average rate of crustal subsidence *a* during the epochs of shallow water deposition. The largest falls and rises in plots III–V, X and XI are characterized by higher *a* (18.8, 18.4, 15.8, 25.6, and 31.5 m/Myr, respectively). Smaller deviations are observed in plots II, VI–VIII with lower *a* (10.3, 7.8, 8.5, and 9.2 m/Myr, respectively). Among the sub-horizontal plots, *a* is rather high only in plot IX (17.2 m/Myr). Therefore, it can be supposed that large-scale falls and rises seen in the plots resulted from changes in the intensity of the process, which caused crustal subsidence in the basin. A common origin of variations in the rate of crustal subsidence in different regions is also indicated by the synchronicity of large-scale falls and rises seen in plots of Fig. 6. This was typical for many cratonic basins, where a quasi-synchronous increase or decrease in the rate of subsidence often took place with intensities variable in space (Beloussov 1980).

Up to 600–800 m of sediments were formed in East Siberia during the Silurian (Fig. 1). Silurian deposits constitute only a small portion of the Upper Proterozoic – Mesozoic 10–15 km thick sedimentary cover of East Siberia, which overlies the Early Proterozoic crystalline basement (Fig. 10) (Egorkin *et al*. 1987; Rosen *et al*. 1994; Pavlenkova 1996; Surkov 2000). Most of the deposits were formed on Early Proterozoic lithosphere prior to the onset of effusion of traps in the Triassic, which could be due to a thermal event. A subsidence of such amplitude in a cool lithosphere required a considerable increase of density in the layer. Contraction of mafic rocks in the lower crust due to a transformation of gabbro into garnet granulites is the only known mechanism, which could be responsible for subsidence of such a scale in a cratonic lithosphere at places located far away from plate tectonic activity (Haxby *et al*. 1976; Artyushkov & Baer 1983; Baird *et al*. 1995). Since subsidence in East Siberia in the Silurian was only a short stage of the general and much more pronounced subsidence, it can be presumed that Silurian subsidence also resulted from phase transformations in mafic rocks of the lower crust.

Reaction rate strongly rises with temperature and increases in the presence of small amounts of water-containing fluid (Ahrens & Schubert 1975; Austrheim 1998). Temperature changes in the old and thick lithosphere could be caused by changes in heat flow from the asthenosphere. Durations of the falls and rises seen in plots of Fig. 6 (7–10 Myr) are much smaller than the time of thermal relaxation in cratonic lithosphere (~ 10^2 Myr). Therefore, subsidence accelerations could not have resulted from temperature changes in the lower crust. Most probably, the increase in the rate of contraction in mafic rocks from phase transformations was caused by a temporary increase in the content of volatiles in the lower crust of East Siberia. Synchronous segregation of volatiles caused by metamorphism in the cool lower crust within the region, ~ 1000 km wide, is highly improbable. We figure out that accelerations in the rate of crustal subsidence in East Siberia occurred during the epochs when infiltration of small volumes of water-containing fluids from the asthenosphere took place. This mechanism has been proposed earlier for many other sedimentary basins (Artyushkov *et al*. 1991, 2000b; Artyushkov 1993). Volatiles could have been generated by small mantle plumes which welled up to the base of the lithosphere and spread rapidly along the boundary. This process was considered in more detail in Artyushkov & Hofmann (1998).

Recently, the mechanism has received additional confirmation provided by geochemical data (Artyushkov *et al*. 2000b). In regions where rapid crustal subsidence occurred during certain epochs without significant lithospheric stretching, evidence has been found for significant changes in composition of the ground waters percolating the sediments. Thus, over the period of 1–3 Myr in the beginning of the Late Devonian, a pelagic basin was formed on the shallow water shelf of the Volga-Urals and Timan-Pechora hydrocarbon basins in the eastern part of the East European Craton (Artyushkov & Baer 1986). Sediments in these basins show extremely high contents of Se, As, Mo, Hg, U and Re (Pushkarev *et al*. 1994; Pisotsky 1999). These elements are found in the layers with both high and low contents of organic matter, therefore any significant influence of organic substances on either the origin or concentration of such elements can be ruled out. Such changes in the content of these elements suggest that they derive from infiltration of dry volatiles from the mantle (ibid.). Oils and bitumens in the above basins include Nd and Sr with isotopic characteristics (ε_{Nd} = –(9-12), and $^{87}Sr/^{86}Sr$ = 0.708–0.719) (Gottikh *et al*. 2000) which are typical of Australian lamprophyres (Nelson 1992). Carbonates with low organic content were accumulated on the northern and western margins of the Peri-Caspian basin during the rapid subsidence in the Visean. These sediments have high uranium content (Pisotsky 1999) – by an order of magnitude higher than the usual uranium content in marine carbonates (Taylor & McLennan 1985). The high uranium content has been attributed to mantle fluids entering the basin. A rapid infiltration of fluids into the lithosphere is possible only if they are surficially active, i.e. decrease the free energy at grain boundaries (condition of Gibbs). In this case, such fluids easily penetrate between the crystals in the form of thin films (10^{-5} cm).

Estimates of maximum possible sea-level changes from the structure of sedimentary successions

Maximum possible amplitudes of eustatic fluctuations (b_m) in the Silurian have been earlier estimated for two specific modes: events with an abrupt sea-level fall and subsequent linear rise, and events of a harmonic form (Artyushkov & Chekhovich 2001). The estimates were based on the following two assumptions: (1) absence of significant erosional features, and (2) presence of all Silurian chronozones in stratigraphic successions. In this study, using the method described in the above paper, and basing on detailed stratigraphic data on Silurian successions in East Siberia (Tesakov *et al*. 1998b, 2000), we have obtained more accurate estimates of b_m. This approach can be applied to other epochs and areas with detailed stratigraphic subdivision.

Eustatic fluctuations with an abrupt initial fall and subsequent linear rise (Fig. 11). Let's denote the initial depth of water by h_w^0, and the fall's amplitude — by b. The water pressure drop caused by the fall results in an isostatic uplift of the lithosphere. Since isostatic recovery is very rapid (Artyushkov 1983), the uplift ought to have occurred almost synchronously with sea-level falls, $\geq 10^{-2}$ Myr long. For the lithosphere ~ 10^3 Myr old, which includes the crust, 45 km thick, the effective elastic thickness of the lithosphere should be about 70 km (Burov & Diament, 1995; Cloetingh & Burov, 1996). In this case, the characteristic width of lithospheric flexure under surface load is of ~ 200 km. The size of the East Siberian basin was considerably larger: 1200×2000 km. Therefore, in the first approximation, vertical crustal displacements under changing water pressure corresponded to the case of local isostasy, and subaerial exposure began when the sea-level fall reached the amplitude as follows:

$$\zeta_{eu}^0 = [(\rho_m - \rho_w)/\rho_m]h_w^0 \approx 0.69h_w^0. \qquad (7)$$

An abrupt fall can be detected when crustal surface reaches the altitude z_0 above sea level where erosion becomes significant. During abrupt sea-level falls, deposition can be neglected. In this situation erosional features will be formed, if the fall's amplitude b reaches the minimum value b_m or exceeds it: $b \geq b_m$, where

$$b_m = 0.69h_w^0 + z_0. \qquad (8)$$

In the Nyuya region (V in Fig. 1), deposition of shallow water carbonates had been taking place since the start of the Silurian. Beginning from the Telychian, carbonate platform had existed over most of the basin. The depth of water on the shoal was 0–5 m. Then the initial depth of water can be assumed to be equal $h_w^0 = 5$ m for the Rhuddanian and Aeronian, and $h_w^0 = 3$ m for the Telychian–Pridoli. Microkarst develops rapidly on carbonates if the altitude of the crustal surface exceeds the maximum amplitude of the tides (D'Argenio *et al*. 1999). Over most of East Siberia, far from the ocean, this amplitude could not exceed $z_0 \approx 3$ m. Stratigraphic successions in East Siberia include numerous diastems — levels of weak subaerial erosion indicating short-term uplifts of sea bottom above the sea level. However, no significant erosional features have been found in the successions. Then, according to (8), amplitudes of the abrupt sea-level falls could not have exceeded:

$$b_m \approx 7 \text{ m} \qquad \text{for the Rhuddanian and Aeronian,} \qquad (9a)$$

$$b_m \approx 5 \text{ m} \qquad \text{for the Telychian–Pridoli.} \qquad (9b)$$

Values of b_m can also be estimated from the variations of chronozones thickness in Silurian successions. Subaerial exposure of a long duration Δt_{sa} results in non-deposition and disappearance of sediments of a certain age from the succession. In East Siberia, sediments from all chronozones are present in shallow water Silurian successions. This indicates that Δt_{sa} did not exceed the duration of two chronozones $2\Delta t_{cz}$: $\Delta t_{sa} \leq 2\Delta t_{cz}$ (Artyushkov & Chekhovich 2001). This constraint, which was used in that paper, is very strong. Not only all chronozones are present in the successions, but their thicknesses change gradually. Superposition of a period of subaerial exposure with two adjacent chronozones will result in a decrease in chronozone thicknesses Δh_{cz}. For example, given a constant deposition rate a and $\Delta t_{cz} = \Delta t_{sa}$, the sum of thicknesses of two chronozones overlapped by a period of non-deposition, equals the thickness of one chronozone (Fig. 12a). In Fischer plots this will be manifested in deflections in the graphs of the types shown in Figs. 12b and 12c. Furthermore, such deflections should take place in all plots, or, at least, most of them. This is not seen in plots of Fig. 6. Therefore, if subaerial exposures occurred in regions I–XI, their duration Δt_{sa} did not exceed that of one chronozone Δt_{cz}:

$$\Delta t_{sa} \leq \Delta t_{cz}. \tag{10}$$

No significant subaerial erosion occurred in East Siberia in the Silurian. For the eustatic event of Fig. 11a, at times, when crustal surface was above sea level, its altitude (ζ) decreased with time as $\zeta = b - 0.69h_w^0 - b\tau - aT\tau$ where $\tau = t/T$ (Fig. 11b). Crustal surface subsided to sea level ($\zeta = 0$) at $\tau_0 = (b - 0.69h_w^0)/(b + aT)$. Then, according to condition (10), gradual changes in the chronozone thicknesses constrain the amplitudes of abrupt sea-level falls as:

$$b \leq b_m = (0.69h_w^0 + a\Delta t_{cz})/(1 - \Delta t_{cz}/T). \tag{11}$$

This parameter decreases with the period of eustatic event T and increases as the average rate of crustal subsidence a rises. In this situation, the minimum values of b_m can be obtained for regions with the lowest rate of subsidence. Under a constant duration of the chronozones Δt_{cz} = 0.48 Myr, the minimum average values of a for the Telychian, Wenlock, Ludlow and Pridoli are shown in Table 3; regions with the slowest deposition are indicated. For the Rhuddanian and Aeronian, we take a for the Nyuya region, which at that time was the only one with shallow water carbonate deposition. In Fig. 13, b_m determined by (11) are plotted as the functions of T for these values of a and Δt_{cz} = 0.48 Myr. The initial depth of water is taken as h_w^0 = 5 m for the Rhuddanian and Aeronian, and h_w^0 = 3 m for the Telychian–Pridoli.

The values of b_m in Fig. 13, are generally larger than those determined by (9a) and (9b) under the constraint 1. However, the altitudes, where erosion takes place in sediments of various types, can be estimated only approximately. In the presence of reliable data, abrupt changes in the chronozone thicknesses can be established quite reliably, therefore constraint 2 appears to be more definite than constraint 1. As it can be seen in Fig. 13, the values of b_m are comparatively large only for the Aeronian ($b_m \geq 18$ m). For the rest of the Silurian, in the interval of $T = 1$–5 Myr, they are in the range of 6–14 m. This is smaller or even much smaller than the amplitudes of ~ 20–100 m commonly attributed to the third-order eustatic events.

Suppose now that chronology of the Silurian was according to Gradstein & Ogg (1996) with relative lengths of the Rhuddanian, Aeronian and Telychian according to Johnson *et al*. (1996) and Tesakov *et al*. (1998a) (Table 2). In Fig. 14, $b_m(T)$ determined according to (11) are plotted for the main units of the Silurian under a and Δt_{cz} characteristic of this chronology. As in Fig. 13, the values of b_m are comparatively large only for the Aeronian ($b_m \geq 19$ m). For the Telychian, $b_m = 9$–20 m in the range of $T = 1.34$–5 Myr. Low values of $b_m = 6$–12 m are characteristic of the Rhuddanian, Wenlock, Ludlow and Pridoli. For both chronologies, constraint 2 also leads to conclude that the amplitudes of eustatic events during most of the Silurian were low.

Eustatic events with a gradual sea-level fall. Let's consider eustatic event of a harmonic form (Fig. 15):

$$\zeta_{eu} = -\,b\sin^2(\pi\tau). \qquad (12)$$

In the Rhuddanian and Aeronian, siliciclastic deposition took place in regions VI and VII (Ilim and Balturino) in the southwestern part of East Siberia. Its rate, most probably, was controlled by the rate of erosion within the vast adjacent landmasses, and had not changed in the conditions of small eustatic fluctuations. Let us assume that initial depth of water equaled $h_w^0 = 5$ m and subsidence rates were as shown in Table 3 at $\Delta t_{cz} = 0.48$ Myr. Then, neglecting

Table 3. *Rates of crustal subsidence during the Silurian in the case when chronozone lengths are assumed to be constant and equal to 0.48 Myr*

Standard subdivision	Number of chronozones (*n*)	Length, Myr	Minimum rate of crustal subsidence (*a*), m/Myr*	Region
Rhuddanian	11	5.3	8.5	Nyuya River
Aeronian	9	4.3	26.3	Nyuya River
Telychian	5	2.4	11.2	Balturino
Wenlock	11	5.3	6.7	Ledyanskaya
Ludlow	13	6.2	9.7	Kochumdek River
Pridoli	5	2.4	8.8	Kochumdek River

*Rock compaction is taken into account (Artyushkov & Chekhovich 2001).

small displacements caused by isostatic recovery in response to sea-level falls, and using relations (5, 6) in Artyushkov & Chekhovich (2001), it follows that maximum possible amplitudes b_m of eustatic events (11) which could have occurred under condition (10) (constraint 2) are equal to those shown in Fig. 16. Large $b_m \geq 17$ m are observed only at $T \leq$ 1.5 Myr in the curve Aeronian-2. In the Early Silurian, shallow water carbonate deposition took place in the Nyuya region (V). Using constraint 1, taking the altitude of erosion equal to $z_0 = 3$ m and using relation (6) (ibid.), we obtain b_m as shown in Fig. 17. Here, at $T \leq 1.7$ Myr, $b_m \leq 13$ m. Thus, the combined application of constraints 1 and 2 leads to produce values of b_m which are considerably smaller than those supposed for third-order eustatic events (20–100 m).

During the Telychian–Pridoli, deposition took place over most of the basin on the carbonate shoal (Tesakov *et al*. 2000). Usual water depths for these regions were ~ 0–5 m (Johnson *et al*. 1997). Under such conditions, deposition practically compensated for accommodation space variations. In this case, the average rate of formation of shallow water carbonates ought to have increased with the increase in the depth of water. Let us assume that, at $h_w \leq$ 5–10 m, the rate of shallow depth deposition was proportional to the depth of water h_w. From relations (9)–(11) in Artyushkov & Chekhovich (2001), it follows that the values of b_m equaled as shown in Figs. 18–21. In the curves plotted under constraint 2 (Figs. 18, 20), large values of $b_m \geq 20$ m were found to be characteristic only of relatively short periods $T \leq 1.3$ Myr under the chronology of Table 2.

Conclusions and discussion

Sea-level changes of the third order with amplitudes of 20–100 m and lengths of ~ 1–10 Myr (eustatic events) are believed to have widely occurred in the Phanerozoic (Haq *et al*. 1987; de Graciansky *et al*. 1998). Tectonic movements are commonly considered to be a complicating factor. Wide occurrence of third-order cycles in sea-level changes has been seldom doubted (Miall 1992, Miall & Miall 2001). A number of eustatic events have been proposed for the Cambrian and earliest Ordovician (Webby & Laurie 1992; Cooper & Nowlan 1999). However, as follows from analysis of the available data on shallow water deposition in East Baltic, eustatic fluctuations did not exceed 10–20 m at that time, while rapid crustal uplifts of ~ 100 m occurred in southern Sweden and eastern Lithuania (Artyushkov *et al*. 2000a). Based on the changes of water depth in cratonic areas, eight large-scale eustatic events have been proposed for the Silurian (Johnson 1996). A large amount of highly detailed stratigraphic data was obtained for this epoch in the East Siberian basin, 2×10^6 km^2 in size (Tesakov *et al*. 2000). Comparison of the results obtained from the modeling of changes of water depth due to eustatic fluctuations with the structure of shallow water successions in this area leads to conclude that, in the Silurian, eustatic events could not have exceeded 20–30 m (Artyushkov & Chekhovich 2001). During the same period of time, rapid, large-scale vertical crustal movements occurred in some regions of East Siberia and in other cratonic areas.

In this paper, we analysed in more detail the role of eustatic and tectonic factors in the formation of Silurian sedimentary successions of East Siberia. Fischer plots are often used for the identification of eustatic events from sedimentary records (e.g., Goldhammer *et al*. 1993). Such plots are commonly based on thickness of elementary cycles of a meter scale in shallow water successions. There are serious doubts about the applicability of this approach because elementary cycles can be random (Burgess *et al*. 2001), i.e. there is no certainty about their timing. Silurian successions of East Siberia are subdivided into chronostratigraphic units – chronozones, each corresponds to time interval ~ 0.5 Myr long. On this basis, we compiled Fischer plots in a different way — basing on chronozone thickness. This allowed us to make a reliable comparative analysis of the changes, which occurred with time in cumulative sediment thickness in a number of regions. Following this approach we have found that eustatic fluctuations in the Silurian were even lower (≤ 5–10 m) than those estimated earlier (≤ 20–30 m according to Artyushkov & Chekhovich 2001). This is in agreement with the results of modeling of changes in the depth of water due to sea-level changes and their comparison with highly detailed stratigraphic successions which was done in this paper. This proves that eustatic events could not have exceeded ~ 20 m; in certain periods of the Silurian they were ≤ 5–7 m. The obtained values are considerably smaller than those commonly supposed for eustatic events (20–100 m).

In Fischer plots based on elementary cycles it is assumed that crustal subsidence was a uniform process. However, it is known that in many sedimentary basins the rate of subsidence had changed in time (Beloussov 1980; Sloss 1988). An analysis of Fischer plots based on the Silurian chronozones indicates that in some regions of East Siberia the rate of subsidence remained almost constant over 10–15 Myr, while in the other regions it had changed by several hundred percent. These changes were of the same sign, but their intensities varied strongly from place to place in the basin. This data can be used to verify the applicability of different mechanisms of crustal subsidence to East Siberia. Rapid crustal uplifts and subsidences are sometimes explained by lithospheric deflections due to changes in the forces acting along the lithosphere with laterally variable thickness (Cloetingh *et al*. 1985). Such displacements tend to decrease with the width of the area (Artyushkov 1974), and are too small to explain the large-scale changes in the rate of subsidence in East Siberia, ≥ 1000 km wide. In the Silurian, subduction took place to the south of the area. Vertical crustal movements can be generated by changes in dynamic topography above subducting plates (Burgess *et al*. 1997; Burgess & Moresi 1999). The intensity of such movements decreases with distance from the convergent plate boundary. In the Silurian, changes in the rate of crustal subsidence were larger in the northern part of East Siberia. Therefore, it can be concluded that changes in dynamic topography could not have had any strong influence on crustal movements in the area. Contraction of mafic rocks in the lower crust caused by phase transformations has also been suggested as a cause of crustal subsidence (Haxby *et al*. 1977; Artyushkov *et al*. 1991; Baird *et al*. 1995). In the absence of strong lithospheric stretching, this is the only mechanism that can explain crustal subsidence of the amplitude of up to 10–15 km in East Siberia during the Late Proterozoic and Phanerozoic. The same mechanism most probably accounts for subsidence during the Silurian (up to 600–800 m) which was only a short episode of this major subsidence. As suggested for many other basins (Artyushkov *et al*. 1991, 2000b), the accelerations of subsidence in East Siberia could have occurred due to infiltration of small volumes of superficially active fluids into the lower crust from the asthenosphere.

The epochs of relative stability of the sea level in the early Paleozoic and the Silurian had lasted for about 70 Myr, or 13% of the Phanerozoic time. These epochs were chosen for research just because original stratigraphic data was available, i.e. the choice was rather accidental. Therefore, it is quite probable that sea level remained stable during most of the Phanerozoic, while the eustatic events proposed earlier, except for the epochs of major glaciations, were connected with the rapid tectonic movements.

Rapid changes of water depth in cratonic areas were responsible for the formation of numerous stratigraphic traps for oil and gas. This phenomenon is commonly explained by eustatic fluctuations of sea level (Posamentier & Allen 2000). If such changes of water depth were really caused by vertical crustal movements, the method of prospecting stratigraphic traps should be completely revised. Studies of rapid regional crustal uplifts and subsidences in cratonic areas, their basic regularities and driving mechanisms are essential for reliable prospecting. Rapid crustal movements can presently occur in some cratonic regions, which are supposed to be inactive. This is characteristic, for example, of the East European Platform (Kashin 1989). Such motions are sometimes accompanied by large and destructive earthquakes, as happened, for example, on the North American Craton and Indian Shield. Therefore, identification of such regions is of importance for earthquake prediction.

Acknowledgements

We thank Yu.I. Tesakov for valuable discussions and providing a large amount of original data on the Silurian in East Siberia. Comments of the reviewers, E.B. Burov and P.M. Burgess, were helpful for making the presentation more clear. The work was supported by the Russian Foundation for Basic Research (grant 00-05-64095).

Appendix. Fischer plots based on elementary cycles for some regions of East Siberia in the Silurian

Silurian sedimentary successions of East Siberia include large stacks of elementary cycles of a meter scale (Sokolov 1985; Tesakov *et al*. 2000). Typical examples are shown in Figs. A.1–A.3. Using shallow water parts of the successions, Fischer plots were compiled (Fig. A.4) for regions III–VII. The plots include falls and rises, up to 40–60 m in the amplitude and from ~ 1 Myr to ~ 15 Myr in duration. Under a constant rate of crustal subsidence and quasi-periodic elementary cycles, the deviations in Fischer plots should reflect sea-level changes. If crustal subsidence is uniform in several regions, Fischer plots will be similar for them, as describing global eustatic fluctuations. In the plots on Fig. A.4, some falls and rises are synchronous to a first approximation, as the general long-term falls by 40–50 m in segment AB of plots III and V during most of the Llandovery. However, during the same period of time AB, asynchronous falls and rises took place in regions VI and VII, with amplitudes of only ~ 10–20 m. A rapid rise of ~ 30 m in segment BC of plot V in the late Telychian had not been accompanied by any significant changes in the other plots. A fall of 40 m in segment DF of plot IV in the Wenlock and early Ludlow took place when no comparable changes occurred in segment DE of plots III and V, and a rapid rise of ~ 40 m took place in segment EF of plot III. No significant changes are seen on plot III within the epoch corresponding to the rise by ~ 30 m in segment FG of plot IV. Such differences in plots III–VII show that they do not describe large-scale eustatic sea-level changes.

In different regions, the numbers of elementary cycles in Fig. A.4 differ considerably. For example, the Rhuddanian and Aeronian in regions V, VI, and VII include 95, 43, and 48 cycles, respectively. In the regions III, IV and V, and VII, the Wenlock comprises 16, 62 and 25 cycles, respectively. The Ludlow includes 6 cycles in region III and 32 cycles in region IV.

Such differences in the numbers of high-frequency cycles lead to conclude that they could not have had eustatic origin. This can be the reason why the plots are so strongly different.

Considerable distortions of the plots can also occur if cycle lengths are not constant, but vary with time. The lengths of the Llandovery, Wenlock, and Ludlow are estimated as 15 Myr, 5 Myr and 4 Myr, respectively (Gradstein & Ogg 1996). Taking relative lengths of the Rhuddanian, Aeronian and Telychian as 1:1.725:1.025 according to Johnson (1996) and Tesakov *et al*. (1998a), the total duration of the Aeronian and Telychian can be estimated as 11 Myr. In plot III (Fig. A.4), the Aeronian with the Telychian, Wenolck and Ludlow include 59, 16, and 6 cycles, respectively. This corresponds to the average lengths of the elementary cycles of 0.19, 0.31 and 0.67 Myr, respectively, with ratios of 1:1.6:3.5. Of course, the determination accuracy of the lengths of the main units of the Silurian was not very high. However, it is very improbable that this inaccuracy could alter the relative lengths of these units by as much as three times and a half. Plot IV includes 62 cycles in the Wenlock and 36 cycles in the Ludlow. The average lengths of the cycles are 0.08 Myr and 0.11 Myr with a ratio of about 1:1.4. In plot IV, the ratio is 1.6:3.5 = 2.2, i.e. quite different from that for plot III. This also indicates that the lengths of meter-scale cycles changed considerably from one unit to another. Thus, in the Silurian, elementary cycles were not synchronous in different regions of East Siberia, and their lengths changed with time. Under such circumstances, Fischer plots based on elementary cycles cannot describe eustatic sea-level changes.

References

AHRENS, T.J. & SCHUBERT, G. 1975. Gabbro-eclogite reaction rate and its geophysical significance. *Review of Geophysics and Space Physics*, **13**, 383–400.

D'ARGENIO B., FERRERI V., RASPINI F.B., AMODIO, S. & BUONOCUNTO, F.B. 1999. Cyclostratigraphy of carbonate platform as a tool for high-precision correlation. *Tectonophysics*, **315**, 357–384.

ARTYUSHKOV E.V. 1973. Stresses in the lithosphere caused by crustal thickness inhomogeneities. *Journal of Geophysical Research*,**78**, 7675–7708.

ARTYUSHKOV, E.V. 1974. Can the Earth's crust be in a state of isostasy. *Journal of Geophysical Research*, **79**, 741–752.

ARTYUSHKOV, E.V. 1983. *Geodynamics*. Elsevier, Amsterdam, 312 pp.

ARTYUSHKOV, E.V. 1993. *Physical Tectonics*. Nauka, Moscow, 456 pp. (in Russian).

ARTYUSHKOV, E.V. & BAER, M.A. 1983. Mechanism of continental crust subsidence in fold belts: the Urals, Appalachians and Scandinavian Caledonides. *Tectonophysics*, **100**, 5–42.

ARTYUSHKOV, E.V. & BAER, M.A. 1986. Mechanism of formation of hydrocarbon basins: the West Siberia, Volga-Urals, Timan-Pechora basins and Permian basin of Texas. *Tectonophysics*, **122**, 247–281.

ARTYUSHKOV, E.V., BAER, M.A., LETNIKOV, F.A. & RUZHICH, V.V. 1991. On the mechanism of graben formation. *Tectonophysics*, **197**, 95–115.

ARTYUSHKOV, E.V. & CHEKHOVICH, P.A. 2000. The East Siberian sedimentary basin in the Silurian: Evidence for a lack of rapid eustatic fluctuations. *Doklady Earth Sciences*, **373**, 793–797.

ARTYUSHKOV, E.V., CHEKHOVICH, P.A. 2001. The East Siberian basin in the Silurian: evidence for no large-scale sea-level changes. *Earth & Planetary Science Letters*, **193**, 183–196.

ARTYUSHKOV, E.V. & HOFMANN, A.W. 1998. The Neotectonic crustal uplift on the continents and its possible mechanisms. The case of Southern Africa. *Surveys in Geophysics*, **19**, 369–415.

ARTYUSHKOV, E.V., LINDSTRÖM, M. & POPOV, L.E. 2000a. Relative sea-level changes in Baltoscandia in the Cambrian and early Ordovician: the predominance of tectonic factor and the absence of large-scale eustatic fluctuations. *Tectonophysics*, **320**, 375–407.

ARTYUSHKOV, E.V., MÖRNER, N.-A., TARLING, D. 2000b. The cause of loss of lithospheric rigidity in areas far from plate tectonic activity. *Geophysical Journal International*, **143**, 752–776.

AUSTRHEIM, H. 1998. Influence of fluid and deformation on metamorphism of the deep crust and consequences for the geodynamics of collision zones. *In:* Hacker, B.R. & Liou, J.G. (eds) *When Continents Collide: Geodynamics and Geochemistry of Ultrahigh-Pressure Rocks.* Kluver, Dordrecht, 297–323.

BAIRD, D.J., KNAPP, J.H., STEER, D.N., BROWN, L.D. & NELSON, K.D. 1995. Upper-mantle reflectivity beneath the Williston basin, phase-change Moho, and the origin of intracratonic basins. *Geology*, **23**, 431–434.

BELOUSSOV, V.V. 1980. *Geotectonics.* Springer-Verlag, Berlin. 330 pp.

BOSENCE, D.W.J., WOOD, J.L., ROSE, E.P.F. & QING, H. 2000. Low- and high-frequency sea-level changes control peritidal carbonate cycles, facies and dolomitization in the Rock of Gibraltar (Early Jurassic, Iberian Peninsula). *Journal of the Geological Society of London*, **157**, 61–74.

BRETT, C.E., BOUCOT, A.J. & JONES, B. 1993. Absolute depths of Silurian benthic assemblages. *Lethaia*, **26**, 25–40.

BURGESS, P.M. & GURNIS, M. 1995. Mechanisms for the formation of cratonic stratigraphic sequences. *Earth & Planetary Science Letters*, **136**, 647–663.

BURGESS, P.M., GURNIS, M. & MORESI, L.N. 1997. Formation of sequences in the cratonic interior of North America by interaction between mantle, eustatic, and stratigraphic processes. *Geological Society of America Bulletin*, **109**, 1515–1535.

BURGESS, P.M. & MORESI, L.N. 1999. Modelling rates and distribution of subsidence due to dynamic topography over subducting slabs: is it possible to identify dynamic topography from ancient strata. *Basin Research,* **11**, 305–314.

BURGESS, P.M., WRIGHT, V.P. & EMERY, D. 2001. Numerical foreward modelling of peritidal carbonate parasequence development: implications for outcrop interpretation. *Basin Research*, **13**, Issue **1**, 1–25.

BUROV, E.B. & DIAMENT, M. 1995. The effective elastic thickness (T_e) of the continental lithosphere: What does it really mean? *Journal of Geophysical Research*,100, 3095–3927.

CHENG, D., TUCKER, M.E., JIANG, M. & ZHU, J. 2001. Long-distance correlation between tectonic-controlled, isolated carbonate platforms by cyclostratigraphy and sequence stratigraphy in the Devonian of South China. *Sedimentology*, **48**, 57–78.

CLOETINGH, S. & BUROV, E.B. 1996. Thermomechanical structure of European continental lithosphere: constraints from rheological profiles and EET estimates. *Geophysical Journal International*, **124**, 695–723.

CLOETINGH, S., MCQUEEN, H. & LAMBECK, K. 1985. On a tectonic mechanism for regional sea level variations. *Earth & Planetary Science Letters*, **51**, 139–162.

COAKLEY, B. & GURNIS, M. 1995. Far-field tilting of Laurentia during the Ordovician and constraints on the evolution of a slab under an ancient continent. *Journal of Geophysical Research*, **100**, 6313–6327.

COOPER, A. & NOWLAN, G.S. (eds.) 1999. Proposed Global Stratigraphic Section and Point for Base of the Ordovician System International Working Group on the Cambrian-Ordovician Boundary, Circular March 1999, Calgary.

DRUMMOND, C.N. & WILKINSON, B.H. 1993a. Aperiodic accumulation of peritidal carbonates. *Geology*, **21**, 1023–1026.

DRUMMOND, C.N. & WILKINSON, B.H. 1993b. On the use of cycle thickness diagrams as recording long-term sea-level change during accumulation of carbonate sequences. *Journal of Geology*, **101**, 687–702.

DRZEWIECKI, P.A. & SIMO, J.A. 2000. Tectonic, eustatic and environmental controls on mid-Cretaceous carbonate platform deposition, south-central Pyrenees, Spain. *Sedimentology*, **47**, 471–475.

EGORKIN, A.V., ZUGANOV, S.K., PAVLENKOVA, N.A. & CHERNYSHEV, N.M. 1987. Results of lithosphere studies from long-range profiles in Siberia. *Tectonophysics*, **140**, 29–37.

ELRICK, M. 1995. Cyclostratigraphy of Middle Devonian carbonates of the eastern Great Basin. *Journal of Sedimentary Research*, **B65**, 61–79.

EMERY, D. & MYERS, K.J. 1996. *Sequence Stratigraphy*. Blackwell Science, Oxford, 297 pp.

FISCHER, A.G. 1964. The Lofer cyclothems of the Alpine Triassic. *Kansas Geological Survey Bulletin*, **169**, 107–149.

GINSBURG, R.N. 1971. Landward movement of carbonate mud: new model for regressive cycles in carbonates (abstract). *American Association of Petroleum Geologists Bulletin*, **55**, 340.

GOLDHAMMER, R.K., OSWALD, E.J. & DUNN, P.A. 1991. Hierarchy of stratigraphic forcing: example from Middle Pennsylvanian shelf of the Paradox basin. *In:* Franseen, E.K., Watney, L.W., Kendall, C.G. St. C. & Ross, W. (eds) *Sedimentary Modelling: Computer Simulation of Methods for Improved Parameter Definition*. *Kansas Geol. Surv. Bull.*, 361–413.

GOLDHAMMER, R.K., LEHMANN, P.J. & DUNN, P.A. 1993. The origin of high frequency platform carbonate cycles and third-order sequences (Lower Ordovician El Paso GP, West Texas): Constraints from outcrop data and stratigraphic modeling. *Journal of Sedimentary Petrology*, **63**, 318–359.

GOTTIKH, R.P., PISOTSKY, B.I. & ZHURAVLEV, D.Z. 2000. Geochemical pecularities of rocks of bitumens and oils of some hydrocarbon provinces: isotopic ratios of Neodim and Strontium. *Doklady Earth Science Section*, **375**, 83–88.

DE GRACIANSKY, P.C., HARDENBOL, J., JAQUIN, T. & VAIL, P.R. (eds.). 1998. *Mesozoic and Cenozoic Sequence Stratigraphy of European Basins*. SEPM Special Publication Series, **60**, Tulsa, 786 pp.

GRADSTEIN, F.M. & J. OGG, J. 1996. A Phanerozoic time scale. *Episodes*, **19**, **1/2**, 3–5.

GURNIS, M. 1992. Rapid continental subsidence following the initiation and evolution of subduction. *Science,* **255**, 1556–1558.

HAGER, B.H. & CLAYTON, R.W. 1989. Constraints on the structure of mantle convection using seismic observations, flow models, and the geoid. *In*: Peltier, W.R. (ed) *Mantle Convection*. Gordon and Breach, New York, 657–766.

HALLAM, A. (ed.). 1992. *Phanerozoic Sea Level Changes*. Columbia Univ. Press, New York, 266 pp.

HAQ, B.U., HARDENBOL, J. & VAIL, P.R. 1987. Chronology of fluctuating sea levels since the Triassic. *Science*, **235**, 1156–1167.

HARRIS, W.B. & LAWS, R.A. 1997. Paleogene stratigraphy and sea-level history of the North Carolina Coastal Plain: Global coastal onlap and tectonics. *Sedimentary Geology*, **108**, 91–120.

HARRISON, G.G.A. 1990. Long-term eustasy and epeirogeny on the continents. *In*: Revell, R.R. (ed) *Sea-Level Change*. Natl. Acad. Press, Washington, DC, 141–158.

HAXBY, W.F., TURCOTTE, D.L. & BIRD, J.M. 1976. Thermal and mechanical evolution of the Michigan basin. *Tectonophysics*, **36**, 57–75.

HOLLAND, C.H. & BASSETT, M.G. (eds.). 1989. A global standard for the Silurian System. Cardiff. *Nat. Mus. of Wales. Geol. Ser.*, **9**. 325 pp.

JOHNSON, J.G., KLAPPER, G. & SANDBERG, CH.A. 1985. Devonian eustatic fluctuations in Euroamerica. *Geological Society of America Bulletin*, **96**, 567–587.

JOHNSON, M.E. 1996. Stable cratonic sequences and a standard for Silurian eustasy. *Geological Society of America Special Paper*, **306**, 202–211.

JOHNSON, M.E., TESAKOV, YU.I., PREDTECHENSKY, N.N. & BAARLI, B.G. 1997. Comparison of Lower Silurian shores and shelves in North America and Siberia. *Geological Society of America Special Paper* **321**, 23–46.

KASHIN, L.A. (compiler) 1989. *Map of Recent Crustal Movements According to Geodetic Data on the USSR Territory. Scale 1:5.000.000. GUGK*, Moscow.

MAURER, F. 2000. Growth mode of middle Triassic carbonate platforms in the western Dolomites (Southern Alps, Italy). *Sedimentary Geology*, **134**, 275–286.

MCKENZIE, D. 1978. Some remarks on the development of sedimentary basins. *Earth & Planetary Sciince Letters*, **40**, 25–32.

MIALL, A.D. 1992. The Exxon global cycle chart: an event for every occasion? *Geology*, **20**, 787–790.

MIALL, A.D. 1997. *The Geology of Stratigraphic Sequences*. Springer, Berlin, 433 pp.

MIALL, A.D., MIALL, C.E. 2001. Sequence stratigraphy as a scientific enterprise: the evolution and persistence of conflicting paradigms. *Earth-Science Reviews*, **54**, 321–348.

MURPHY, M.A. & SALVADOR, A. (eds.). 1999. International Stratigraphic Guide: An abridged version. *Episodes*, **22** (**4**), 255–271.

NELSON, D.R. 1992. Isotopic characteristics of potassic rocks: evidence for the involvement of subducted sediments in magma. *Lithos*, **28**, 403–420.

OSLEGER, D.A. & READ, J.F. 1991. Relation of eustasy to stacking patterns of meter-scale carbonate cycles, Late Cambrian, USA. *Journal of Sedimentary Petrology*, **61**, 1225–1252.

PAVLENKOVA, N.I. 1996. Crust and upper mantle structure in Northern Eurasia from seismic data. *Advances in Geophysics*, **37**, 1–133.

PISOTSKY, B.I. 1999. *Expression of the Processes of a Reducing Fluidization in Hydrocarbon Provinces and Role of Mantle Components in Genesis of Hydrocarbons*. Rehabilitation Thesis, VNIIGeosystems, Moscow, 357 pp. (in Russian).

POSAMENTIER, H.W. & ALLEN, G.P. 2000. *Siliciclastic Sequence Stratigraphy – Concepts and Applications*. SEPM Concepts in Sedimentology and Paleontology, **7**, SEPM, 216 pp.

PUSHKAREV, YU.D., GOTTIKH, R.P., PISOTSKY, B.I., ZHURAVLEV, D.Z. & AKHMEDOV, A.M. 1994. Isotope compositions of Sr, Pb, Nd, Os and REE distribution in oils, bitumens and black shales as indicators of matter sources, migration ways and genesis of hydrocarbon fluids. *Eighth Intern. Conference on Geochronology, Cosmochronology and Isotope Geology, Abstracts*, Berkley, p. 257.

READ, J.F., KOERSCHNER, W.F. III, OSLEGER, D.A., BOLLINGER, G.A. & CORUH, C. 1991. Field and modelling studies of Cambrian carbonate cycles, Virginia Appalachians – reply. *Journal of Sedimentary Petrology*, **61**, 647–652.

ROSEN, O.M., CONDIE, K.C., NATAPOV, L.M. & NOZHKIN, A.D. 1994. Archean and Early Proterozoic evolution of the Siberia Craton: A preliminary assessment. *In*: Condie, K.C. (ed) *Archean Crustal Evolution*. Elsevier, Amsterdam, pp. 411–459.

ROSS, C.A. & ROSS, J.R.P. 1987. Late Paleozoic sea-levels and depositional sequences. Cushman Foundation for Foraminiferal Research, Spec. Publ. **24**, 137–149.

SADLER, P.M., OSLEGER, D.A. & MONTANEZ, I.P. 1993. On the labeling, length, and objective basis of Fischer plots. *Journal of Sedimentary Petrology*, **63**, 360–368.

SCHWARZACHER, W. 2000. Repetitions and cycles in stratigraphy. *Earth-Science Reviews*, **50**, 51–75.

SCRUTTON, C.T. 1998. The Palaeozoic corals, II: structure, variation and palaeoecology. *Proceedings of Yorkshire Geological Society*, **52**, Part **1**, 1–57.

ŞENGÖR, A.M.C. & NATAL'IN, B.A. 1996. Paleotectonics of Asia: Fragments of a syntacsis in the tectonic evolution of Asia. *In*: Jin, An & Harrison, M. (eds) *The Tectonic Evolution of Asia*, Cambridge, Cambridge Univ. Press, 486–640.

SLEEP, N.H. 1971. Thermal effects of the formation of Atlantic continental margin by continental break up. *Geophysical Journal of Royal Astronomical Society*, **24**, 325–360.

SLOSS, L.L. 1988. Tectonic evolution of the craton in Phanerozoic time. *In*: Sloss L.L (ed) *Sedimentary Cover – North American Craton, US. Geol. Soc. Am. Boulder, CO,* pp. 25–51.

SOKOLOV, B.S. (ed) 1985. *Reference Section of the Moyero River of the Silurian of the Siberian Platform* (in Russian). Nauka, Novosibirsk, 176 pp.

SOKOLOV, B.S. (ed) 1992. *Sucsessions and Fauna of the Silurian of the North of the Tunguska Syneclise* (in Russian). Nauka, Novosibirsk, 193 pp.

SURKOV, V.S. & KOROBEINIKOV, V.P. (eds) 2000. *Tectonic Map of Siberia. Scale 1:5.000.000*. Siberian Research Institute of Geology, Geophysics and Mineral Resources, Novosibirsk.

TAYLOR, S.R. & MCLENNAN, S.M. 1985. *Continental Crust: its Composition and Evolution*. Blackwell Scientific Publications, Oxford, 312 p.

TESAKOV, YU.I. 1981. Evolution of ecosystems of ancient platform sedimentary basins. *In*: Bogolepov, K.V. & Zharkov, M.A. (eds) *The Problems of Evolution of Geological Processes*. Nauka, Novosibirsk, pp. 186–199.

TESAKOV, YU.I., PREDTECHENSKY, N.N., KHROMYKH, V.G., BERGER, A.YA. & BOGOLEPOVA, O.K. 1986. *Fauna and Flora of the Polar Areas of the Siberian Platform* (in Russian). Nauka, Novosibirsk, 216 pp.

TESAKOV, YU.I., JOHNSON, M.E., PREDTECHENSKI, N.N., KHROMYKH, V.G. & BERGER, A.YA. 1998a. Eustatic fluctuations in the East Siberian Basin (Siberian Platform and Taymyr Peninsula). *In*: Landing, E. & Johnson, M. (eds) *Silurian Cycles, Linkages of Dynamic Stratigraphy with Atmospheric, Oceanic, and Tectonic Changes*. James Hall Centennial Volume, *The New York State Museum Bull*., **491**, 63–73.

TESAKOV, YU.I., PREDTECHENSKY, N.N. & KHROMYKH, V.G. 1998b. Stratigraphy of the Silurian of the Siberian Platform, *Russian Geology and Geophysics*, **39**, 1335–1356.

TESAKOV, YU.I., PREDTECHENSKY, N.N., LOPUSHINSKAYA, T.V., KHROMYKH, V.G., BAZAROVA, L.S., BERGER, A.YA. & KOVALEVSKAYA, E.O. 2000. *Stratigraphy of the Hydrocarbon Basins of Siberia. Silurian of the Siberian Platform* (in Russian), SO RAN, "GEO", Novosibirsk, 403 pp.

WATKINS, R., COOROUGH, P.J. & MAYER, P.S. 2000. The Silurian Dicoelosia communities: temporal stability within an ecologic evolutionary unit. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **162**, 225–237.

WEBBY, B.D. & LAURIE, J.R. (eds) 1992. *Global Perspectives on Ordovician Geology*. Balkema, Rotterdam, 524 pp.

WILKINSON, B.H., DRUMMOND, C.N., ROTHMAN, E.D. & DIEDRICH, N.W., 1997. Stratal order in peritidal carbonate sequences. *Journal of Sedimentary Research*, **B67**, 1068–1062.

WILSON, J.L. 1975. *Carbonate Facies in Geological History*. Springer-Verlag, Berlin, 471 pp.

ZOBACK, M.L. 1992. First- and second order patterns of stresses in the lithosphere: the World stress map project. *Journal of Geophysical Research*, **97**, 11703–11728.