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The East Siberian basin in the Silurian: evidence for no large-scale sea-level changes

E.V. Artyushkov[a,*], P.A. Chekhovich[b]

[a] Institute of Physics of the Earth, B. Gruzinskaya 10, GSP-5, 123995 Moscow, Russia
[b] Institute of the Lithosphere of Marginal Seas, Staromonetny 22, 109180 Moscow, Russia

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Abstract

According to conventional ideas, numerous eustatic sea-level changes occurred during the Phanerozoic with amplitudes 20–100 m and periods $T = 1$–3 Myr (third-order cycles). At the same time, it is widely recognized that tectonic factors have an important role in such water-depth changes. Rapid, large-scale sea-level changes have been suggested for the Silurian, for which detailed and continuous stratigraphic successions are available in the East Siberian sedimentary basin, $\sim 2 \times 10^6$ km^2 in size. These show slow deposition at depths ≤5–10 m proceeded for 10–20 Myr in many regions and enable the mathematical analysis of maximum eustatic sea-level changes, with periods of $T = 1$–3 Myr (third-order), that could have occurred during the Silurian. The amplitudes of such events could not exceed ~20–30 m, and, for some epochs, could not be larger than 8–10 m. At the same time, rapid water-depth changes of up to ~100 m occurred in some other cratonic areas. As the Silurian had a relatively stable sea level, these must be attributed to rapid crustal uplift and subsidence. The absence of third-order eustatic fluctuations with amplitudes ≥10–20 m has also been demonstrated for the Cambrian and earliest Ordovician. It is probable that no significant sea-level changes also occurred at many other epochs, while rapid changes in water depth resulted from large-scale, vertical crustal movements.

Keywords: Siberia; Silurian; sea-level changes; tectonic

1. Introduction

Stratigraphic records exhibit considerable changes in sedimentary facies through time indicating fluctuations of water depth in sedimentary basins (e.g. [1–3]). These fluctuations are also recorded in the migration of coastlines along basin slopes and are clearly visible in seismic reflection profiles [4]. Such phenomena have been widely interpreted as a result of eustatic sea-level changes [1,2,4,5] with typical eustatic curves (e.g. Fig. 1) including a number of sea level rise and fall events with periods ~1–3 Myr and amplitudes ~20–100 m – the so-called 'third-order cycles' or 'eustatic events'. These are usually superimposed on long-term sea-level changes with amplitudes of ≥10–100 m. Numerous third-order cycles have also been suggested for the Paleozoic [1,6,7]. Third-order cycles in water-depth changes are

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* Corresponding author. Fax: +7-095-2556040.
E-mail address: pchekh@ilran.ru (E.V. Artyushkov).

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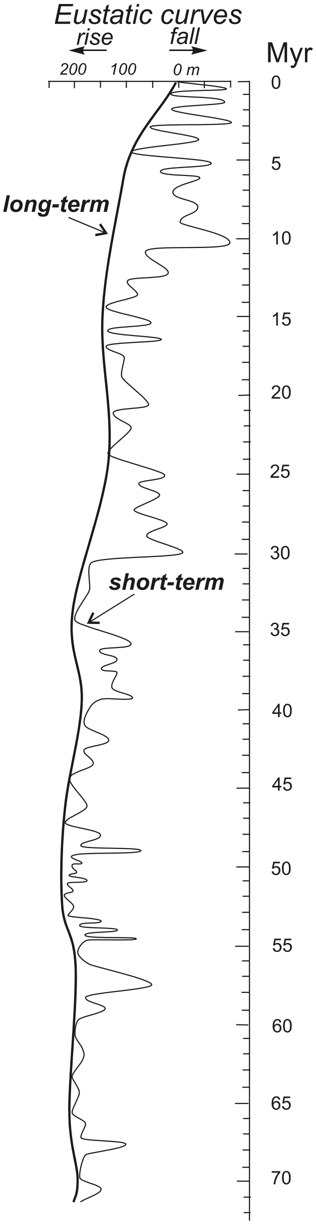


Fig. 1. Eustatic sea-level curve for the Cenozoic (modified after [4]).

widely considered to be important for the generation of hydrocarbon fields [8]. At times of rapid regressions, sands were forming within rivers on the exposed shelf, and in the sea near to the coast, providing good reservoirs for oil and gas, with subsequent transgressions depositing clays which are good caps to such stratigraphic traps. However, the influence of tectonic movements on changes in water depth has also been well established (e.g. [9,10]), casting serious doubts on the possibility of revealing third-order global sea-level changes in view of the present accuracy of geochronological methods [3,11]. In addition, no physical mechanisms are known to account for such large-scale sea-level changes in the absence of large ice sheets [12].

Nevertheless, the wide occurrence of eustatic events in the Phanerozoic is commonly considered to be a well established fact (e.g. [4,5,13]), with numerous third-order cycles suggested for Paleozoic times [1,6,7,14], including eight eustatic events during the Silurian [7] (Fig. 2), and a number of events during the Cambrian and earliest Ordovician [6,14,18] when the East Baltic remained at a depth of ≤10 m or emerged above sea level for no more than ~10 m. These East Baltic fluctuations indicate that any eustatic changes did not exceed ±10 m [19]. In marked contrast, large-scale, rapid changes in water depth occurred at the same time in Sweden, Lithuania, Australia, North America and Kazakhstan [6,18] that can only have resulted from tectonic movements if eustatic changes were so small. In order to resolve whether the Silurian eustatic events in Fig. 2 were really as large as indicated, the results of analyses of the detailed, continuous stratigraphic successions for the Silurian 2×10^6 km^2 East Siberian basin [20–26] are presented and discussed.

2. Depth analysis

A wide set of paleontological and sedimentological data are commonly used for determination of past changes in water depth [15,17,27,28]. Fossil assemblages of benthic biota together with the character of deposition enable shelf slopes (Figs. 2 and 3) to be divided into six zones [15]. Zone BA 1 comprises the central and shore-facing parts of the coastal shoal and also the lagoon between the shoal and the coastal beach. As the East Siberian basin was mostly far from the ocean, tidal amplitudes were likely to have been only a few meters, so this zone indicates water depths (h, see also Table 1) from 0 to ~10 m. Zone BA 2 includes the outer slope of the shoal and the uppermost shelf down to a depth of penetration of normal (fair-weather) waves so h would range from 5–10 m (depending on the shoal height) to 10–15 m. Zones BA 3 and BA 4 are the middle and lower parts of the shallow shelf, distinguished by containing different biota, with the bottom of BA 3 conventionally being taken at $h \sim 30$ m, i.e. below the normal wave base, and the bottom of BA 4 corresponding to both the wave base of seasonal storms and the base of the photic zone (where the amount of light is sufficient for an intensive growth of algae) at a depth of about 40–60 m, $h \sim 50$ m on average. Zone BA 5, on the upper part of the deep shelf, marks the depth at which algae and most hermatype corals disappear. Waves of seasonal storms should not reach this depth, although it may be affected by severe (millennial) hurricanes, i.e. a maximum of 150–180 m. However, if Silurian wave activity was lower than at present [15], as is likely, then the base of Zone BA 5 would be closer to 120 m [17]. Zone BA 6 would not be affected by any wave activity and corresponds to deep shelf with water depths ≥120 m in which stagnant conditions would often arise.

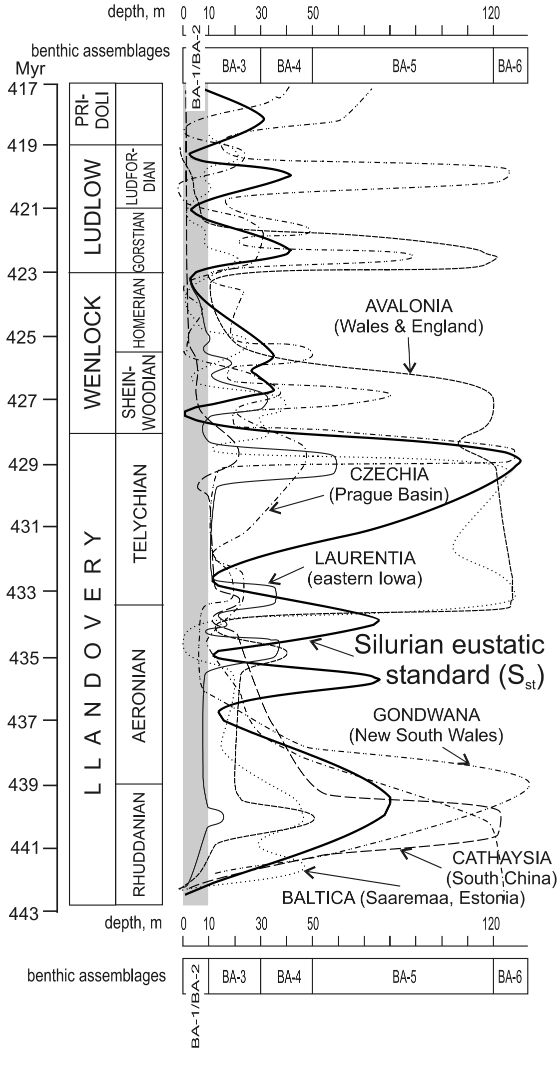


Fig. 2. Eustatic curve for the Silurian – 'the Silurian standard' (S_{st}) – and eustatic curves for six regions which were used for compilation of S_{st} (modified after [7]). The original curves in [7] were plotted using benthic assemblages of biota BA 1–BA 6 [15] (see Section 2). These curves are redrawn using time scale [16] and absolute water depths corresponding to assemblages BA 1–BA 6 [15,17].

Table 1
List of symbols

h	depth of water
h_0	depth of water before eustatic event
b	amplitude of event
b_m	minimum amplitude of resolvable events
T	duration of event
t	time
τ	dimensionless time (t/T)
Δt_{cz}	duration of time interval corresponding to chronozone
h_{cz}	thickness of chronozone
Δt_{nd}	duration of subaerial exposure and non-deposition
z_0	minimum altitude where subaerial exposure becomes evident
a	tectonic subsidence during eustatic event
ζ	ordinate of crustal surface with respect to sea level
ζ_{eu}	eustatic signal
ζ_t	tectonic subsidence
ζ_d	thickness of deposited sediments
ζ_1, ζ_3	change in ζ determined by Eqs. 5 and 9 when crustal surface is below sea level
ζ_2, ζ_4	changes in ζ determined by Eqs. 6 and 10 when crustal surface is above sea level
τ_1, τ_3	moments of time when crustal surface emerges to sea level
τ_2, τ_4	moments of time when crustal surface subsides to sea level
w	probability for absence of chronozone in sedimentary sequence

Another division of the shelf slope has been proposed [29] that, in modified form, has been applied to East Siberia during the Silurian [20–26]. Depth zones 1, 2, 3 and 4 correspond to Zones BA 6, BA 5, BA 4 and BA 3, respectively (Fig. 3). Depth zone 5 is the upper part of shallow shelf, between the coastal shoal and the normal wave base, and zone 6 is the outer slope of the coastal shoal (5–10 m). These two depth zones correspond to Zone BA 2. Zone 7 is the central part of the shoal with $h \leq 5$ m. Zones 8 and 9 are, respectively, the inner slope of the shoal, and the lagoon. Zones 7–9 are comprised by Zone BA 1. The very specific biota of these zones is drastically different from those of open marine environment of depth zone 5 and deeper zones 2–4. Under conditions of carbonate deposition, the sediments in zones 7–9 would include large volumes of primary dolomites, while gypsum and anhydrite would form in zones under conditions of intensive evaporation. In regions of siliciclastic deposition, in zones 6–8, the floor is strongly affected by tidal currents, which produces bi-directional (herring-bone) and multidirectional cross bedding. These features enable very easy distinction between the deeper ≥ 10 m depth zones (1–5) and the shallower zones 6–9. In the shallow zones, a rapid sea-level fall or crustal uplift of ≥ 10 m would result in subaerial exposure and erosion. Conversely, a rapid rise of sea level or crustal subsidence of ≥ 10 m would result in sediments and biota corresponding to the deeper zones. Consequently, in regions of slow deposition, even very small relative sea-level changes of ~ 10–20 m can be easily identified, if they are short enough. Such estimates of sea-level changes are especially accurate for coastal shoals, with $h \leq 5$ m, that allow relative sea-level changes of ≥ 5 m to be identified. Hence in the following analysis, emphasis will be given to the observations corresponding to deposition in the shallow zones, 6–9. Such sea-level change analyses in the East Siberian basin are facilitated by there being numerous exposures along the rivers, enabling a number of continuous Silurian stratigraphic successions to be compiled [20–22,25,26]. They have been divided into 54 intervals – chronozones – that can be correlated with the standard graptolite and conodont scales [25] as this extensive basin (Fig. 4) had good connections to the ocean. These chronozones correspond to time intervals $\Delta t_{cz} = 0.3$–1.1 Myr that are comparable to, or shorter than those of third-order cycles $T = 1$–3 Myr.

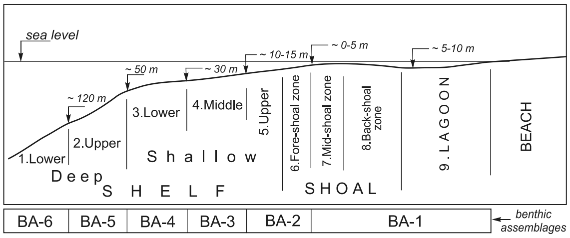


Fig. 3. Zones BA 1–BA 6 of benthic assemblages on a sea slope [15] and facies zones 1–9 [24,26]. These are based on benthic assemblages and the character of deposition. Modified after [24].

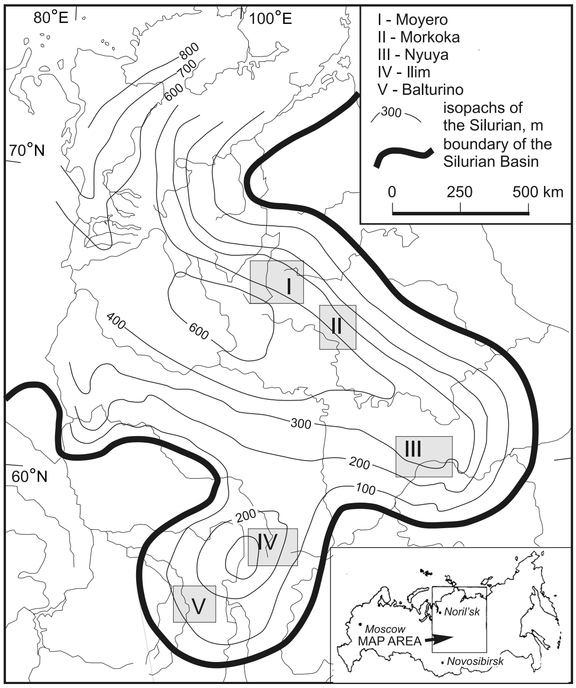


Fig. 4. The occurrence of sediments of the Silurian East Siberian basin (modified after [20]).

3. The evolution of the East Siberian basin in the Silurian

In the Late Ordovician, deposition occurred all over the East Siberian basin. In the Ilim and Balturino regions in the south (Fig. 4) and in the Nyuya region in the southeast, the depth of water in the Ordovician is poorly constrained, but deposition was continuous across the Ordovician–Silurian boundary. However, since the start of the Silurian, sea bottom remained in zones 6–9 (Fig. 5) [20]. Deposition continued under these conditions for ~12 Myr (443–431 Myr) in the Ilim region, for ~16 Myr (443–427 Myr) in the Balturino region, and for ~20 Myr (443–423 Myr) in the Nyuya region. It is probable that deposition at these very shallow depths continued in all these regions until the earliest Devonian, but the upper parts of the sedimentary successions have been eroded. Near to the Ordovician–Silurian boundary, subaerial erosion occurred in the northern and central basin parts, with a transgression commencing at the start of the Silurian. In 1–2 Myr, water depths $h \geq 120$ m were reached, corresponding to zone 1 (BA 6) (Moyero curve in Fig. 5). In the Morkoka region, closer to the basin margin, h was smaller, corresponding to zone 2 (BA 5) (Fig. 5). After filling these depressions with sedi-

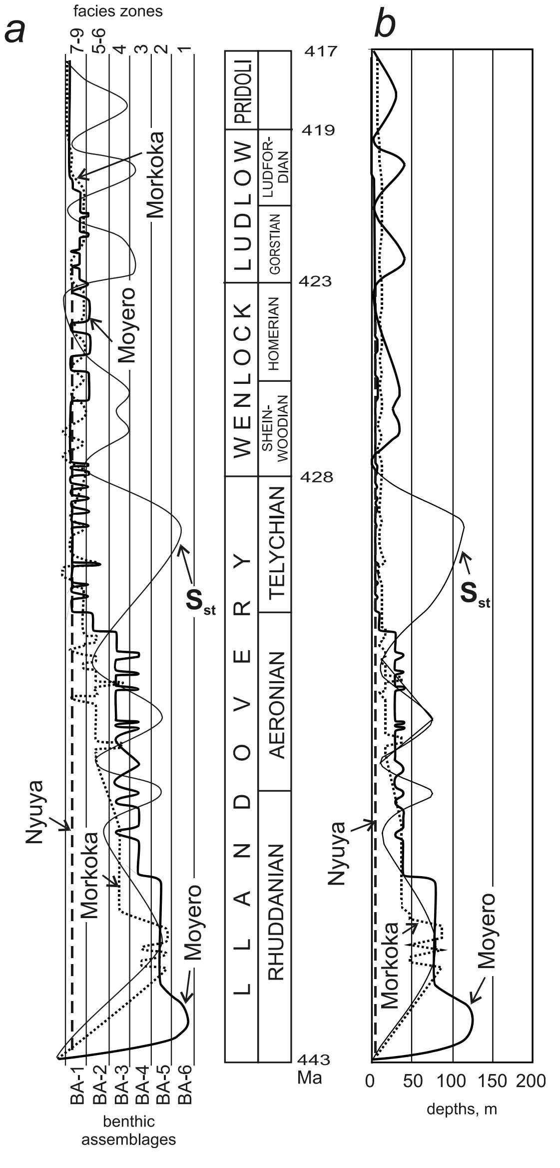


Fig. 5. Water-depth changes in some regions of the Silurian East Siberian basin. (a) Curves plotted using facial zones 1–9 (modified after [20–23,26]), (b) same curves redrawn using absolute water depths by [15,17].

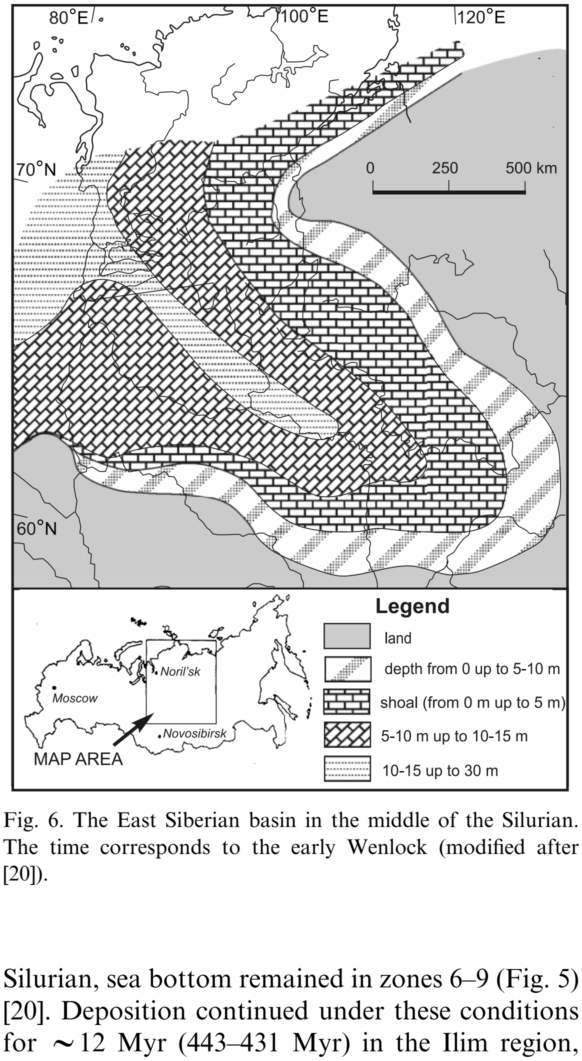


Fig. 6. The East Siberian basin in the middle of the Silurian. The time corresponds to the early Wenlock (modified after [20]).

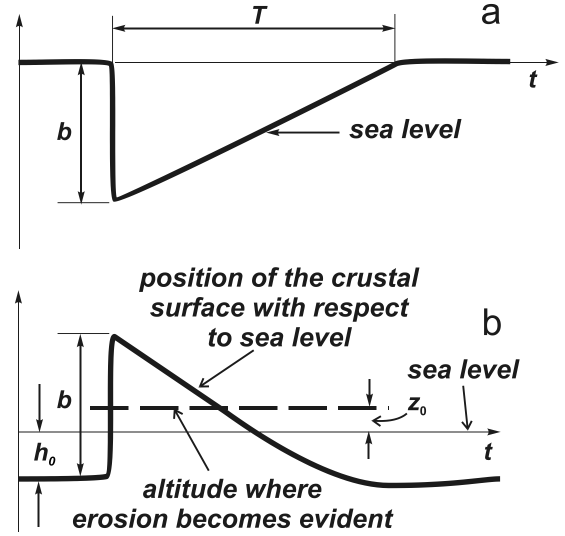


Fig. 7. Eustatic event and changing crustal surface. (a) Eustatic event with an abrupt sea-level fall and subsequent linear sea-level rise. (b) Corresponding position of the crustal surface with respect to sea level. b is the amplitude of event, T its duration, h_0 initial depth of water, z_0 the altitude where subaerial erosion becomes evident.

ments, deposition at $h \leq 5$–10 m (zones 6–8) occurred in the Morkoka region [22] and in zones 7–9 in the Moyero region [21,23], both persisting until the end of the Silurian, 417–432 Myr ago. In the middle of the Silurian, a narrow band of shelf, $h \geq 10$–15 m, spread along the basin axis (Fig. 6). On either side of it, deposition took place in zones 6–9, and a shoal with $h \leq 5$ m covered a large part of the basin. In the Late Silurian, deposition at $h \leq 10$ m occurred all over the basin, with a shoal over most of it. A complete regression took place during 1–2 Myr after the start of the Devonian. Thus, during the Rhuddanian–Aeronian, deposition at $h \leq 10$ m occurred in the Ilim, Balturino and Nyuya regions, and in the Telychian–Pridoli stages, this took place over most of the basin (Fig. 6). In the Nyuya, Moyero and Morkoka regions, deposition at $h \leq 10$ m occurred synchronously 422–432 Myr ago (Fig. 5). Thus, on the evidence for water-depth changes within the East Siberian basin, large-scale eustatic events are precluded during the entire Silurian [30].

4. Magnitudes of resolvable eustatic events with an abrupt regressive phase

To the simplest approximation, which can be considered analytically, a eustatic event can be represented as an instantaneous sea-level fall followed by a linear rise over the period of time T (Fig. 7a). The sea bottom would emerge above sea level if the event amplitude (b) exceeds the initial water depth (h_0). During the following sea-level fall, a finite rate of the crustal subsidence is taken into account in Fig. 7b. To produce erosion visible in the sedimentary records, the sea bottom should emerge above sea level for a certain altitude (z_0) so:

$$b \geq h_0 + z_0 \tag{1}$$

In the Llandovery, siliciclastic deposition occurred at $h \leq 10$ m on the basin margins. As almost no terrestrial vegetation existed in the Silurian, sands and silts would be eroded extremely rapidly even at very low altitudes. However, the Llandoverian successions in East Siberia include complete sets of all the chronozones and, in many cases, their thickness (h_{cz}) only changed gradually from one chronozone to another (Fig. 8). This precludes significant erosion. Consequently, at that time, the crustal surface can never have risen higher than $z_0 \approx 10$ m above sea level. Taking $h_0 \approx 10$ m in Eq. 1, then abrupt sea-level falls could not exceed $b = b_m \sim 20$ m.

Carbonate deposition took place 417–432 Myr ago, with $h \leq 10$ m over most of the basin and reef

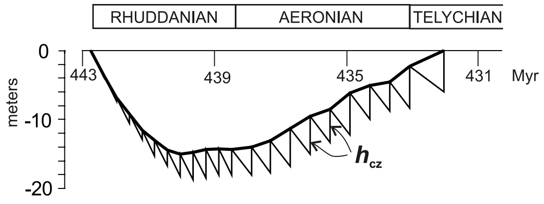


Fig. 8. Thickness of sediments (h_{cz}) of the Llandoverian chronozones in the Ilim region. The stratigraphic intervals are characterized by specific biota. See Fig. 4 for location. The presence of all the chronozones in the succession and gradual changes in h_{cz} indicate no significant erosion of the deposits.

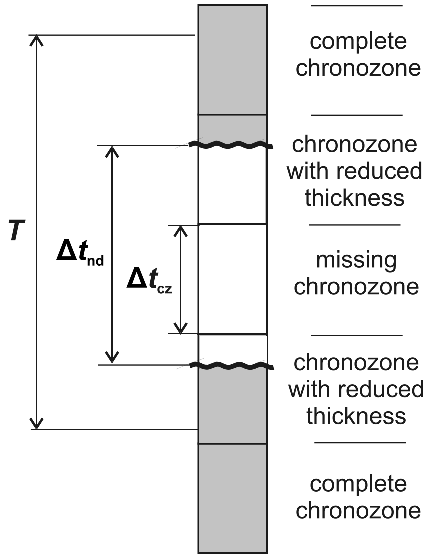


Fig. 9. The relationships between the period of subaerial exposure and non-deposition. Non-deposition is for Δt_{nd} duration, and time intervals, Δt_{cz} long, corresponding to the chronozones. At $\Delta t_{nd} \geq 2\Delta t_{cz}$, one chronozone is missing in the stratigraphic succession with a 100% probability.

build-ups on a vast shoal with $h \leq 5$ m. As karst and microkarst develop rapidly on carbonate platforms at times of subaerial exposure [31], then, low amplitude tides would allow exposure to karst formation at z_0 of a few meters above sea level. Episodes of subaerial exposure of the shoal in East Siberia were numerous, but of very short duration and the sea bottom never rose higher than a few meters above sea level (Tesakov, personal communication). Short-term regressions most probably resulted from sea-level fluctuations due to the precession or a combination of precession and obliquity periodicities. Taking $h_0 \sim 5$ m and $z_0 \sim 3$ m in Eq. 1, then b could not exceed $b_m \sim 8$ m. Eustatic events can also be indicated by gaps in stratigraphic records due to non-deposition during subaerial exposure. If such events have a duration of Δt_{nd}, then sediments of a chronozone corresponding to a time interval Δt_{cz}, that partially overlapped a period of non-deposition, would still be preserved in the succession (Fig. 9). A chronozone would only disappear completely from the succession, with a 100% probability, if Δt_{nd} exceeds Δt_{cz} by at least twice (Fig. 9). The minimum necessary Δt_{nd} would be:

$$\Delta t_{nd} = 2\Delta t_{cz} \tag{2}$$

If a tectonic crustal subsidence occurred at a rate a/T, then for the eustatic event of Fig. 7a, with no erosion during the subaerial exposure, using Eq. 2, the event could be resolved at the minimum amplitude:

$$b_m = (h_0 + 2a\Delta t_{cz}/T)(1-2\Delta t_{cz}/T)^{-1} \tag{3}$$

Consequently b_m rises as a and Δt_{cz} increase.

In the Llandovery, the lowest mean Δt_{cz} was typically 0.36 Myr for the Rhuddanian, when the slowest subsidence ($a/T = 6.8$ m/Myr) occurred in the Ilim region. The minimum amplitude (Eq. 3) is plotted (Fig. 10) for the Rhuddanian as a function of T for these values of the parameters and with $h_0 = 10$ m. At $T = 1.4$–3 Myr, $b_m = 20$–30 m (see also Table 2). However, as discussed above, values of $b \geq 20$ m are precluded by the absence of significant erosion. In the Late Silurian, the lowest mean $\Delta t_{cz} = 0.31$ Myr was typical of the Ludlow when the subsidence rate was $a/T = 17$ m/Myr in the Moyero region. Taking $h_0 = 5$ m on the shoal, Eq. 3 for the Ludlow is plotted (Fig. 10) and, at $T = 1.3$–3 Myr, $b_m = 20$–30 m. However, according to Eq. 1, at that time b_m could not have exceeded 8 m.

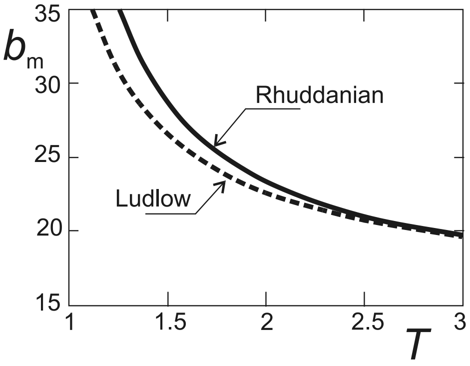


Fig. 10. Minimum magnitudes b_m (in m). These are for eustatic events with an abrupt sea-level fall and duration T (Fig. 7a), which would ensure the absence of one chronozone in stratigraphic successions of the Rhuddanian and Ludlow.

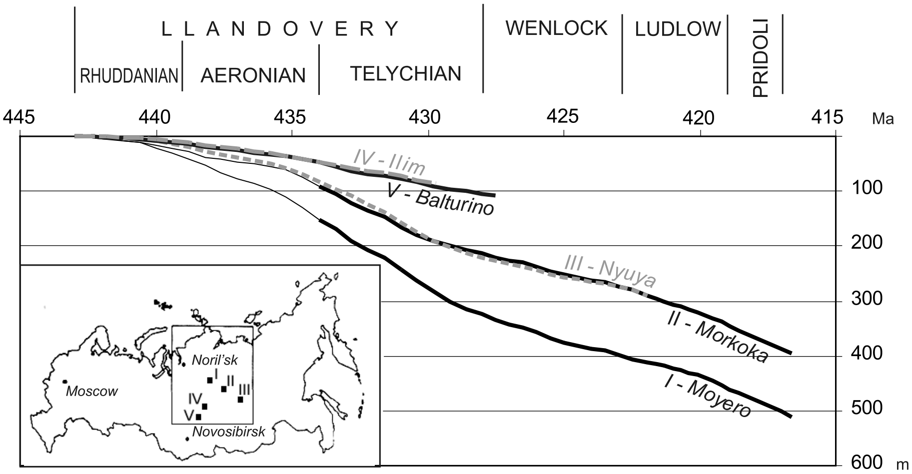


Fig. 11. The curves of Silurian deposition in some regions of East Siberia. These are plotted using the data by [22]. Epochs of deposition at very shallow depths ≤10 m are marked by broad lines.

5. Magnitudes of resolvable eustatic events with a gradual regressive phase

The curves of Silurian deposition, in the same regions as considered above, are plotted (Fig. 11) using the present sediment thickness. Epochs of deposition at $h \leq 10$ m are marked by broad lines. The Silurian deposits, now exposed at the surface, had been overlain by younger sediments which were eroded later. In the Ilim, Balturino and Nyuya regions, eroded sediments were a few hundred meters thick and could not produce significant compaction of the Silurian rocks. In the Moyero and Morkoka regions, the overlying deposits were thicker. However, according to the data of petroleum exploration [22], these regions were far outside the area of weak compaction of Silurian carbonates (marginal porosity of 16%). Hence, in the following estimates compaction of these rocks was taken as 10%. Consequently, for the Moyero and Morkoka regions, the initial thicknesses of carbonates were increased by 11% as compared to those shown in Fig. 11. The rate of crustal subsidence at $h \leq 10$ m ranged from ∼5 m/Myr, in the Balturino region during the Telychian, to ∼23 m/Myr in the Morkoka region during the Pridoli.

Suppose that the eustatic event has a form (Fig. 12):

Table 2
Minimum amplitudes b_m (in m) of eustatic events

Epoch	Regressive phase	Constraint	T	b_m
Rhuddanian–Aeronian	abrupt	1	1–3	20
Rhuddanian	abrupt	2	1.4–3	20–30
Rhuddanian	gradual	2	1.3–3	15–20
Telychian–Pridolian	abrupt	1	1–3	8
Wenlock	gradual	1	1–3	13–22
Wenlock	gradual	2	2–3	23–24
Ludlow	abrupt	2	1.3–3	20–30
Ludlow	gradual	1	1–3	13–24
Ludlow	gradual	2	1.5–3	19–22

Abrupt and gradual regressive phases (Figs. 7a and 12, respectively) can be resolved in the Silurian of East Siberia using the absence of erosional features (constraint 1) and completeness of stratigraphic sequences (constraint 2). T – duration of events (in Myr).

$$\zeta_{\mathrm{eu}} = -b\sin^2(\pi\tau) \quad (4)$$

where $\tau = t/T$. In the Early Silurian, predominantly siliciclastic deposition occurred on the basin margins. Its rate ($\mathrm{d}\zeta_\mathrm{d}/\mathrm{d}\tau$) was mostly determined by the intensity of erosion of the vast adjacent landmasses. Under such circumstances, $\mathrm{d}\zeta_\mathrm{d}/\mathrm{d}\tau$ can be taken as constant and equal to the rate of crustal subsidence, a/T, so that, in the absence of eustatic events, $h = h_0$. Using the ordinate of the crustal surface with respect to sea level as ζ, then, at $\zeta < 0$, $h = -\zeta$, and, at the time of eustatic event (Eq. 4):

$$\zeta_1 = -h_0 + b\sin^2(\pi\tau) \text{ at } \zeta_1 < 0 \quad (5)$$

The falling sea level reaches the bottom of the sea ($\zeta = 0$) at $\tau = \tau_1 = (1/\pi)\arcsin(h_0/b)^{1/2}$, and, at the time of subaerial exposure, in the absence of significant erosion, and at the rate of crustal subsidence a/T, then:

$$\zeta_2 = -h_0 + b\sin^2(\pi\tau) - a(\tau - \tau_1) \text{ at } \zeta_2 > 0 \quad (6)$$

Subaerial exposure ceases at time $\tau = \tau_2$, where τ_2 is the second root of Eq. 6. The duration of the exposure and non-deposition is $\Delta t_{\mathrm{nd}} = (\tau_2 - \tau_1)T$. According to Eq. 2, preservation of all the chronozones in the successions would occur if $(\tau_2 - \tau_1)T \leq 2\Delta t_{\mathrm{cz}}$. The minimum amplitude b_m of event (Eq. 4), which ensures this condition for the Rhuddanian, is a function of T (Fig. 13). At $T = 1.7$–3 Myr, $b_\mathrm{m} = 15$–20 m, and $b_\mathrm{m} < 30$ m at $T > 1.3$ Myr. The mean rate of carbonate deposition, $\mathrm{d}\zeta_\mathrm{d}/\mathrm{d}\tau$, in zones 6–9, i.e. at very shallow depths, generally increases with the water depth – ζ. Suppose that this rate is proportional to the water depth, then:

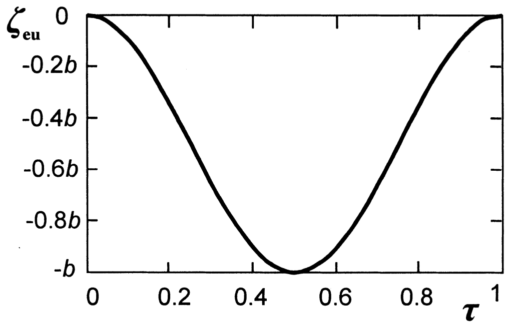


Fig. 12. Eustatic event of harmonic type ζ_{eu}. This is determined by Eq. 4 with a gradual sea-level fall of the amplitude *b*.

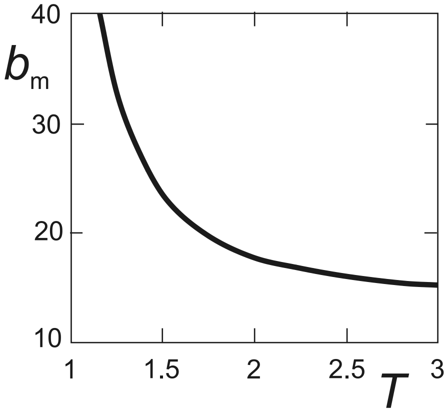


Fig. 13. Minimum amplitudes b_m (in m). These data are for eustatic events (Eq. 4) with a gradual sea-level fall and duration T (in Myr), which would guarantee the absence of one chronozone in the stratigraphic successions of the Rhuddanian.

$$\mathrm{d}\zeta_\mathrm{d}/\mathrm{d}\tau = -(a/h_0)\zeta \quad (7)$$

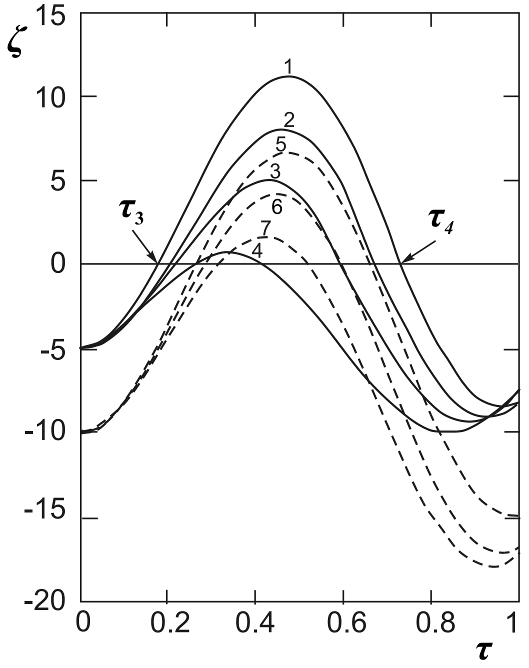
The rate of eustatic sea-level changes (Eq. 4) is $\mathrm{d}\zeta_{\mathrm{eu}}/\mathrm{d}\tau = -\pi b\sin 2\pi\tau$, and that of tectonic subsidence is $\mathrm{d}\zeta_\mathrm{t}/\mathrm{d}\tau = -a$. At times when the crustal surface is below sea level, the rate of change of its position with respect to sea level is $\mathrm{d}\zeta/\mathrm{d}\tau = \mathrm{d}\zeta_\mathrm{t}/\mathrm{d}\tau - \mathrm{d}\zeta_{\mathrm{eu}}/\mathrm{d}\tau + \mathrm{d}\zeta_\mathrm{d}/\mathrm{d}\tau$. Using Eq. 7, then:

$$\mathrm{d}\zeta/\mathrm{d}\tau = -a + \pi b\sin 2\pi\tau - (a/h_0)\zeta \text{ at } \zeta \leq 0 \quad (8)$$

Under the initial condition $\zeta(0) = -h_0$, the solution of Eq. 8 is:

$$\zeta_3 = -h_0 + \{\pi b/[4\pi^2 + (a/h_0)^2]\}\{(a/h_0)\sin 2\pi\tau - 2\pi\cos 2\pi\tau + 2\pi\exp[-(a/h_0)\tau]\} \text{ at } \zeta_3 \leq 0 \quad (9)$$

The time, τ_3, is when the falling sea level reaches sea bottom so that deposition ceases (Fig. 14). In the absence of significant erosion of carbonates at low altitudes, the last term in the right-hand side of Eq. 8 can be neglected, and the solution of Eq. 8 becomes:



curve number	h_0, m	a, m	b, m
1	5	10	20
2	5	20	20
3	5	30	20
4	5	50	20
5	10	10	20
6	10	20	20
7	10	30	20

Fig. 14. Relative sea-level changes ζ (in m). These are defined by Eq. 9 at the epochs of marine deposition ($\zeta<0$) at $0\le\tau\le\tau_3$ and at $\tau_4\le\tau\le1$, and by Eq. 10 at the epoch of subaerial exposure ($\zeta>0$) at $\tau_3<\tau<\tau_4$. h_0 is the initial depth of water, a is the magnitude of the crustal subsidence during the eustatic event, b is the amplitude of the event, τ is dimensionless time, τ_3, τ_4 are the times of the beginning and end of subaerial exposure in curve 1.

$$\zeta_4 = -a(\tau-\tau_3)-(b/2)\cos 2\pi\tau+$$
$$(b/2)\cos 2\pi\tau_3 \text{ at } \zeta_4>0 \qquad (10)$$

Consequently subaerial exposure becomes evident, when the maximum of Eq. 10 reaches z_0:

$$\max(\zeta_4) = z_0 \qquad (11)$$

For the Silurian carbonates on the shoal, z_0 can be taken as 3 m and h_0 as 5 m. The rate of crustal subsidence was $d\zeta_t/dt = 15$ m/Myr in the Morkoka region during the Wenlock, and 17 m/Myr in the Moyero region in the Ludlow. The corresponding values of b_m that are necessary to fulfil Eq. 11 are functions of T (Fig. 15). In the range of $T = 1$–3 Myr, events (Eq. 4) with $b\ge b_m = 13$–22 m could be identified in the Wenlock, and with $b\ge b_m = 13$–24 m in the Ludlow (see also Table 2).

Designated by τ_4 (Fig. 14) is the time when, after a period of subaerial exposure, the altitude (Eq. 10) of the crustal surface again reaches sea level with a start of new transgression. Then, at $\tau\ge\tau_4$, ζ is described by Eq. 9 under the condition $\zeta_3(\tau_4) = 0$. According to Eq. 2, one chronozone will be definitely missing in the succession at:

$$(\tau_4-\tau_3)T\ge 2\Delta t_{cz} \qquad (12)$$

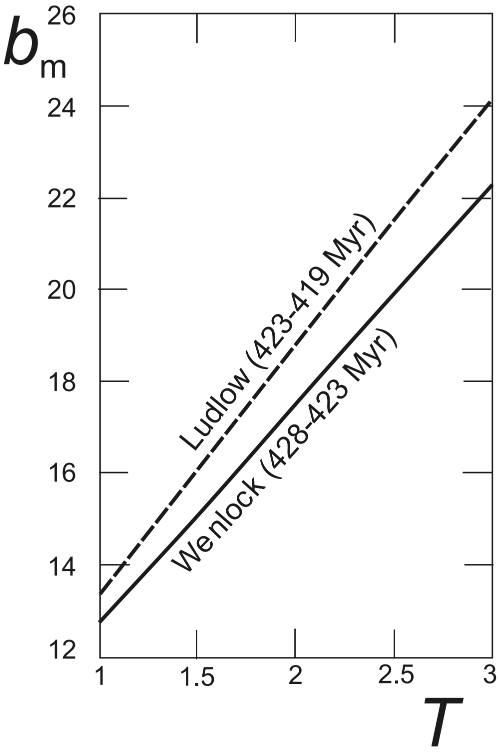


Fig. 15. Minimum amplitudes b_m (in m) of eustatic events. These data are for eustatic events (Eq. 4) of duration T (in Myr), which is sufficient for revealing subaerial erosion at the altitude $z_0 = 3$ m in the Telychian–Pridoli. The initial depth of water is $h_0 = 5$ m.

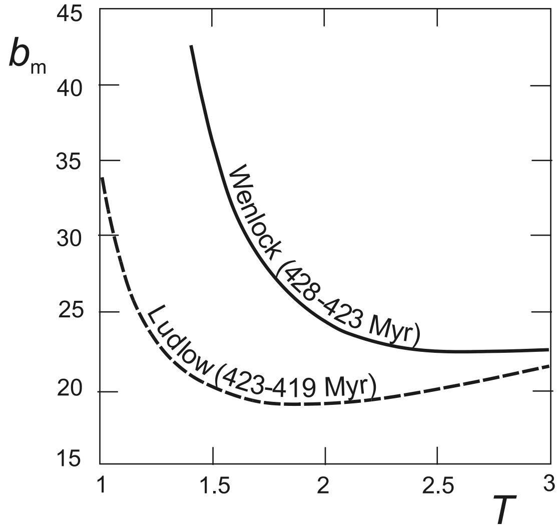


Fig. 16. The minimum amplitudes b_m (in m). These data are for eustatic events (Eq. 4) of duration T, which would ensure the absence of one chronozone in stratigraphic successions of the Wenlock and Ludlow. The initial water depth is $h_0 = 5$ m.

Taking $h_0 = 5$ m and $\Delta t_{cz} = 0.45$ Myr for the Wenlock and $\Delta t_{cz} = 0.31$ Myr for the Ludlow, then, for the above subsidence rates in the Morkoka region in the Wenlock, and in the Moyero region in the Ludlow, the smallest b_m, which would ensure revealing eustatic events (Eq. 4), can be determined (Fig. 16). In the Wenlock, events with $b \geq b_m = 23$–24 m could be revealed for $T = 2$–3 Myr. In the Ludlow, events with $b \geq b_m = 19$–22 m could be reliably resolved at $T = 1.5$–3 Myr.

6. Maximum possible magnitudes of eustatic events in the Silurian

When estimating the minimum amplitudes b_m of eustatic events which could not be missed in the stratigraphic successions of East Siberia in the Silurian and some of its subdivisions, two constraints were used: (1) the absence of erosional features, and (2) the completeness of the successions. Altitudes, where erosion arises, can be estimated only approximately. As gaps in stratigraphic succession can be established more reliably, constraint 2 is more definite. In the Rhuddanian and Aeronian, based on constraint 1, events with an abrupt phase are precluded at $b \geq b_m = 20$ m (see Table 2). Constraint 2 allows resolution of Rhuddanian events with $b_m \approx 15$–30 m for $T = 1.3$–3 Myr. In the Telychian–Pridoli, constraint 1 ensures revelation of events with an abrupt sea-level fall at $b \geq b_m = 8$ m. Using constraint 2, in the Ludlow, at $T = 1.3$–3 Myr, such events could be resolved at $b \geq b_m = 20$–30 m. Constraint 2 allows events with a gradual regressive phase in the Wenlock and Ludlow to be identified that have $b_m = 19$–24 m at T from 1.5–2 Myr to 3 Myr. Thus, in most cases, the maximum amplitudes of eustatic events that could be missed are $b_m \sim 8$–30 m. This is below or near the lower limit of $b \sim 20$–100 m, that is commonly supposed for eustatic third-order cycles. Furthermore, values of $h_0 = 10$ m and $z_0 = 10$ m are being used for the Llandovery, and $h_0 = 5$ m, $z_0 = 3$ m for the Telychian–Pridoli stages. In many regions, deposition occurred at shallower depths, h_0, and significant erosion would become evident at lower altitudes z_0, thus decreasing b_m considerably. Similarly, using constraint 2 under condition $\Delta t_{nd} = 2\Delta t_{cz}$ ensures the disappearance of one chronozone with a 100% probability. For shorter periods of non-deposition, when $\Delta t_{cz} < \Delta t_{nd} < 2\Delta t_{cz}$, one chronozone could also be absent with a probability:

$$w = (\Delta t_{nd} - \Delta t_{cz}) / \Delta t_{cz} \tag{13}$$

For example, $w = 50\%$ at $\Delta t_{nd} = 1.5\Delta t_{cz}$, and there is a high probability that b_m can be decreased. A considerable overlap of the time interval corresponding to a chronozone, with a period of non-deposition, results in a remarkably reduced sediment thickness. The very gradual changes in the thickness of chronozones in East Siberia preclude this possibility. Thus, most probably, the actual eustatic events were considerably smaller than those given in Table 2.

7. Rapid changes in water depth as a consequence of vertical crustal movements

The relative stability of sea level in the Silurian, as evidenced in East Siberia, contradicts the occurrence of the large-scale eustatic fluctuations in curve S_{st}, 'the Silurian standard' (Fig. 2), which was compiled as an average of water depth in six areas [7]. Furthermore, these water-depth changes were not synchronous. For example, 439–440 Myr ago, in Southern China, Czechia, and Southeastern Australia, the water depth was $\geq$120 m. A few million years later, sea bottom has risen to a depth h of a few tens of meters in Southern China and Czechia and to $h \sim 10$ m in Southeastern Australia. Consequently a eustatic sea-level fall by $\sim$100–120 m could be supposed. However, at the same time, shallow shelves existed in Eastern Iowa, England and Wales, and in the East Baltic. Similarly, some 433 Myr ago, England, Wales and East Baltic subsided to $h \sim 120$ m, while sea deepening in another four regions did not exceed a few tens of meters. Similar large differences between the regional curves can be seen in the rest of the Silurian. Under a slowly changing sea-level regime, the above changes in water depth can only be due to rapid tectonic movements. Therefore, curve S_{st} is not a eustatic curve, but is simply the average of regional tectonic movements in six arbitrary chosen regions. Large-scale crustal movements of short duration, $\sim$1–2 Myr, took place episodically in many other areas [32,33], particularly in East Baltic during the Cambrian [19]. At the start of the Silurian, rapid sea deepening by $\geq$100 m occurred in the central and northern parts of East Siberia (see the Moyero curve in Fig. 5). Since glaciation took place in the Southern Hemisphere in the Late Ordovician–Early Silurian [34], the transgression could be supposed to have resulted from the melting of the ice sheet, but, at that time, slow deposition at a depth $\leq$10 m continued on the basin margins (the Nyuya curve in Fig. 5). Hence the transgression must be of tectonic origin. At the same time rapid sea deepening, by $\sim$1–2 km, occurred on the European passive margin of the Uralian Ocean [35]. This is far beyond the magnitude of sea-level changes of $\sim$100–200 m due to melting of ice sheets. Several mechanisms have been proposed for rapid uplifts and subsidences in cratonic areas. They can be caused, for example, by changes in the force acting along the lithosphere [36], upwelling of small plumes [37], changes in time of the position of subduction zones, and the rate and dip angle of subduction [38], and rapid subsidences can be due to the infiltration of volatiles from the plumes into the lower crust, which catalyze phase transformations in mafic rocks. In order to distinguish between such major tectonic influences on sea level and those of genuine eustatic origin, detailed analyses of stratigraphic data of the same type of those in [38] will be necessary to identify a relative role of these mechanisms.

8. Discussions and conclusions

It is commonly supposed that eustatic sea-level changes with amplitudes $b \sim 20$–100 m and periods $T = 1$–3 Myr (third-order cycles) occurred during most of the Phanerozoic [1,2,4,5], particularly in the Silurian [7]. However, in the Silurian, slow deposition occurred at very shallow depths, $\leq$5–10 m, in many regions of East Siberia [26]. The analysis presented here shows that, at this time, eustatic sea-level changes of a third-order could not generally have exceeded $\sim$20–30 m, and, at some epochs, could not be larger than 8–13 m. With such a relatively stable Silurian sea level, rapid changes in water depth in other cratonic areas [7] must be attributed to rapid crustal movements on a regional scale. Very slow deposition at depths $\leq$10 m also occurred in the East Baltic during the Cambrian and earliest Ordovician, also indicating the absence of large-scale eustatic events during this $\sim$45 Myr long period [19]. At this time, rapid changes of water depth, up to $\sim$50–100 m, occurred in Southern Sweden and Lithuania [19], Australia and North America [6], and in Kazakhstan [18]. These changes, currently being interpreted as resulting from eustatic events, must also be attributed to rapid, regional crustal uplift and subsidence. Such features have direct economic importance as numerous hydrocarbon fields occur in stratigraphic traps formed by rapid regressive–transgressive events [8]. Their possible location can be easily predicted for genuine eustatic events that are synchronous and nearly uniform all over the world. However, to locate traps formed due to water-depth changes as a result of rapid crustal movements, it is necessary to know physical mechanisms of such movements and their space distribution within each region. This will require special analyses. The analyses presented here are for regions selected merely because of the high quality of the data available for them. It is probable that large-scale eustatic events did not occur during other long epochs; possibly for most of the Phanerozoic [11]. The third-order cycles currently being proposed for such epochs will similarly mainly reflect rapid, regional crustal movements. Further studies are necessary to identify other long periods of relative stability of sea level, as well as those eustatic events that actually occurred. Such major tectonic movements in cratonic areas, commonly supposed to be relatively stable, indicate a highly significant, largely unrecognized tectonic mechanism that operates in such regions.

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References

[1] A. Hallam, Phanerozoic Sea Level Changes, Columbia University Press, New York, 1992, 266 pp.

[2] D. Emery, K.J. Myers, Sequence Stratigraphy, Blackwell Science, Oxford, 1996, 297 pp.

[3] A.D. Miall, The Geology of Stratigraphic Sequences, Springer, Berlin, 1997, 433 pp.

[4] B.U. Haq, J. Hardenbol, P.R. Vail, Chronology of fluctuating sea levels since the Triassic, Science 235 (1987) 1156–1167.

[5] P.C. de Graciansky, J. Hardenbol, T. Jaquin, P.R. Vail, Mesozoic and Cenozoic Sequence Stratigraphy of European basins: SEPM Special Publication Series 60, Tulsa, 1998, 786 pp.

[6] B.D. Webby, J.R. Laurie, Global Perspectives on Ordovician Geology, Balkema, Rotterdam, 1992, 524 pp.

[7] M.E. Johnson, Stable cratonic sequences and a standard for Silurian eustasy, Geol. Soc. Am. Spec. Pap. 306 (1996) 202–211.

[8] H.W. Posamentier, G.P. Allen, Siliciclastic Sequence Stratigraphy – Concepts and Applications: SEPM Concepts in Sedimentology and Paleontology 7, SEPM, 2000, 216 pp.

[9] F. Maurer, Growth mode of middle Triassic carbonate platforms in the western Dolomites (Southern Alps, Italy), Sediment. Geol. 134 (2000) 275–286.

[10] O. Catuneanu, A.R. Sweet, A.D. Miall, Recyprocal stratigraphy of the Campanian–Peleocene Western Interior of North America, Sediment. Geol. 134 (2000) 235–255.

[11] A.D. Miall, The Exxon global cycle chart: an event for every occasion?, Geology 20 (1992) 787–790.

[12] G.G.A. Harrison, Long-term eustasy and epeirogeny on the continents, in: R.R. Revell (Ed.), Sea-Level Change, Natl. Acad. Press, Washington, DC, 1990, pp. 141–158.

[13] W. Schwarzacher, Repetitions and cycles in stratigraphy, Earth-Sci. Rev. 50 (2000) 51–75.

[14] M.R. Saltzman, J.P. Davidson, P. Holden, B. Runnegar, K.C. Lohman, Sea-level-driven changes in ocean chemistry at an Upper Cambrian extinction horizon, Geology 23 (1995) 893–896.

[15] C.E. Brett, A.J. Boucot, B. Jones, Absolute depths of Silurian benthic assemblages, Lethaia 26 (1993) 25–40.

[16] F.M. Gradstein, J. Ogg, A Phanerozoic time scale, Episodes 19 (1996) 3–5.

[17] M.E. Johnson, Extent and bathymetry of North American Platform seas in the Early Silurian, Paleoceanography 2 (1987) 185–211.

[18] A. Cooper, G.S. Nowlan, Proposed Global Stratigraphic Section and Point for Base of the Ordovician System International Working Group on the Cambrian–Ordovician Boundary, Circular, Calgary, 1999.

[19] E.V. Artyushkov, M. Lindström, L.E. Popov, 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 (2000) 375–407.

[20] Yu.I. Tesakov, Evolution of ecosystems of ancient platform sedimentary basins, in: K.V. Bogolepov, M.A. Zharkov (Eds.), The Problems of Evolution of Geological Processes (in Russian), Nauka, Novosibirsk, 1981, pp. 186–199.

[21] Yu.I. Tesakov, N.N. Predtechensky, V.G. Khromykh, A.Ya. Berger, O.K. Bogolepova, Fauna and Flora of the Polar Areas of the Siberian Platform (in Russian), Nauka, Novosibirsk, 1986, 216 pp.

[22] B.S. Sokolov, Successions and Fauna of the Silurian of the North of the Tunguska Syneclise (in Russian), Nauka, Novosibirsk, 1992, 193 pp.

[23] M.E. Johnson, D. Kaljo, J.-Y. Rong, Silurian eustasy, Spec. Pap. Paleontol. 44 (1991) 145–163.

[24] M.E. Johnson, Yu.I. Tesakov, N.N. Predtechensky, B.G. Baarli, Comparison of Lower Silurian shores and shelves

in North America and Siberia, Geol. Soc. Am. Spec. Pap. 321 (1997) 23–46.

[25] Yu. I, Tesakov, N.N. Predtechensky, V.G. Khromykh, Stratigraphy of the Silurian of the Siberian Platform, Russ. Geol. Geophys. 39 (1998) 1335–1356.

[26] Yu.I. Tesakov, N.N. Predtechensky, T.V. Lopushinskaya, V.G. Khromykh, L.S. Bazarova, A.Ya. Berger, E.O. Kovalevskaya, Stratigraphy of the Hydrocarbon Basins of Siberia. Silurian of the Siberian Platform (in Russian), SO RAN, 'GEO', Novosibirsk, 2000, 403 pp.

[27] C.T. Scrutton, The Palaeozoic corals, II: structure, variation and palaeoecology, Proc. Yorks. Geol. Soc. 52 (1998) 1–57.

[28] R. Watkins, P.J. Coorough, P.S. Mayer, The Silurian Dicoelosia communities: temporal stability within an ecologic evolutionary unit, Palaeoclimatol. Palaeogeogr. Palaeoecol. 162 (2000) 225–237.

[29] J.L. Wilson, Carbonate Facies in Geological History, Springer, Berlin, 1975, 471 pp.

[30] E.V. Artyushkov, P.A. Chekhovich, The East Siberian sedimentary basin in the Silurian: Evidence for a lack of rapid eustatic fluctuations, Dokl. Earth Sci. 373 (2000) 793–797.

[31] B. D'Argenio, V. Ferreri, A. Raspini, S. Amodio, F.P. Buonocunto, Cyclostratigraphy of a carbonate platform as a tool for high-precision correlation, Tectonophysics 315 (1999) 357–384.

[32] E.V. Artyushkov, M.A. Baer, Mechanism of formation of hydrocarbon basins: the West Siberia, Volga-Urals, Timan-Pechora basins and Permian basin of Texas, Tectonophysics 122 (1986) 247–281.

[33] E.V. Artyushkov, Physical Tectonics (in Russian), Nauka, Moscow, 1993, 456 pp.

[34] M.J. Hambrey, The Late Ordovician–Early Silurian glacial period, Palaeogeogr. Palaeoclimatol. Palaeoecol. 51 (1985) 273–289.

[35] E.V. Artyushkov, M.A. Baer, P.A. Chekhovich, Early Paleozoic geodynamics of the Urals and Pai-Khoi: Evidence for rapid subsidence in the absence of crustal extension, Russ. Geol. Geophys. 12 (2000) 1670–1689.

[36] S. Cloetingh, H. McQueen, K. Lambeck, On a tectonic mechanism for regional sea level variations, Earth Planet. Sci. Lett. 51 (1985) 139–162.

[37] E.V. Artyushkov, M.A. Baer, F.A. Letnikov, V.V. Ruzhich, On the mechanism of graben formation, Tectonophysics 197 (1991) 95–115.

[38] P.M. Burgess, M. Gurnis, L.N. Moresi, Formation of sequences in the cratonic interior of North America by interaction between mantle, eustatic, and stratigraphic processes, Geol. Soc. Am. Bull. 109 (1998) 1515–1535.