Doklady Earth Sciences, Vol. 388, No. 1, 2003, pp. 21–25. Translated from Doklady Akademii Nauk, Vol. 388, No. 4, 2003, pp. 515–520.
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GEOLOGY

The Origin of Water-Depth Changes in Past Epeiric Seas

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Received October 4, 2002

As inferred from numerous available seismostratigraphic and lithological data [1, 2, and others], Phanerozoic epeiric seas experienced frequent and significant water-depth changes. Identification of regularities in these changes and their physical mechanisms is one of the basic geodynamic problems. The third-order cycles with amplitudes of ~20–100 m and a duration of 1–3 Ma are of particular importance for oil and gas prospecting and geological correlation. Major eustatic sea level fluctuations are usually considered the main responsible factor [1 and others], although some researchers admit the influence of tectonic movements. Rapid eustatic fluctuations (≤1–3 Ma) with an amplitude of ~20–100 m can be largely attributed to the formation of large ice sheets and their degradation. In the Phanerozoic, these processes were rare, but the third-order cycles were almost constant. Therefore, the eustatic origin of the third-order cycles is sometimes doubtful [2].

Numerous eustatic third-order fluctuations were previously proposed for the Cambrian–initial Ordovician and Silurian. Recently, it was established, however, that sea level fluctuations did not exceed 10–20 m during the former epoch [3] and significant eustatic sea level changes with a sharp regressive phase and harmonic-type fluctuations did not occur during the Silurian [4]. Rapid water-depth changes recorded in some basins during these time intervals were in fact related to tectonic movements. In this work, we estimate maximal values of Silurian eustatic sea level fluctuations of an arbitrary form and consider the mechanism responsible for changes in the crustal subsidence rate in eastern Siberia. The history of this region was characterized by the existence of extremely shallow (0- to 5-m-deep) sea basins or spacious shoals and semiisolated (0- to 10-m-deep) lagoons located beyond the shoal zone [5]. Based on paleontological and lithological data, the shallow-water sections are commonly divided into successions of elementary (meter-scale) cycles corresponding to ≤1-Ma-long time intervals. During every cycle, the water depth first slightly increased and then gradually decreased as a result of sediment accumulation up to the minimal value at the end of the cycle. In such situations, the third-order cycles are usually discriminated using the Fischer plot [6 and others] based on the following three assumptions: (1) the crustal subsidence rate is constant in every area (Fig. 1, line *OO*'); (2) the elementary cycle duration is constant with time; and (3) the elementary cycle duration is equal in all areas.

The thickness of every elementary cycle is compared with the hypothetical thickness of sediments that would accumulate under crustal subsidence with a constant rate when the newly formed accommodation space is filled. Equal thickness values (Fig. 1a, *AC*) imply that sea level remained stable during the sedimentation cycle. If the sediment thickness *AB* exceeds the tectonic subsidence *AC* (Fig. 1b), this is attributed to sea level rise by the *BC* value during the sedimentation cycle. However, if the thickness *AB* is lower relative to the tectonic subsidence *AC* (Fig. 1c), this is attributed to sea level drop by the *BC* value. This scheme is used for the construction of successions of numerous elementary cycles where point *C* in every cycle adjoins point *O* of the next cycle. It is believed

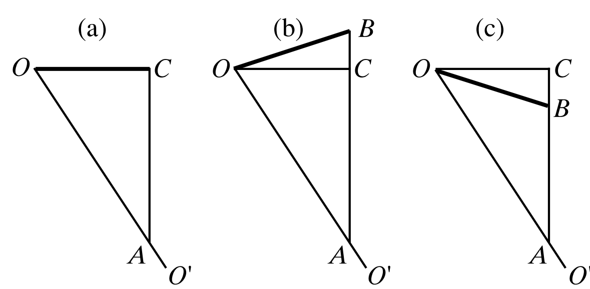

Fig. 1. Fischer plots based on meter-scale elementary cycles in the shallow-water succession deposited in different conditions: (a) absence of sea level changes, (b) sea level rise by the *BC* value during the cycle, (c) sea level drop by the *BC* value during the cycle. Line *OO*' shows crustal subsidence at a constant rate. Crustal subsidence during a cycle is equal to *AC*.

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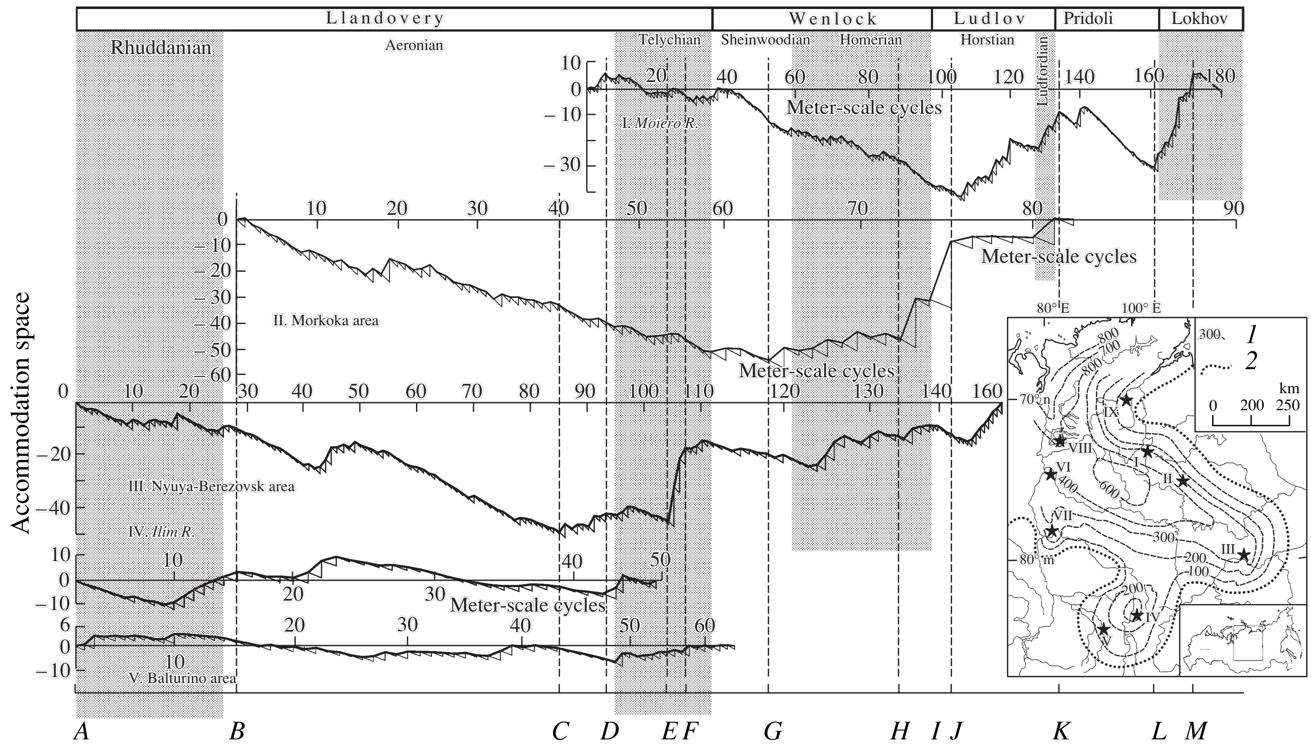

Fig. 2. Fischer plots based on meter-scale elementary cycles in Silurian shallow-water successions [5] of five areas in eastern Siberia. Location of the areas (inset in the right): (I) Moiero River; (II) Morkoka; (III) Nyuya–Berezovsk; (IV) Ilim River; (V) Balturino; (VI) Turukhansk; (VII) Kochumdek River; (VIII) Igarka; (IX) Ledyansk; (*1*) thickness of Silurian sediments, m; (*2*) boundaries of the basin.

that the broken line drawn along upper boundaries of cycles *OC* approximates the slower (≥1- to 10-Ma long) sea level changes.

In Figure 2, Fischer plots are compiled using the data on elementary cycles from five areas of eastern Siberia [5]. In every area, plots correspond to the Silurian time interval with extremely shallow-water sedimentation settings (≤5–10 m). One can see prolonged (~10–15 Ma) sea level drops (~40–50 m) at intervals *AC*, *BA*, and *DJ* in plots III, II, and I, respectively. Shorter (~1–3 Ma) sea level changes with amplitudes of 30–40 m are typical of the third-order cycles (intervals *EF* in plot III, *HI* in plot II, and *JK* and *LM* in plot I). Eustatic fluctuations are practically uniform over the planet. Therefore, provided that Fischer plots really describe such fluctuations, they should be similar for all areas. However, Figure 2 clearly shows that plots significantly differ from each other and the third-order cycles are asynchronous. Significant sea level drops in plots III and II (*AC* and *BA*, respectively) temporally correspond to only slight changes in plots IV and V.

Thus, plots in Fig. 2 compiled in line with the classical scheme do not show eustatic sea level fluctuations. Hence, assumptions (1)–(3) made for eastern Siberia are invalid for the Silurian. Indeed, plot II shows that 59 elementary cycles (0.19 Ma long, on average) took place in the Aeronian and Telychian (total duration 11 Ma), whereas only 22 elementary cycles with a twice longer duration (0.41 Ma) are distinguished in the Wenlock and Ludlow (9 Ma long, in total). This means that the elementary cycle duration varied; i.e., assumption (2) is invalid for these epochs. Plots I, II, and III compiled for the Wenlock include 59, 14, and 29 cycles, respectively. Hence, the elementary cycle duration was substantially different in the studied areas; i.e., assumption (3) is also invalid.

The constant duration of elementary cycles and their synchronism in different areas imply a eustatic nature of small-scale water-depth fluctuations (≤1 m) and the consequent cyclicity [9]. However, this postulate is questioned by some researchers, because sediment redeposition by bottom currents can also be responsible for water-depth changes in marginal areas of basins [10 and others]. The analysis of available data supports this conclusion at least for some Silurian sections of eastern Siberia.

Based on numerous thoroughly described sections of eastern Siberia, the 26-Ma-long Silurian interval [7] has been subdivided into 54 synchronous intervals (chronozones) that correlate with the standard stratigraphic scale [5]. Based on the thickness of shallow-water sediments in each chronozone, Fischer plots were constructed for several areas of this region (Figs. 3, 4). Plots corresponding to areas I–V in Figs. 2 and 4 are sharply different. For instance, plots in Fig. 4 (as well as those in Fig. 3) and lack short (1–3 Ma) third-order cycles that are well seen in Fig. 2. This once again demonstrates that Fischer plots, which are compiled according to the standard procedure based on elementary cycles with indefinite ages, cannot be used to discriminate major eustatic fluctuations. Therefore, many third-order eustatic events, which were identified by other researchers for some Phanerozoic intervals [6 and others], may turn out to be artifacts.

Plots compiled for the Wenlock–Pridoli of the Turukhansk and Kochumdek River areas (Fig. 3) show that deviations of their curves (VI and VII, respectively) from the horizontal axis are insignificant (≤5–7 m). According to standard interpretation [6], this suggests a lack of significant (±5–7 m) eustatic fluctuations. Indeed, let us assume that sea level rises and drops of tens of meters occurred during this epoch. In this case, the plots will not deviate from the horizontal axis only when low and high crustal subsidence rates almost entirely compensate the sea level rises and drops. Planetary sea level changes and regional vertical movements of the crust are independent processes. The probability of their mutual compensation is negligible even for a single area, and the probability of their simultaneous compensation in two areas is practically equal to zero. Moreover, insignificant (below ±10 m) deviations of the Wenlock–Pridoli curve from the horizontal axis are typical of the Ledyanka area (IX), located approximately 1000 km away from areas VI and VII. In Fig. 4, plots I and II (terminal Ludlow–Pridoli) and plot VIII (Ludlow) are practically horizontal. Under such circumstances eustatic fluctuations in the Wenlock–Pridoli (11 Ma) could not exceed ±5–7 m.

The earlier Silurian interval (Llandovery) is marked by an approximately equal decrease (15 m) in plots IV and V compiled for the Ilim and Balturino areas, respectively (Fig. 4). Since plots for other areas are absent, this negative peak could be interpreted as a sea level drop by 15 m. However, plot III shows that sea level drop in the Nyuya–Berezovsk area in this epoch had a similar form but three times greater magnitude (45 m). Since eustatic fluctuations should be globally equal, such a difference in plots suggests a significant contribution of tectonic movements. Deviations of curves from the horizontal axis can be attributed to both eustatic fluctuations and changes in the crustal subsidence rate. These factors are independent and differently vary with time. Therefore, their comparable contribution should displace plots III–V in phase. Hence, the contribution of eustatic fluctuations to deviation from the horizontal axis in all plots can be responsible only for a minor part of the observed total deviation. The total deviation for the Llandovery in plots IV and V amounts to 15 m (Fig. 4). Consequently, eustatic fluctuations, which constitute an insignificant share of this value, did not exceed ±5–7 m in the Llandovery or the entire Silurian.

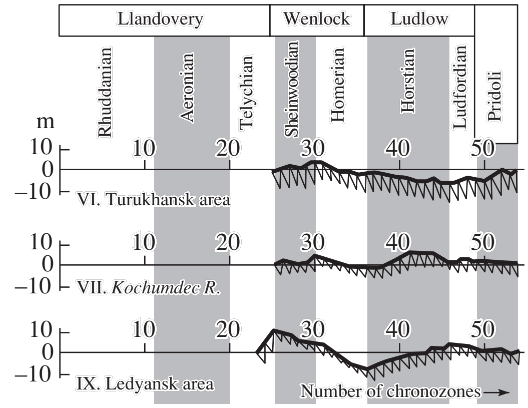

Fig. 3. Fischer plots based on the synchronous interval (chronozone) thickness in shallow-water successions [5] of southwestern and northern areas of eastern Siberia. Location of areas is shown in the inset in Fig. 2.

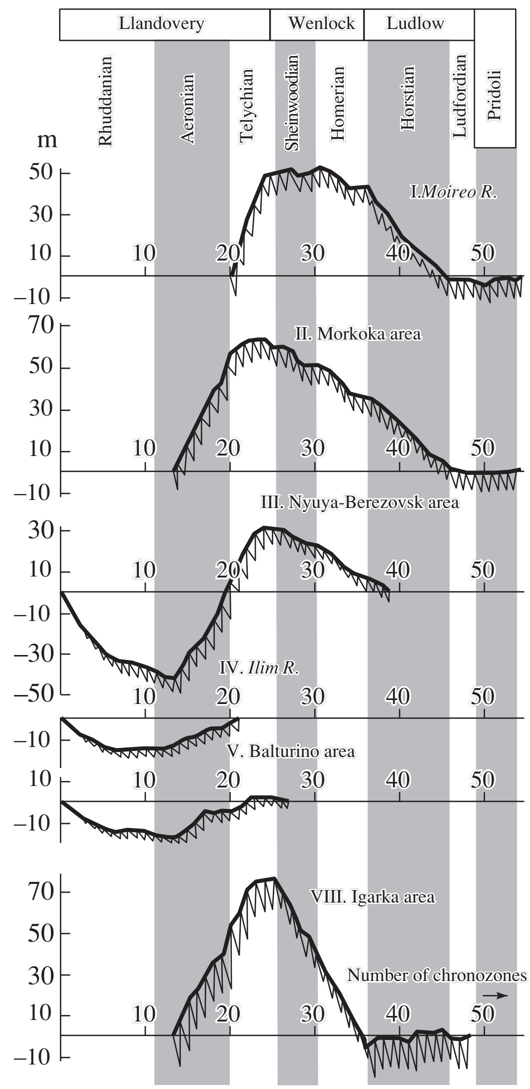

Fig. 4. Fischer plots based on the synchronous intervals (chronozone) thickness in shallow-water successions [5] of central area of eastern Siberia. Location of areas is shown in the inset in Fig. 2.

Plots shown in Figs. 3 and 4 are based on an assumption that time intervals corresponding to chronozones (chrons according to the current stratigraphic nomenclature) are equal in duration. However, one cannot rule out that duration of these units was variable with time as that of elementary cycles. In this case, the chron-based plots are unsuitable for the estimation of maximal eustatic fluctuations. Crustal subsidence depressions were continuously filled with sediments in the studied areas. Under such conditions, change in chron duration by the Δt_{ch} value should produce change in the corresponding chronozone thickness by $\Delta h_{ch} = a\Delta t_{ch}$, where a is the crustal subsidence rate. The Δh_{ch} value is proportional to a, which differed by several times in the studied areas. Therefore, changes in chron duration by Δt_{ch}, which is equal for different areas, should result in different variations in chronozone thickness Δh_{ch}, which is proportional to a. However, the analysis of Fischer plots shows that no significant variations in Δh_{ch} are observed in some section intervals that include several chronozones. Hence, the duration of chrons was approximately constant. This is quite a surprising result that makes it possible to increase accuracy in the dating of Llandoverian events by an order of magnitude.

In contrast to Llandovery plots IV and V (Fig. 4) and Wenlock–Pridoli plots VI, VII, and IX (Fig. 3), where deviations from the horizontal axis are insignificant, plots I–III and VIII (Fig. 4) show higher deviations (30–75 m). Their duration is 10–15 Ma. Since the sea level was almost stable, a significant rises and drops in curves imply substantial increase and decrease in the crustal subsidence rate, respectively. In the studied areas, subsidence rate changes were synchronous at the first approximation, but differed in local values. Silurian sequences of eastern Siberia lack significant hiatuses, suggesting only quasi-synchronous variations in the crustal subsidence rate rather than noticeable uplifts during the Llandoverian epoch, because the sealevel was nearly stable. Let us consider the probable mechanism of these variations.

Crustal subsidence in sedimentary basins is usually attributed to the thermoelastic contraction of crustal and mantle rocks under cooling [11]. The duration of this process is usually equal to ~100 Ma. In the Silurian, the lithosphere beneath eastern Siberia was ~1 Ga old. Therefore, cooling of the lithosphere could not contribute much to its subsidence. Moreover, it could not be responsible for significant changes in the subsidence rate over the time interval of ~10–15 Ma. Forces acting along the lithosphere with a laterally variable thickness produce its vertical displacement [12]. Temporal changes in the forces cause vertical crustal movements, which in turn lead to water-depth changes [13]. The crustal displacement related to this mechanism is inversely proportional to the square of the width (L^2) of the lithospheric inhomogenity thickness [12]. This can provide water-depth changes by ~50–100 m only in narrow areas (no more than several hundreds of kilometers). In the eastern Siberian Basin, ≥1000 km across, this mechanism could only result in insignificant (≤10 m) vertical crustal displacements. The crustal uplift and subsidence can also be caused by changes in the mantle dynamic topography above subsiding lithospheric plates [14] as a result of displacements of subduction zones at the Earth's surface and changes in the subduction rate or dip angle of subducted slabs. In the Silurian, subduction occurred beneath the Siberian Craton from the south (in modern coordinates). The intensity of movements caused by changes in subduction parameters should decrease away from the collisional boundary. However, changes in the Silurian crustal subsidence rate increased rather than decreased to the north, precluding a substantial role of the proposed mechanism.

Silurian sediments (up to 600–800 m thick) compose only a small part of the eastern Siberian sedimentary cover with the total thickness of 10–14 km. In the absence of strong extension, the crustal subsidence pattern described above acquired a significant compaction of rocks in the crust and (or) mantle. The only mechanism which could provide gradual crustal subsidence over ~1 Ga is a slow rock contraction in the lower crust due to the phase transformation of gabbro into garnet granulites [15]. This process was most likely responsible for the Silurian subsidence in eastern Siberia. Its substantial accelerations and decelerations in areas I–III and IX were synchronous with an accuracy of several million years. The phase transformation acceleration and induced increase in the subsidence rate can be related to rock heating due the variation of the astenospheric heat flow. As in other cratonic areas, lithosphere thickness beneath the vast eastern Siberian Basin was probably significantly variable across the region. Therefore, the time of lower crust heating by the astenospheric heat flow is proportional to the square of the lithosphere thickness was also variable across the region. The heating time averages ~100 Ma for ancient cratons with a thick lithosphere. If heating time is highly variable across the basin, synchronous temperature changes in the lower crust with an accuracy of several million years are hardly possible. Phase transformations in the mafic lower crust are also accelerated in the presence of a small amount of water-containing fluid. Within the lithosphere with a laterally variable thickness, it is impossible to provide the quasi-synchronous fluid release in the lower crust due to the heating of rocks by the astenospheric heat flow and the decomposition of hydrous minerals. Therefore, the phase transformation acceleration is more likely caused by an abrupt infiltration of surface-active volatiles from small mantle plumes into the lower crust through the mantle lithosphere [15]. In our opinion, this can explain multiple episodes of crustal subsidence acceleration that were typical of the majority of epicontinental sedimentary basins.

In some cratonic areas, 10*n*- to 100*n*-m-scale water-depth changes were repeated in the Silurian during the periods of one to several million years [8], e.g., in Iowa

(North America), England, Czechia, and Estonia (Europe), southeastern China, and southeastern Australia. Since the sea level was almost constant, such changes in paleodepths indicate rapid crustal uplifts and subsidences in cratonic areas, which are usually considered rather stable regions. Rapid crustal uplifts under conditions of a practically stable sea level also occurred in Lithuania and southern Sweden during the Cambrian [4]. Cambrian sections of the eastern Baltic region and Silurian sections of eastern Siberia were selected for the analysis because of the availability of high-precision stratigraphic data. It is not inconceivable that the sea level remained almost stable and rapid changes in water depth were mainly caused by tectonic movements during the majority of other ice-free Phanerozoic epochs. In this case, we should radically change present-day methods of the prospecting for nonstructural oil and gas traps that are based on the assumption of global synchronism in water-depth changes [1]. Therefore, further investigations should be aimed at the study of regularities and physical mechanisms that were responsible for regional tectonic movements, which resulted in rapid water-depth changes in epeiric sea basins.

ACKNOWLEDGMENTS

We express our sincere gratitude to Yu.I. Tesakov for numerous original data and useful discussions.

This work was supported by the Russian Foundation for Basic Research, project no. 00-05-64095.

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