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SILURIAN DEPOSITION IN EAST SIBERIA AND THE ABSENCE OF LARGE-SCALE EUSTATIC FLUCTUATIONS

E.V. Artyushkov and P.A. Chekhovich*

United Institute of the Physics of the Earth of the RAS,
10 ul. B. Gruzinskaya, Moscow, 123810, Russia
**Institute of the Lithosphere of Marginal and Intracontinental Seas of the RAS,*
22 per. Staromonetnyi, Moscow, 109180, Russia

The concept of time-dependent eustatic fluctuations has been largely recognized, and a number of eustatic events with magnitudes from 20 to 100 m and durations 1 to 3 m. y. (third-order cycles) have been suggested for the Phanerozoic. Eight cycles were distinguished in the Silurian on the basis of sea depth variations in different regions. East Siberia in Silurian time was occupied by a large sea, and its bottom fill has been well documented in many sections. Slow continuous deposition for 10 to 20 m. y. in peritidal environments (≤10 m) recorded in some Silurian sections rules out large-scale eustatic events. The magnitude of the Silurian events could not exceed ~10–20 m, as follows from analysis of eustatic fluctuations and sedimentation rates in the sections. The absence of large-scale eustatic events in the Cambrian and earliest Ordovician inferred in an earlier study in the East Baltic regions, along with the results from the Silurian sections of Siberia, casts doubt on the existence of rapid large-scale eustatic fluctuations over the greatest part of the Phanerozoic. Considerable sea-depth changes that occurred in Cambrian and Silurian deposition basins at a relatively stable water level are rather of tectonic origin. Rapid crustal uplift and subsidence on the background of slow deepening of the basins is a specific type of tectonic movements on platforms.

Silurian, tectonic movements, eustatic fluctuations, epicontinental seas, numerical modeling, East Siberia

INTRODUCTION

Sections of sedimentary basins on continent periphery often show repeated alternation of shallow and deeper-water facies [1–4]. Changes in sea depth are also traceable from numerous episodes of advance and retreat of past shorelines on passive margins well detectable in seismic profiles [5]. Seismic and stratigraphic correlations indicate that sea-level changes occurred simultaneously on geographically dispersed continental margins, which was attributed to eustatic fluctuations [5–7], and numerical eustatic curves were obtained for the Mesozoic and Cenozoic (see the Cenozoic eustasy in Fig. 1).

Regression-transgression cycles with magnitudes from 20 to 100 m and durations 1 to 3 m. y. have received special attention and are called “third-order cycles” or “eustatic events” (Fig. 1). Many eustatic events were distinguished for Paleozoic time as well [2, 8, 9] (see the Silurian eustasy with eight ~30–130 m peaks in Fig. 2).

Geological and seismic studies of past sea depths is now an important objective of stratigraphy and petroleum geology, widely used for geological correlations [14]. Many hydrocarbon deposits in nonstructural traps occur in alluvium accumulated on emerged shelf or in sand deposited in peritidal environments during regressions [15]. The study of rapid sea-level changes is thus of prime interest to hydrocarbon exploration.

Rapid changes in sea depth is a commonly accepted fact but their synchroneity over separated continents is doubted [4, 16, 17] because of insufficient accuracy of biostratigraphic scales for events longer than ~1 m. y.

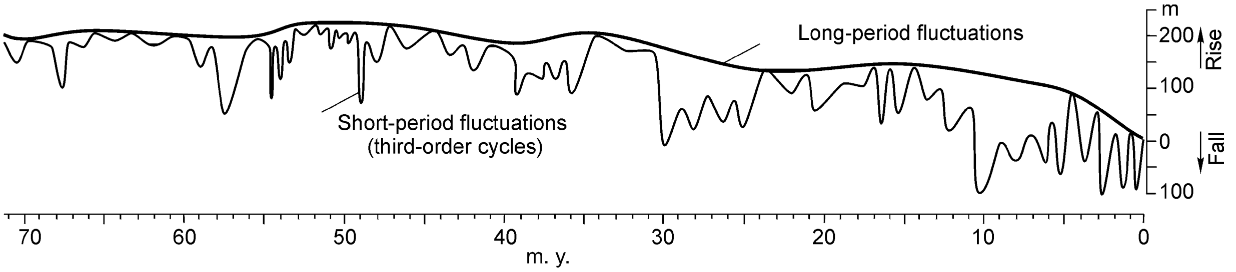


Fig. 1. Hypothetical Cenozoic eustasy (modified after [5]). Long-period (≥10 m. y.) fluctuations of ~50–200 m on eustatic curve are superposed with third-order cycles of magnitudes from 20 to 100 m and durations of 1 to 3 m. y.

Additional tectonic changes of sea depths [18–20] make it impossible to prove the existence of each specific eustatic event [13].

The nature of rapid eustatic fluctuations is another serious problem [21]. The simplest explanation would be that great volumes of water may have moved to the land during glaciations. However, large ice sheets occurred rarely [22], whereas third-order cycles are distinguished throughout the Phanerozoic, including the warm Paleocene and Eocene epochs (Fig. 1). Water-level rise may be caused by an abrupt increase in spreading rate in mid-oceanic ridge systems [23], but this was rarely of global scale and cannot account for worldwide rapid sea rise (~100–300 m/m. y.) typical of many eustatic events. Subsidence of sea floor during cooling of crust and mantle in mid-oceanic ridges taking tens of millions of years is also unable to explain sea-level falls of 20–100 m in ~1 m. y.

MAXIMUM EUSTATIC FLUCTUATIONS IN THE CAMBRIAN-EARLIEST ORDOVICIAN

As stated above, it is difficult to separate eustatic and tectonic causes of rapid sea-level changes, except for major glaciation periods. A different approach is to study regions not subject to rapid eustatic fluctuations and vertical crustal movements, where sea depths changed insignificantly for ≥10 m. y. and deposition occurred at slow rates.

These conditions were found in late Early Cambrian—middle Tremadocian (Early Ordovician) sections in Baltic [24, 25] whose different parts (from Eastern Lithuania to Southern Ladoga) existed in peritidal environments in a water depth from 0 to ~10 m, and the sea floor occasionally emerged to low altitudes above sea level. Sedimentation was very slow (~1 m/m. y. on the average) and could not keep up with significant subsidence. Thus neither rapid sea-level rise nor crustal subsidence above ~10 m can have occurred during that time (for about 45 m. y.).

The territory from northern Estonia to southern Ladoga was an area of sand deposition, and the 20–30 m thick sands have remained unconsolidated. Land vegetation was almost absent. If the loose sands had emerged to ≥10 m above the sea they would have been washed out very soon, but the sections over the greatest part of the territory preserve all main stratigraphic units, often as thin as a few meters. Therefore, rapid sea-level falls or crust uplift, if any, could not exceed 10–20 m.

Data on regressions and transgressions on different continents reveal a number of eustatic events in the Cambrian and earliest Ordovician, including four large events in the Late Cambrian [14, 26, 27]. As the sea level at that time was almost invariable, these fluctuations may have been caused by regional tectonic movements. For example, pelagic deposition in stable conditions in a large basin in latest Cambrian southern Sweden suggests a sea depth of ≥150 m, and the sea floor rose for several tens of meters above the water 1–2 m. y. later. Without the knowledge that eastern Baltic remained at ≤10 m below the sea in the latest Cambrian-earliest Ordovician, the rapid regression in southern Sweden would have been explained by a sea-level fall of ~200 m, as did Erdtman [28] suggesting the Acerocare regressive eustatic event. However, this regression was predominantly of tectonic origin, as the sea level remained almost invariable. Thus, a tectonic event in a sedimentary basin has been isolated to an accuracy of ~10 m.

WATER DEPTHS IN THE PALEOZOIC

In this study possible eustatic fluctuations in the Silurian-earliest Devonian are investigated based on data

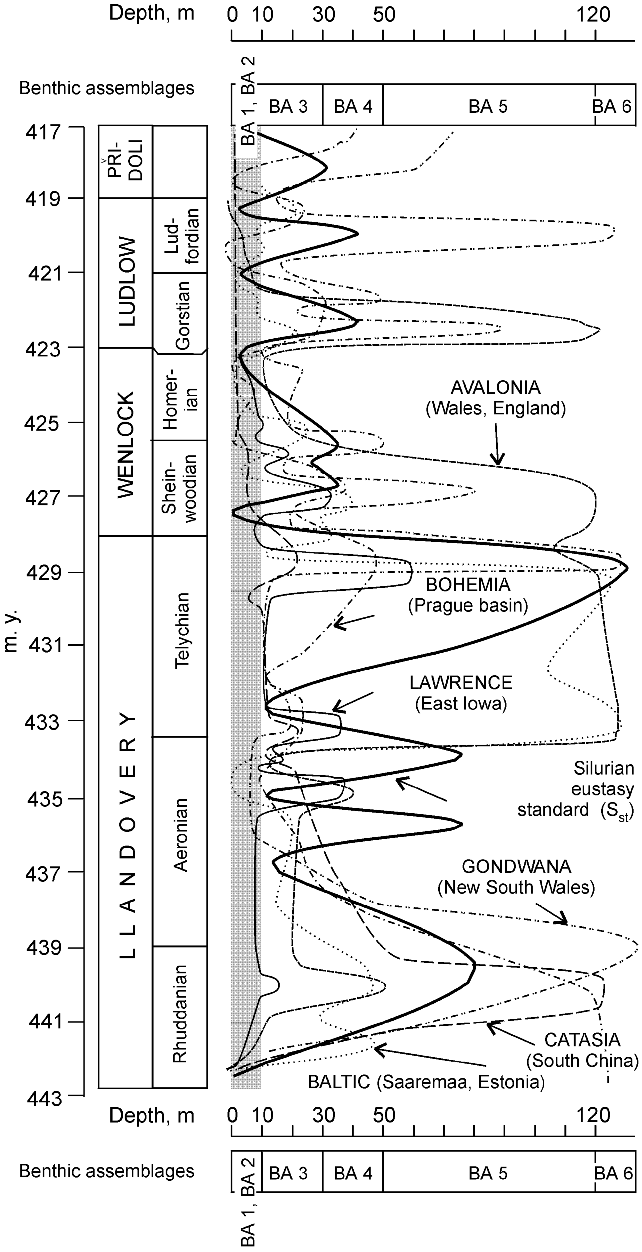


Fig. 2. Silurian eustasy in six epicontinental basins and a standard obtained by averaging regional curves. Curves based on benthic assemblages BA 1—BA 6 (after [9], with regard to corresponding sea depths [10, 11], Fig. 3). Exact timing is now available only for lower and upper Silurian boundaries and for stage boundaries [12]. Division of Llandovery into Rhuddanian, Aeronian, and Telychian substages is less certain. Hereafter duration of these units is given according to [9, 13]. Proceeding from recentmost estimate of Llandovery (15 m. y.), their durations is assumed 1.5 times longer [12]. S_{st} curve includes eight transgression-regression peaks with magnitudes 30-130 m. Sea depth changes in different regions are asynchronous and irregular and are thus more likely due to regional-scale crustal uplift than to eustasy.

from East Siberia [29–35]. Sea depth dynamics is reconstructed from paleontology and sedimentology [10, 24, 25, 36, 37] rather than seismic stratigraphy, as the periphery of many Paleozoic sedimentary basins experienced erosion. The sea depths are estimated from diagnostic benthic assemblages and from the type and structure of sediments.

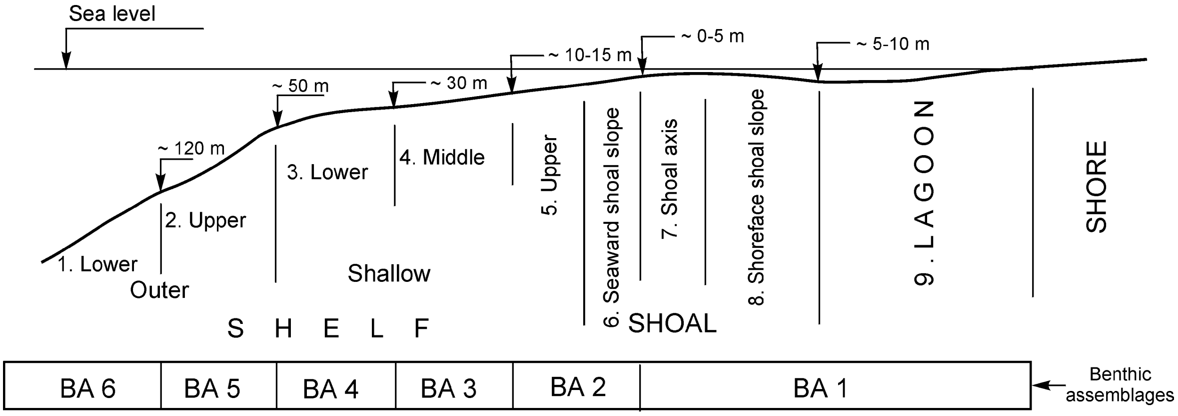


Fig. 3. BA 1—BA 6 [10], correlated to zones 1–9 distinguished from seafloor biota and deposition environments [29, 32–35, 38, 39].

The basin margins are most often divided into six zones (Fig. 3, BA 1–BA 6) [10]. BA 1 corresponds to the peritidal zone (axial and landward parts of shoal together with restricted lagoon), where the sea depth varies from 0 on the shore to ~10 m in the lagoon, and is 0–5 m on the shoal. The zone is distinguishable from typical shallow-water biota and specific sedimentary structures produced by tidal currents.

BA 2 includes outer shoal and upper shallow shelf above the normal (fairweather) wave base, with depths from 10 to 15 m in epicontinental seas, far from oceans, where tides are very low.

BA 3 and BA 4 correspond to middle and lower shallow shelf above seasonal storms (40–60 m, ~50 m in the average). This depth approaches the lower limit of the photic zone where enough light penetrates to maintain intense growth of algae. The BA 3–BA 4 biotas are different but both are more diverse and include attached-shell animals (larger than in BA 2) and abundant hermatypic corals in tropics; sediments bear numerous effects of seasonal storms. The BA 3/BA 4 boundary is hereafter assumed at 30 m.

BA 5 occupies upper outer shelf where algae and the greatest part of reef builders disappear. The sea floor in BA 5 was inhabited by trilobites, small freely lying brachiopods, worms, rare solitary corals, and sponges. These depths are inaccessible for normal seasonal storms but may be subject to millenial storms. BA 6 communities occur in lower outer shelf below 150–180 m in modern seas, below the wave base of millenial storms, which is most often an area of stable deposition of finely laminated clays and silts. BA 6 involves no shelly organisms, and bottom-dwellers are mostly burying animals. The BA 5/BA 6 boundary is hereafter assumed at 120 m [11], taking into account that Silurian wave activity may have been weaker than it is now [10].

A more detailed facies division of the bathymetric profile is used for shallow-water carbonate platforms [38]. It includes nine zones and was used in a modified form for the Silurian of East Siberia and Podolia (Fig. 3) [26–32, 39, 40]. Zones 1–4 of this scale correspond to BA 6–3. Zone 5 is the lower part of BA 2, upper shelf from the normal wave base (10–15 m) to the lowermost seaward slope of shoal (5 to 10 m, as a function of its height). The seaward slope of shoal corresponds to zone 6 or to upper BA 2 (5–10 m), and its axis belongs to zone 7 (0–5 m). The shoreface slope of shoal with depths from ~5 to ~10 m corresponds to zone 8, and the lagoon at its back corresponds to zone 9 (0–10 m). Zones 7–9 together are correlated to BA 1.

ACCURACY OF ESTIMATES OF SEA DEPTH CHANGES IN DIFFERENT ZONES

The depth of wave base provides rather rigorous constraints on some boundaries of zones 1–9, namely 120–180 m for the lower boundary of zone 2 (wave base of millenial storms), ~50 m for the zones 2/3 boundary (wave base of seasonal storms), and 10–15 m for the zones 4/5 boundary (fairweather wave base). Sea depths between these boundaries are, however, more difficult to estimate. In the Silurian, the depth of zone 2 was from ~50 to ~120 m (~70 m), and a sea-level change about this order of magnitude can be easily missed. The depth range in zones 3–4 (lower and middle shallow shelf) was ~35–40 m. The sea depths in these zones may be estimated to an error as great as the total range of ~35–40 m, as the same benthic assemblages can live at different depths depending on temperature, turbidity, and salinity of water, the type of substrate, food availability, and hydrodynamic activity [36, 41].

Unlike zones 2–4, zone 5 (~10 m) and zones 6–9 (~10 m) correspond to very small depth ranges. Precise estimates can be obtained for extremely shallow water (zones 6–9), as the sea floor emerges at a sea-level fall or crustal uplift about 10 m, and a ≥ 10 m higher stand or crustal subsidence moves the floor from zones 6–9 to zone 5 or deeper. The subtlest eustatic fluctuations and vertical crust movements are detectable in zone 7, the shoal axis (0–5 m).

Herebelow we mostly use data on deposition in zones 6–9. Only few species, which have adapted to the conditions of repeatedly emergent sea floor and ephemeral isolated basins arising at low tides, can survive in peritidal environments (shoal axis and shoreface part of restricted lagoon). Tidal currents in zone 7 produce bimodal and multidirectional cm-scale cross bedding in sands deposited in environments of siliciclastic sedimentation. The conditions of carbonate deposition in zones 7–9 are favorable for stromatolites, inarticulate brachiopods, and some ostracod species, as well as for the formation of voluminous dolomites and gypsum-bearing sediments formed at intense evaporation. These features differ the sediments of zones 7–9 from more distal offshore facies.

SILURIAN—EARLY DEVONIAN EVOLUTION OF THE EAST SIBERIAN SEA

The Silurian deposition basin in East Siberia occupies an area of about 2,000,000 km^2 (Fig. 4) and is the second largest after North America. Silurian deposits are exposed in river valleys over large territories of East Siberia and are penetrated by numerous boreholes. Their facies analysis and biostratigraphy provided detailed continuous Silurian-lowermost Devonian sections from many regions [29–35]. The Silurian biostratigraphy and lithology in the Siberian sections are more reliable than in other sections worldwide which are often composite.

The Silurian section of the Siberian Platform is divided into 54 regional stratigraphic units (cycles or chronozones) corresponding to biochrons. The basin always had good connection with ocean in the northwest (in the present frame of reference). The chronozones have been correlated to the standard international scale [34]. The time-dependent dynamics of sea depths can be observed due to their assignment to zones 1–9 within each chronozone, obtained for some sections from paleontological and lithological data [30, 31, 33]. The mean duration of Silurian chronozones (Δt_{cz}) is in the range of 0.3–1.1 m. y. (Table 1) and is shorter than or comparable to

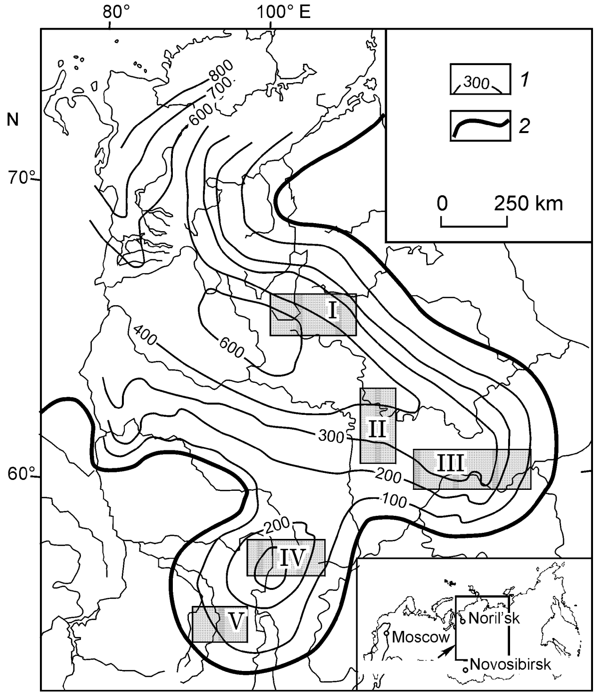


Fig. 4. East Siberian deposition basin (after [30]). ***1*** **— isopachs of Silurian deposits, m;** ***2*** **— limits of Silurian deposition basin. Roman numerals denote study regions: I — Moiero, II — Morkoka, III — Nyuya-Berezov, IV — Ilim, V — Baltura. Inset shows study area.**

Table 1

Duration of Main Silurian Stratigraphic Units

Standard scale unit	Duration, m. y. (after [12] taking into account [13])	Number of chronozones (after [34])	Mean duration of chronozones, m. y.
Rhuddanian	4	11	0.36
Aeronian	5.5	9	0.61
Telychian	5.5	5	1.1
Wenlockian	5	11	0.45
Ludlovian	4	13	0.31
Pridolian	2	5	0.4

third-order cycles (T = 1–3 m. y.), which provides reliable discrimination of the corresponding variations of paleodepths.

In the Ordovician, East Siberia was covered by a shallow sea. Marine deposition at the Ordovician/Silurian boundary was broken by a subaerial gap in the northern and central parts, followed by rapid flooding to ≥120 m (zone 1) in 1–2 m. y. [30, 32]. These conditions occurred, for instance, in the catchment of the Moiero River (Fig. 4). The basin periphery (Ilim and Baltura regions in the south and Nyuya-Berezov region in the southeast) was an area of continuous marine deposition. Ordovician sea depths cannot be reliably estimated for the lack of fauna, and since the earliest Silurian the sea floor was in zones 7–9 (≤10 m).

The original basin was shoaling with deposition. In the middle Early Silurian (Fig. 5), it was as shallow as ~10 m (occasionally to 15–20 m) on the periphery in the Ilim, Baltura, and Nyuya-Berezov regions, and gradually deepened northeastward to ≥120 m. The basin may have been bounded by shallow-water zones in the southwest and northeast as well, but no Silurian deposits are preserved there.

In the earliest Wenlockian (Fig. 6), the basin was as shallow as ≤10 m over its greatest part, and 20–30 m depths were restricted to a narrow strip in the center. The basin was fringed by a broad shoal bar (0–5 m), with an up to ~5 m deep lagoon southeast of it; similar lagoons must have existed in the southwest and northeast but their deposits were later washed out. The sea deepened northwestward to several tens of meters. In the latest Silurian (Pridolian), a half-restricted shelf (~10 m) persisted in the central part (Fig. 7). Peritidal deposition continued for 1–2 m. y. in the earliest Devonian and was followed by a regression.

TIME-DEPENDENT SEA DEPTH CHANGES IN SOME REGIONS OF EAST SIBERIA

Southeastern and southern periphery of the basin. The peritidal environment, possibly with brief excursions of flooding to 10–15 m, persisted for about 22 m. y. (from the earliest Silurian to earliest Devonian) in the southeastern periphery of the basin (Nyuya-Berezov region) [29, 30, 34] (Fig. 4), and at least till the earliest Wenlockian (17 m. y. since the onset of the Silurian) in the south of the basin (Baltura region), but the Baltura section misses two lowermost Silurian chronozones (about 0.7 m. y.). The Ilim section preserves peritidal facies that accumulated for 12 m. y. from the earliest Silurian to the Early Telychian. The duration of deposition in these regions may have been longer but the uppermost section may have been eroded. The sediments are predominantly siltstones, dolomites, red-color rocks, abundant stromatolites, and gypsum-bearing rocks at some depths. The sea floor was at zones 8 and 9, on the shoreface shoal slope and in restricted lagoon [29, 30]. As there is no exact indication of depth zones for each chronozone in [29, 30], the bathymetric curve is shown in rectilinear intercepts: in zone 9 in Fig. 8, *a* and at 10 m, roughly corresponding to the maximum depth of this zone, in Fig. 8, *b*.

Moiero region. Silurian deposits in this region are exposed for about 90 km in 50–80 m high bluffs along the middle course of the Moiero River [30–32, 35]. The type section contains a continuous sequence of almost unaltered Silurian and lowermost Devonian sediments. The section is divided into ~200 stratigraphic units [32] providing a detailed sea depth assignment to zones 1–9 (Fig. 8, *a*). The Llandoverian deposition was preceded by subaerial water erosion. Then, the sea floor submerged to lower outer shelf (≥120 m, zone 1) in the earliest Rhuddanian, for ~1 m. y. (Fig. 8, *a*, *b*). The ensuing deposition was accompanied by basin shoaling. About 1 m. y. later the sea floor moved to upper outer shelf (zone 2), and by the late Rhuddanian, in 3 m. y., it had occurred in zone 3, in lower shallow shelf, in water depths ≤50 m.

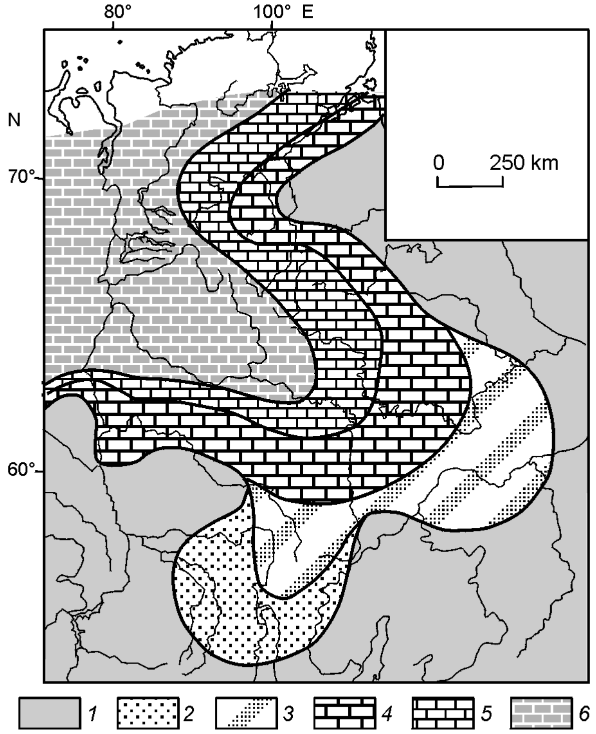


Fig. 5. East Siberian deposition basin in Middle Llandoverian (after [30]). ***1*** **— land;** ***2*** **— peritidal zone with water depth from 5 to 10 m;** ***3*** **— water depths to 15–20 m;** ***4*** **— middle and upper shallow shelf;** ***5*** **— lower shallow shelf;** ***6*** **— outer shelf.**

For ~5 m. y. from the latest Rhuddanian, the sea floor was in the middle of shallow shelf (zone 4, 10–15 to ~30 m), with brief episodes of flooding to zone 3 (lower shallow shelf). In the latest Aeronian, the sea floor moved to zone 5 with depths of 10–15 m for a short time, and the environment at the Aeronian/Telychian boundary corresponded to zone 9 (restricted lagoon). Till the Ludlovian, the sea floor was in zones 7–9, in the shoal axis, on its shoreface slope, and in the lagoon, at depths within 0–10 m. From the latest Ludlovian to regression in the early Lochkovian (Early Devonian), for 3–4 m. y., the sea floor was in the repeatedly emerged peritidal zone.

Morkoka region. The bathymetric curve (Fig. 8, *a*) is based on a continuous section including 117 stratigraphic units [33]. The region occurred closer to the basin margin than the Moiero region (Fig. 4) and had shallower water depths, corresponding to upper outer shelf (50–120 m, zone 2), after a nondeposition gap at the Ordovician/Silurian boundary. In the middle Rhuddanian, the sea floor moved for ~3 m. y. to middle shallow shelf (zone 4, 15 to ~30 m). Then it occurred mostly in zones 5 and 6 (5 to 15 m) from the late Aeronian to the latest Silurian, and in peritidal conditions (zones 6–9, 0–10 m) for ~4 m. y. from the latest Rhuddanian to late Aeronian, with only a single brief episode of flooding to zone 5 (10–15 m) in the middle Telychian. Unlike the Moiero region, zones 6 and 7 (seaward slope and axis of shoal) cannot be separated from the faunal evidence, and are considered jointly as zone 6.

THE ABSENCE OF LARGE-SCALE EUSTATIC FLUCTUATIONS

The Silurian—earliest Devonian East Siberian sea had always included large regions where deposition continued for ~10–20 m. y. in peritidal environments at sea depths 0–10 m (Fig. 8). Peritidal conditions existed in the Baltura, Ilim, and Nyuya-Berezov regions since the beginning of the Silurian, in the Moiero and Morkoka regions since the latest Aeronian, and spread over the greatest part of the basin since the earliest Wenlockian.

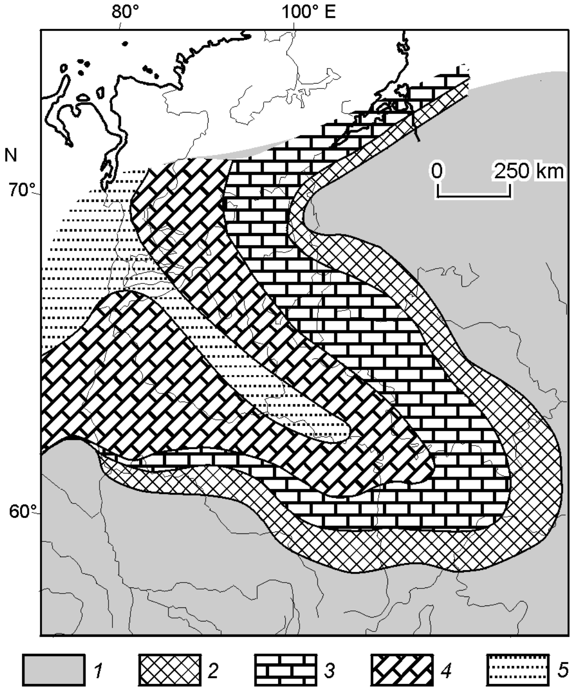


Fig. 6. East Siberian deposition basin in Middle Silurian-Early Wenlockian (after [30]). ***1*** **— land;** ***2*** **— peritidal zone with water depth to ~10 m, locally to 20 m;** ***3*** **— peritidal zone with water depth from 0 to 5 m;** ***4*** **— seaward slope of shoal and upper shallow shelf with water depths ~5–15 m;** ***5*** **— middle shallow shelf with water depths ~15–30 m.**

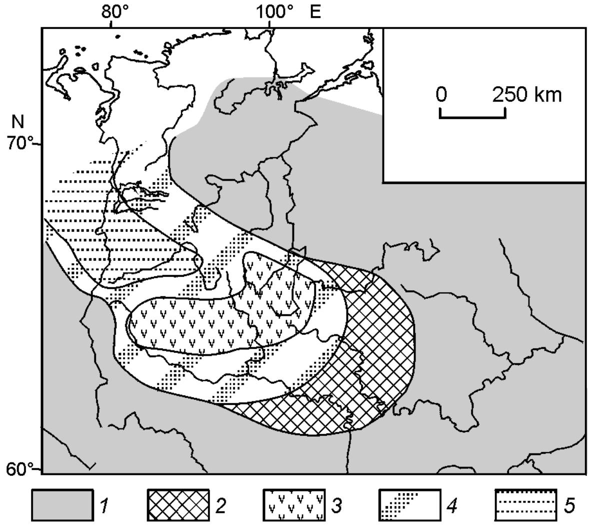


Fig. 7. East Siberian deposition basin in latest Silurian (Pridolian, after [30]). ***1*** **— land;** ***2*** **— shallow lagoon with water depth 0 to 5 m;** ***3*** **— half-restricted lagoon with depths to ~10 m;** ***4*** **— peritidal zone around half-restricted lagoon, water depths 0–5 m;** ***5*** **— seaward slope of shoal, water depths to ~10 m.**

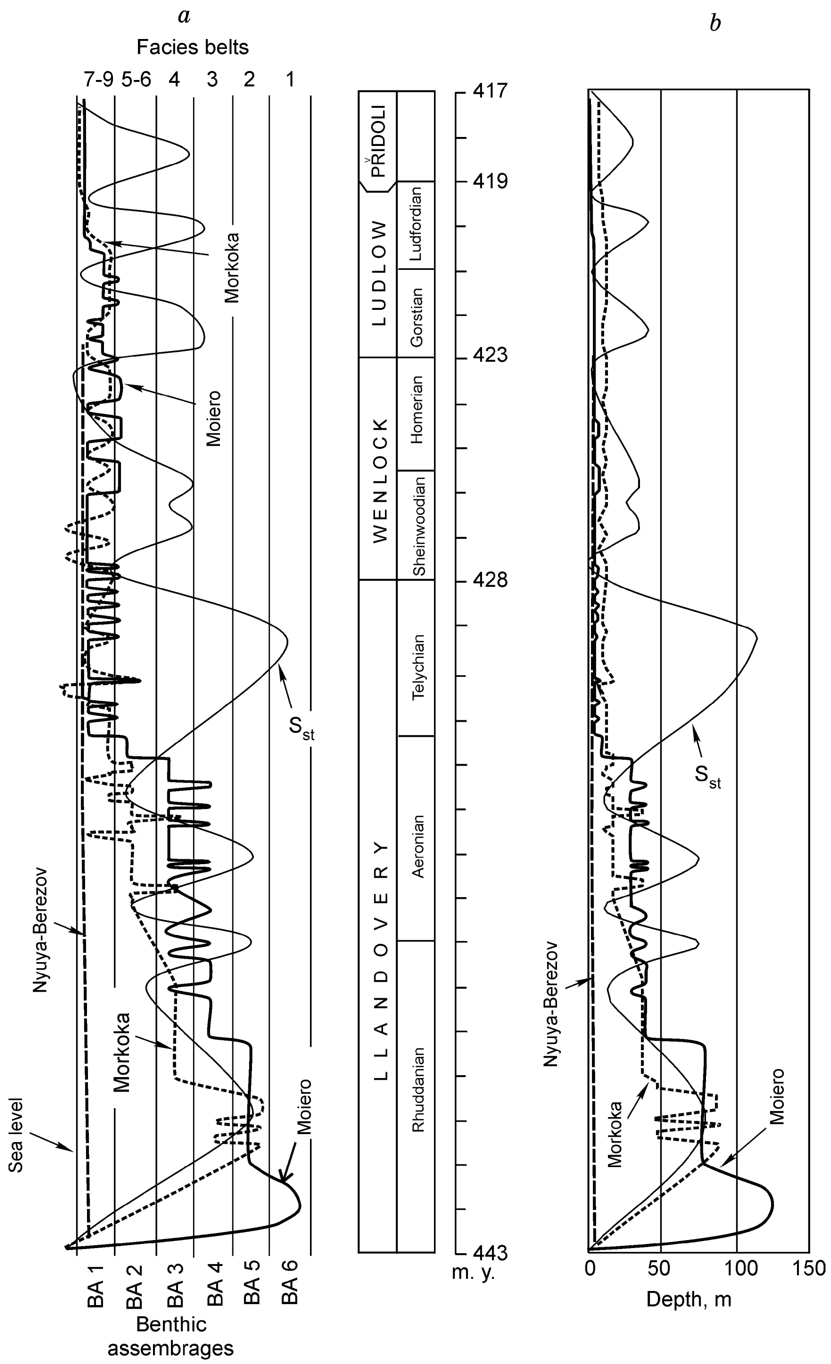


Fig. 8. Time-dependent sea depths in different regions of East Siberia in Silurian time. *a* — scale of zones 1–9 (after [29, 30, 32, 33]), *b* — scale of absolute depths (after [10, 11]). Existence of areas of continuous peritidal (≤10 m) deposition for ≥ 10 m. y. throughout Silurian is evidence for absence of 1–3 m. y. eustatic cycles with ~20–100 m sea-level changes.

Peritidal deposition occurred simultaneously in the Nyuya-Berezov, Moiero, and Morkoka regions for ~12 m. y., from the earliest Telychian to the early Ludlovian (Fig. 9).

The time of peritidal deposition is shown by solid line in the curves in Fig. 9. The sedimentation rates did not exceed ~20 m/m. y., which rules out 1–3 m. y. eustatic fluctuations [42]. A ≥10 m sea-level rise would bring the sea floor from zones 6–9 to zone 5 or deeper, which can be easily recognized from benthic assemblages and

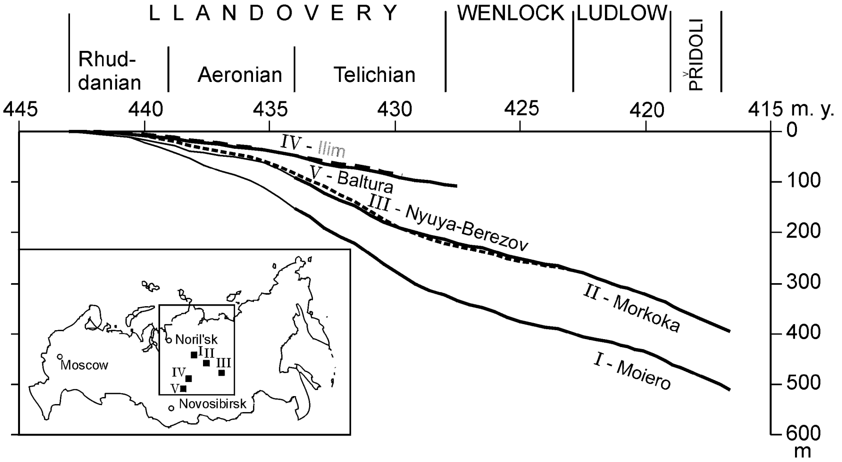


Fig. 9. Silurian deposition in different regions of East Siberia (after [34]). Solid line shows time when sea floor was in zones 6 to 9 at depths ≤10 m. Inset shows location of regions marked by Roman numerals.

sedimentology. A ≥20 m water-level fall would place the sea floor in subaerial conditions, exposed to erosion. However, no signature of these episodes is found in the Silurian-Lower Devonian sections, i.e., 1–3 m. y. eustatic cycles never exceeded ±20 m. More exactly the largest eustatic events in Silurian-early Devonian time can be estimated with regard to absolute rates of crustal subsidence.

RATES OF CRUSTAL SUBSIDENCE IN PERITIDAL ENVIRONMENTS

Deposition in zones 6–9 occurred at different rates in various regions and changed with time (Fig. 9). For sea depths to remain shallow, the crustal subsidence should be more or less balanced by sedimentation. Therefore, the solid parts of the curves in Fig. 9 can be used to estimate the rate of subsidence in different regions of east Siberia, neglecting weak eustatic fluctuations to a first approximation. The curves are based on the present-day sediment thicknesses [34]. Silurian deposits, now exposed, originally had a greater thickness, as they consolidated under the load of overlying younger deposits which were then eroded. Consolidation being proportional to load, it can be neglected in the Ilim, Baltura, and Nyuya-Berezov regions in which the sands above Silurian sediments were as thin as a few hundred meters.

Silurian peritidal carbonates in the Moiero and Morkoka regions were later covered by thicker sediments and lava flows. Carbonate silt is most often strongly consolidated in the upper several meters of sections and further consolidation is slower because of decreased porosity (to ~30–35%). Weakly consolidated Silurian carbonates in East Siberia have a porosity of 16% [33], i.e., ~15–20% lower than the original porosity of carbonates. The Moiero and Morkoka carbonates are located outside this area and must be less consolidated. For the lack of exact estimates, hereafter a consolidation of 10% is assumed. The subsidence rates are, correspondingly, 11% higher than those associated with the curves in Fig. 9. Mean sedimentation rates in peritidal environments, roughly equal to the rates of crustal subsidence at different stages of the Silurian (Table 2), vary from ≈5 m/m. y. in the Baltura region in Telychian time to ≈25 m/m. y. in the Moiero region in the Pridolian.

MAIN INDICATORS OF SUBAERIAL GAPS

The presence of numerous diastemes, surfaces of weak subaerial erosion, indicates that the floor of the East Siberian sea repeatedly emerged above sea level. However, the studied Silurian sections include the complete series of chronozones, without significant hiata, which places constraints on the maximum possible magnitude of eustatic fluctuations.

A considerable rise of the sea floor above water level produces well-defined erosional landforms of rugged topography with deeply incised river valleys. Mostly siliciclastic deposition occurred in the Nyuya-Berezov, Ilim, and Baltura regions in Rhuddanian and Aeronian time, and continued in the Telychian in the Baltura region. In the absence of land vegetation, the Silurian sands and siltstones would be rapidly eroded already at a small altitude

Table 2

Mean Rates of Crustal Subsidence (m/m.y.) in Peritidal Environments in Different Regions of East Siberia (after [34])

Standard stratigraphic unit	Moiero*	Morkoka*	Nyuya-Berezov	Ilim	Baltura
Rhuddanian			11.2	6.8	8.4**
Aeronian			20.6	8.3	8.6
Telychian	17	9	11.4		**4.9**
Wenlockian	18.3	15.1	**11.9**		
Ludlovian	**17.2***	20.4			
Pridolian	25.2	**22.9**			

Note. Least mean subsidence rates are in bold.
***Taking into account possible 10% consolidation of sediments.**
****For time corresponding to nine chronozones.**

($z_0 \cong 10$ m), but the sections bear no signature of erosion, and the sea floor thus never rose higher than ~10 m above sea level.

The chronozones in many Silurian sections (h_{cz}) are very thin in some intervals (e.g., 0.2 to 6.2 m for Rhuddanian and Aeronian time in the Ilim region) and differ in thickness for only one or two meters. The preservation of all chronozones and their smooth thickness variations indicate that early Silurian regressions, if any, were accompanied by erosion of just a few meters of sediments, and the sea floor never rose higher than ~10 m above sea level.

Since the Telychian, peritidal carbonate deposition started in the Nyuya-Berezov, Moiero, and Morkoka regions and lasted as long as the latest Silurian in the two latter regions. Sheet erosion can be very slow at small altitudes. Karst and microkarst features develop rapidly if altitudes are above the highest tide [43] and would have been broadly distributed at altitudes $z_0 \geq 3$ m in these continental regions where the tide was relatively low. The absence of karst indicates that the sea floor in the Moiero and Morkoka regions never rose higher than ~3 m above sea level from Telychian to Pridolian time.

Features of subaerial exposure reveal even very short regressions. Long subaerial gaps are recorded as missing parts of sections over large areas. Deposits of a chronozone are always preserved if they are at least partially synchronous to the gap (Fig. 10, *a*). A section misses one chronozone to a 100 % probability if the corresponding interval of a duration Δt_{cz} does not exceed a half of the subaerial gap Δt_{sa}:

$$\Delta t_{cz} \leq \Delta t_{sa}/2 \tag{1}$$

The completeness of the Silurian chronozone sequence in East Siberia means that the duration of subaerial gaps, if any, never exceeded two biochrons. Another, less rigorous, condition indicating that a section may miss a chronozone is that the duration of the corresponding biochron is at least longer than the half gap

$$\Delta t_{sa} \geq \Delta t_{cz} \leq \Delta t_{sa}/2 \tag{1a}$$

Then the probability that a section misses a chronozone (Fig. 10, *b*) is

$$\nu = (\Delta t_{sa} - \Delta t_{cz})/\Delta t_{cz}. \tag{2}$$

For instance, at $\Delta t_{cz} = (2/3)\Delta t_{sa}$, $\nu = 50\%$, and at $\Delta t_{cz} = (3/4)\Delta t_{sa}$, $\nu = 33\%$. A considerable overlap of the subaerial gap and the biochron notably reduces the chronozone thickness: to a half or more at $\Delta t_{sa} = \Delta t_{cz}$ and constant sedimentation rate (Fig. 10, *c*). This apparently never occurred, judging by smooth chronozone thickness variations. Therefore, the duration of subaerial gaps did not exceed a time span corresponding to one chronozone, to a high probability:

$$\Delta t_{sa} \leq \Delta t_{cz}. \tag{1b}$$

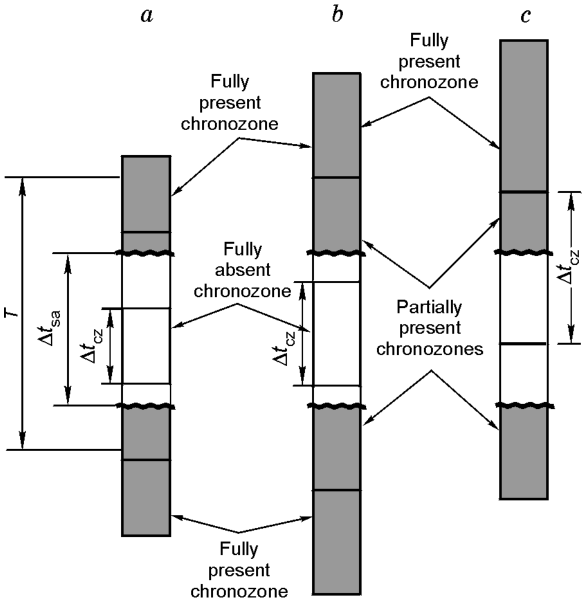


Fig. 10. Subaerial gap of duration Δt_{sa} and time intervals corresponding to individual chronozones. *a* — at $\Delta t_{sa} \geq 2\Delta t_{cz}$, when section misses one chronozone to 100% probability, *b* — at $\Delta t_{sa} \geq \Delta t_{cz} \geq \Delta t_{sa}/2$, when section misses one chronozone to probability defined by equation (2), *c* — at $\Delta t_{sa} = \Delta t_{cz}$, when at constant sedimentation rate a chronozone is twice or more thinner.

The validity of the latter condition is supported by the fact that the correlation of Silurian sections in East Siberia is based on smaller-scale stratigraphic units, twice as numerous as chronozones [32, 33, 35]. The greatest possible rapid eustatic fluctuations can be estimated using both criteria (absence of notable erosion and section completeness), with predetermined initial sea depth and behavior of fluctuations.

EUSTATIC EVENTS WITH RAPID REGRESSION

Eustatic events (Fig. 1) include a regression and a transgression. It is commonly assumed that regression is rapid and brief and the following transgression is slow [5]. The simplest approximation of this behavior is an instantaneous sea-level fall of magnitude b followed by continuous rise to the original level for the time T (Fig. 11, *a*). Let the initial sea depth be h_0. If erosion becomes notable at an altitude z above sea level (Fig. 11, *b*), a eustatic event is detectable when its magnitude b exceeds or equals the minimum value ($b \geq b_m$), where

$$b_m = h_0 + z_0. \tag{3}$$

As noted above, erosion of siliciclastic deposits in the Early Silurian would manifest itself at an altitude z_0 ~10 m. The sections in the south and southeast of the territory were apparently deposited in a peritidal environment at depths h_0 ~0–5 m, or locally to ~10 m. Assume that z_0 = 10 m, h_0 = 5–10 m. Then from (3) it follows that the least fluctuations of the type of Fig. 11, *a* in the early Silurian, detectable from signature of erosion (condition 1) is

$$b_m = 15\text{–}20 \text{ m}. \tag{4}$$

From the Telychian to the latest Silurian, peritidal carbonate deposition occurred at sea depths 0–5 m, and erosional landforms would then develop at altitudes $z \geq z_0 = 3$ m. Assuming in (3) that h_0 = 5 m, z_0 = 3 m, we obtain that erosion becomes notable at $b \geq b_m$, where

$$b_m = 8 \text{ m}. \tag{5}$$

Now we estimate the maximum magnitude b_m using the condition of section completeness. The corresponding

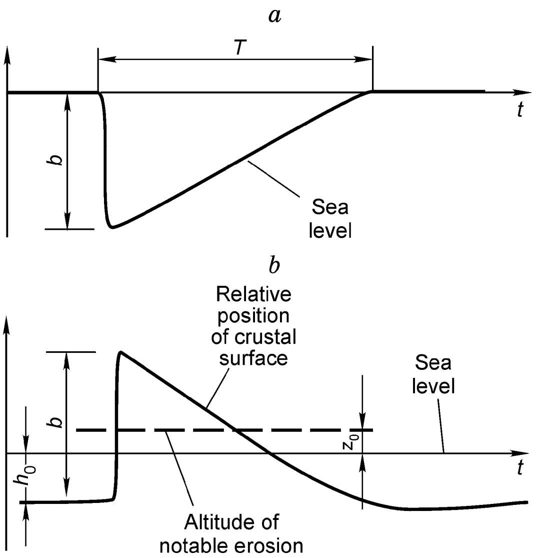


Fig. 11. Eustatic event. *a* — with abrupt sea-level fall for magnitude *b* and subsequent rise for time *T*, *b* — corresponding time-dependent variations in relative position of crustal surface. As a result of tectonic subsidence during subaerial gap, height of crustal surface above sea level decreases faster than sea-level rises. h_0 is initial water depth, z_0 is height of crustal surface above sea level at which subaerial erosion becomes visible.

derivation is given in Appendix I, and the values b_m as a function of the duration T are shown in Fig. 12, *a*, *b* and in Tables 3 and 4. The value b_m decreases with T and increases with the duration of Δt_{cz} corresponding to individual chronozones, dissimilar for different stratigraphic units of the Silurian. The duration of subaerial gaps decreases at higher rates of tectonic subsidence. Therefore, for each unit of the standard Silurian scale, the least b_m are obtained for the regions with the slowest subsidence. The b_m values are especially small at the condition (1b) (Table 3). At h_0 = 5 m, they are 8–24 m for Rhuddanian, Wenlockian, Ludlovian, and Pridolian time. At h_0 = 10 m, b_m is 14–19 m for the Rhuddanian; for the Aeronian it is 13–26 m at h_0 = 5 m, T = 1–3 m. y., and from 19 to 30 m at h_0 = 10 m, T = 1.2–3 m. y. Given (1), b_m is higher. At h_0 = 5 m, b_m varies from 13–22 to 30 m in the Rhuddanian, Wenlockian, and Ludlovian over the main portion of the interval T = 1–3 m. y. typical of third-order cycles.

According to (4) and (5), in the absence of notable erosion (condition 1), the greatest possible fluctuation b_m is 15–20 m for Rhuddanian and Aeronian and 8 m for Telychian-Pridolian time. Table 3 shows that one may occasionally arrive at lower b_m using the conditions of section completeness and smooth variations in chronozone thickness. For instance, for the Rhuddanian it is 8–12 m at h_0 = 5 m and 14–19 m at h_0 = 10 m. Most b_m values found using condition (1b) are higher than those corresponding to erosion-free conditions. However, section completeness is a more reliable criterion than absence of erosion, as the altitude at which sediments of different types become eroded can be estimated in a very tentative way, whereas the fact that a section misses sediments of a certain age or their thickness is reduced is easily detectable in the presence of diagnostic fauna. Note that the section completeness indicates the absence of both considerable subaerial gaps and subaqueous erosion.

EUSTATIC EVENTS WITH SLOW REGRESSION

Assume that a eustatic event with a magnitude b and duration T behaves in a harmonic way (Fig. 13), with slow rise and fall of sea level. In the Rhuddanian and Aeronian, siliciclastic deposition in the south and southeast of the territory was slow, most likely controlled by the rate of erosion of the vast adjacent land. Under these conditions, the rate of sedimentation is roughly equal to the rate of tectonic subsidence, and the influence of small sea-level changes is insignificant. As in the case of rapid regression (Fig. 11, *a*), the duration of subaerial gaps decreases with subsidence rate. The b_m values at which the gaps are detectable from a missing chronozone or its reduced thickness (conditions (1) and (1b)), are calculated in Appendix II and shown in Fig. 14, *a*. It is seen from the figure and from Table 3 that at the condition (1b) and h_0 = 5 m, b_m is 8–9 m for the Rhuddanian and 10–22 m

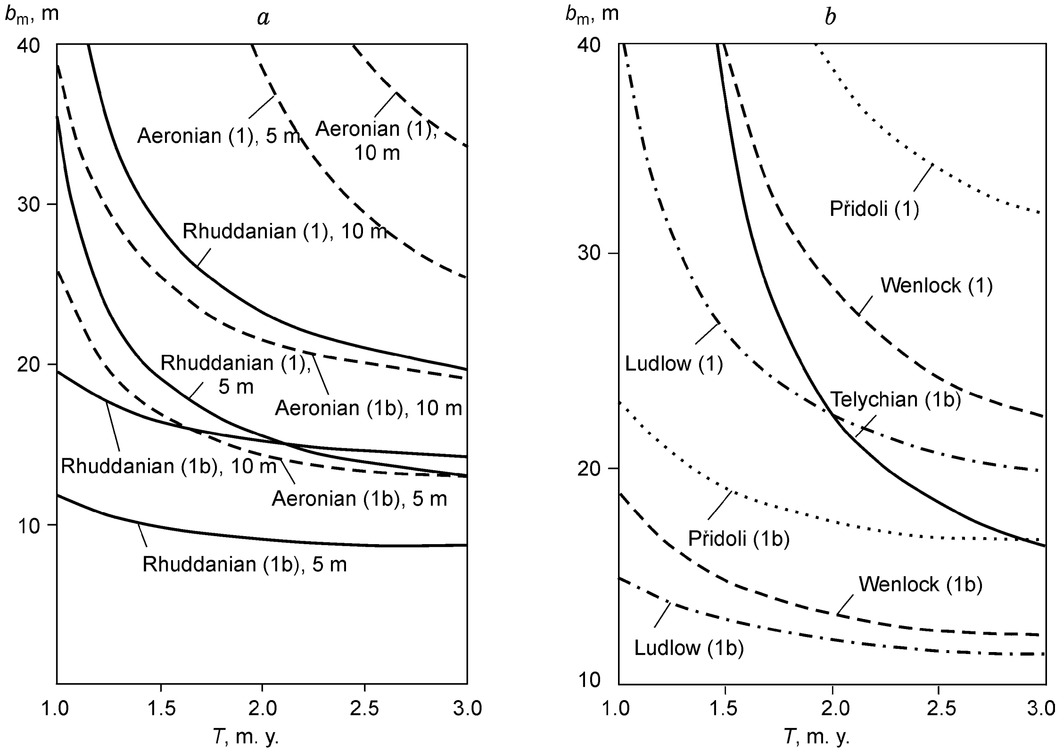


Fig. 12. Maximum magnitudes b_m (in m) of eustatic events with rapid regression (Fig. 11, *a*) and total duration T (m. y.). *a* — In Rhuddanian and Aeronian at observed structure of sedimentary section; *b* — in Telychian-Pridolian at invariable observed structure of sedimentary section. Curves obtained at condition (1) when eustatic event is detectable to 100% probability from missing or strongly reduced chronozone are labeled by 1. Each curve is accompanied by indication of sea depth before eustatic event (5 or 10 m).

for the Aeronian. At h_0 = 10 m, b_m = 13–16 m at T = 1–3 m. y. for the Rhuddanian and b_m = 15–20 m at T = 1.4–3 m. y. for the Aeronian.

Figure 14, *b* shows maximum magnitudes b_m of a harmonic event which may have occurred in the Rhuddanian and Aeronian leaving no traces of erosion. For Rhuddanian and Aeronian time they are within 17–21 m at h_0 = 5 m and within 22–27 m at h_0 = 10 m. Estimated in the absence of erosion, b_m increases with T (Fig. 14, *a*). Maximum magnitudes of eustatic events which may have occurred in Rhuddanian and Aeronian time can be estimated as the least b_m for each T chosen from both indicators (Fig. 14, *c*). If all chronozones are present in the section, b_m is between 10 and 23 m for the Rhuddanian and between 16 and 26 m for the Aeronian. Given that the thickness of chronozones varies smoothly, the condition (1b) appears more realistic. Then, b_m is 7 to 23 m. It is commonly assumed that third-order cycles have magnitudes of 20 to 100 m [5, 7], and b_m in Fig. 14, *c* are below or about the lower limit of this range.

In the Telychian-Pridolian, deposition occurred mostly in peritidal environments at sea depths ≤5 m. Mean rate of carbonate deposition in these conditions as a rule increases with depth ($-z$). Then, assuming smooth sea-level changes, b_m can be estimated with regard to the final subsidence rate. Assume that subsidence, occurring at a constant rate, reaches a value a for the time of eustatic event T, and that the sedimentation rate is proportional to depth ($-z$). At a relatively large magnitude of the event, the sea floor emerges some time later during sea-level fall (Fig. 15) and then becomes flooded again during transgression.

The greatest magnitude b_m of harmonic events which may have occurred in Telychian-Pridolian time can be estimated using the conditions of complete carbonate sections (1) and smooth variations in chronozone thickness (1b). These values are calculated in Appendix II and plotted as T functions in Fig. 16, *a*. The corresponding ranges of b_m are given in Tables 3 and 4. At the condition (1b), they are no greater than 13–20 m for the Wenlockian and Ludlovian and are in the range of 17 to 25 m for the Pridolian. For the Telychian with long mean durations

Table 3

Minimum Magnitudes of Eustatic Events Detectable in Silurian Sections of East Siberia, Condition (1b), (A.I.2a)

Time interval	Criterion*	Regression	Initial water depth (h_0), m	Duration of event (T), Ma	Minimum magnitude (b_m), m	Reference to figure
Rhuddanian—Aeronian	1	Rapid	5	1–3	15	
	1	»	10	1–3	20	
Rhuddanian	2	»	5	1–3	8–12	12, *a*
	2	»	10	1–3	14–19	12, *a*
	1	Slow	5	1–3	17–21	14, *b*
	1	»	10	1–3	22–25	14, *b*
	2	»	5	1–3	8–9	14, *a*
	2	»	10	1–3	13–16	14, *a*
Aeronian	2	Rapid	5	1–3	13–26	12, *a*
	2	»	10	1.2–3	19–30	12, *a*
	1	Slow	5	1–3	18–23	14, *b*
	1	»	5	1–3	22–27	14, *b*
	2	»	5	1–3	10–22	14, *a*
	2	»	10	1.1–3	15–30	14, *a*
Telychian—Pridolian	1	Rapid	5	1–3	8	
Telychian	2	»	5	1.7–3	16–30	12, *b*
	1	Slow	5	1–3	11–17	15
	2	»	5	1.8–3	19–32	16
Wenlockian	2	Rapid	5	1–3	12–19	12, *b*
	1	Slow	5	1–3	12–19	15
	2	»	5	1–3	13–16	16
Ludlovian	2	Rapid	5	1–3	12–15	12, *b*
	1	Slow	5	1–3	13–24	15
	2	»	5	1–3	13–20	16
Pridolian	2	Rapid	5	1–3	16–24	12, *b*
	1	Slow	5	1–3	15–30	16
	2	»	5	1–3	17–25	16

***1 — no notable erosion; 2 — complete section plus smooth changes in thicknesses of chronozones.**

of chronozones (1.1 m. y.), b_m is below 30 m only at $T \geq 1.8$ m. y.; it is higher under the condition (1), but relatively small for the Wenlockian and Ludlovian (19–30 m at $T = 1.5$–3 and 1.1–3 m. y., respectively).

A eustatic event can be also indicated by erosion if during regression the crust surface reached the altitude z_0 at which erosion becomes notable. For Telychian-Pridolian carbonates we may assume that $z_0 = 3$ m $h_0 = 5$ m. The magnitude b_m of harmonic events detectable in these conditions is calculated in Appendix II. The maximum magnitudes of eustatic events which may have occurred in Telychian-Pridolian time can be estimated as the least of the two *b* sub m values corresponding to conditions (1) and (1b) (Fig. 16, *a*, *b*). These magnitudes are within 10–22 m for the Telychian, Wenlockian, and Ludlovian and 13–30 m for the Pridolian.

Table 4

Minimum Magnitudes of Eustatic Events Detectable in Silurian Sections of East Siberia, Condition (1), Criterion 2 (A.I.2)

Time Interval	Regression	Initial water depth (h_0), m	Duration of event (T), Ma	Minimum magnitude (b_m), m	Reference to figure
Rhuddanian	Rapid	5	1.1–3	13–30	12, *a*
	»	10	1.4–3	20–30	12, *a*
	Slow	5	1.4–3	10–15	14
	»	10	1.3–3	15–30	14
Aeronian	Rapid	5	2.5–3	25–30	12, *a*
	»	10	1–3	≥34	12, *a*
	Slow	5	2–3	16–1	14
	»	10	2.5–3	24–30	14
Telychian	Rapid	5	1–3	≥59	
Wenlockian	»	5	1.9–3	22–30	12, *b*
	Slow	5	1.5–3	19–30	16
Ludlovian	Rapid	5	1.3–3	20–30	12, *b*
	Slow	5	1.1–3	19–30	16
Pridolian	Rapid	5	1–3	≥32	12, *b*
	Slow	5	1.5–3	28–35	16

SEA DEPTH CHANGES CORRESPONDING TO EUSTATIC EVENTS AND RAPID VERTICAL MOVEMENTS OF THE CRUST

According to our estimates, the Silurian 1–3 m. y. eustatic fluctuations did not exceed 10–30 m. However, synchronous sea-depth changes in some regions reached magnitudes of ~30–120 m (Fig. 2) and were apparently associated with rapid crustal uplift and subsidence, as sea-level fluctuations were weak. The subsidence curve can be obtained from the sea depth curve by subtracting time-dependent sediment thickness. Johnson [9] failed to do this, but rapid vertical crustal movements in the regions shown in Fig. 2 were most likely of the same sign and about the same magnitude as the sea-depth changes, at relatively slow sedimentation.

The curves in Fig. 2 differ significantly for different regions. The sea deepened to ≥100 m in the Gondwanian basins (New Southern Wales) and Catasia (South China platform) between 439 and 442 m. y. (Rhuddanian) and shoaled for about the same magnitude in these regions and in the Prague basin in Europe in the following several million years. However, sea-depth changes in the Baltic and Avalonian regions of that time did not exceed 50 m, and Iowa in North America remained at ≤20 m. At 433–434 m. y. (Late Aeronian), Baltic and Avalonia deepened from 0–20 m to ≥120 m, whereas the basins of Southeastern Australia, South China, Iowa, and Prague existed in peritidal environments. About 430 m. y. ago (late Telychian), Baltic rose from ≥120 m to several tens of meters while southeastern Australia subsided from ~15–20 m to ≥120 m. Abrupt flooding followed by rapid shoaling occurred in England and Southeastern Australia in the latest Wenlockian (423–422 m. y.), while elsewhere the sea depths were very shallow. A similar peak is revealed in southeastern Australia about 420 m. y., in the Ludfordian (Late Ludlovian), but no considerable sea-depth changes are traceable at that time in other regions.

Such strong difference between the curves indicates a significant contribution of unevenly distributed tectonic movements to the sea-depth changes. This could be concluded without East Siberian stratigraphy, but the relative stability of the Silurian sea level in Siberia suggests a tectonic origin of large-scale sea-depth changes there. Thus, the standard for Silurian eustasy reported in [9] actually records averaged tectonic movements rather than eustasy and would look different for other regions.

The basins in Fig. 2 evolved on platforms, commonly interpreted as stable tectonic environments, but experienced repeated uplift and subsidence in the Silurian up to ~100 m for ~1 m. y. Episodes of rapid vertical

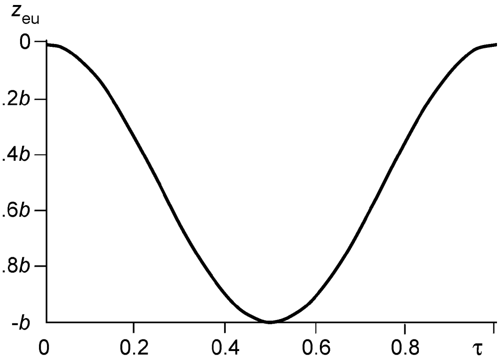


Fig. 13. Sine-shaped eustatic event (A.II.1) with smooth sea-level fall and rise for magnitude *b*.

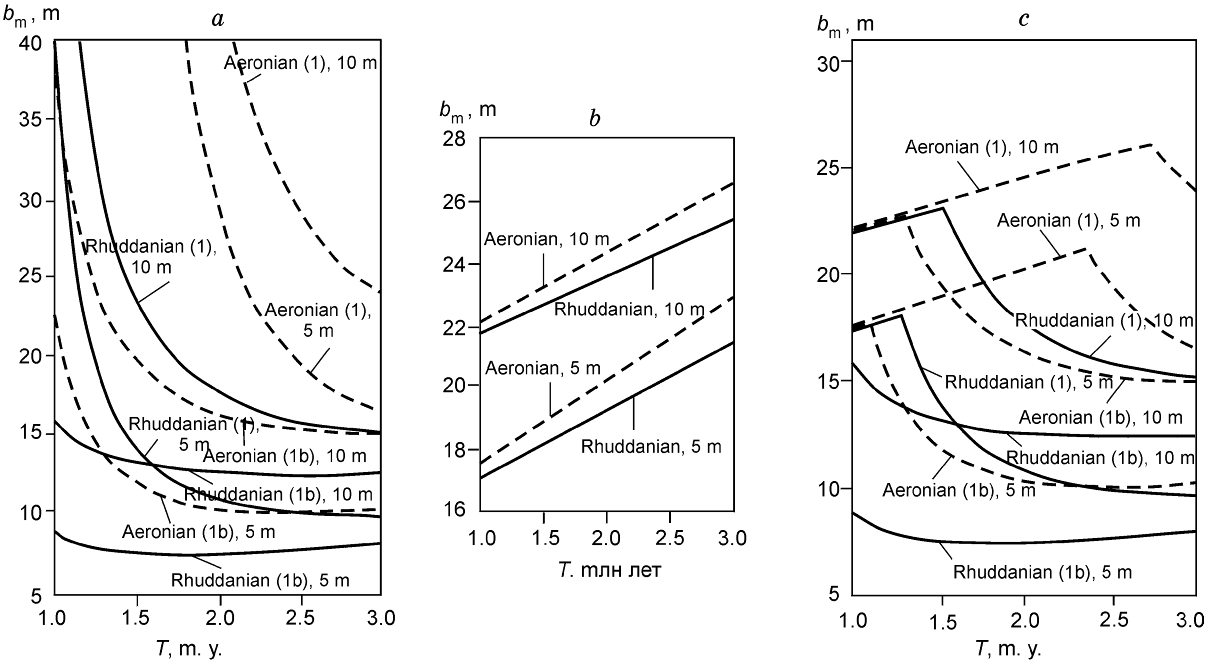
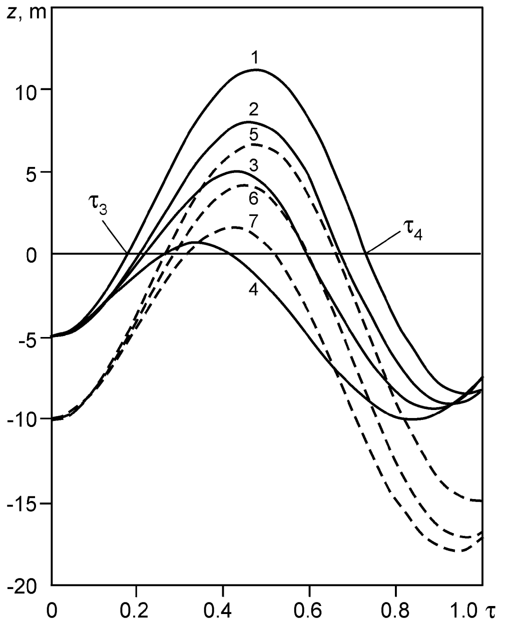


Fig. 14. Maximum magnitudes b_m (in m) of sine-shaped eustatic events (see Fig. 13) in Rhuddanian and Aeronian time: *a* — at conditions (1) and (1b) providing observed structure of sedimentary sections; *b* — in absence of notable erosion; *c* — at both conditions. Designations on curves follow Fig. 12.

movements (uplift, subsidence, and uplift followed by subsidence) often occurred in different times in other platforms as well. For instance, an ~100 m deepening of the sea for ~1 m. y. followed a subaerial gap in northern and central East Siberia (Fig. 8, *b*, curves for the Moiero and Morkoka regions). This transgression may be attributed to sea-level rise caused by melting of a large ice sheet which existed in the late Ordovician in the southern hemisphere [44]. However, in the earliest Silurian, the periphery of the East Siberian sea remained at depths as shallow as ~10 m (Fig. 8, *b*). Therefore, no eustatic sea-level rise occurred at that time, and the deepening was caused by tectonic factors. Note that a coeval crustal subsidence on the European passive margin of the Ural ocean [45] far exceeded the sea-level rise associated with melting of Phanerozoic ice sheets (≥1000 m against ~100–200 m), and thus was of tectonic origin as well. A major eustatic rise associated with ice sheet melting, if it really existed, rather occurred in the Late Ordovician.

Rapid crustal uplift on platforms (~100 m/m. y.) occurred in the Cambrian as well, in Southern Sweden and Eastern Lithuania [24, 25]. Repeated brief episodes of uplift which then gave way to rapid subsidence were inferred for many sedimentary basins [46]. For example, the eastern East European platform underwent an uplift on the



Curve No.	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. 15. Relative sea-level changes (in m) described by (A.II.10) at time of marine deposition and by (A.II.11) at time of subaerial gaps. h_0 is initial sea depth, a is tectonic subsidence during a eustatic event, b is magnitude of event, $\tau = t/T$ is normalized time, τ_3 and τ_4 are, respectively, times of beginning and end of subaerial gap on curve 1.

shelf for ~1 m. y. at the Middle/Late Devonian boundary, accompanied by weak volcanism from a deep-seated source. It was soon followed by rapid subsidence which produced relatively deep seas in the Timan-Pechora, Volga-Ural, and Caspian basins.

Several mechanisms were suggested to explain crustal movements of this type. One explanation invokes small fluid-bearing mantle plumes which rise to the lithospheric base [47] and produce a weak isostatic swell at the initial stage of their evolution. Then infiltration of minor volumes of fluids into the lower crust causes abrupt acceleration of phase transition from gabbro to denser garnet granulites accompanied by rapid subsidence of the crust. This mechanism may account for the small uplift over the greatest part of East Siberia at the Ordovician/Silurian boundary followed by rapid crustal subsidence in the earliest Silurian. Another mechanism attributes vertical crustal movements within intracratonic basins to changing horizontal stresses in the lithosphere [48]. It is also hypothesized that crustal uplift and subsidence on platforms may be caused by reorganization of lower mantle flows and deflections of the lithosphere associated with changes in the position of subduction zones relative to cratons [49, 50]. The applicability of these mechanisms to specific episodes of uplift and subsidence on platforms requires special consideration.

CONCLUSIONS

It has been commonly accepted that repeated sea-depth changes in the Phanerozoic are associated with eustatic fluctuations of magnitudes from 20 to 100 m and durations of 1–3 m. y. (third-order cycles) [2, 5, 7], additionally controlled by tectonic movements [18]. Frequent eustatic changes are very seldom doubted [4, 51].

Eustatic events are most often distinguished through statistical analysis of time-dependent sea depths in different regions. The Silurian eustasy standard (Fig. 2) including eight ~30–130 m transgression-regression peaks was obtained by averaging sea-depth changes in six cratonic regions [9]. We suggest a quite different approach. We consider the large and well-documented region of the East Siberian deposition basin, which included areas of slow peritidal deposition in a water depth 0–10 m continuing for 10–20 m. y. throughout the Silurian and earliest Devonian. A rapid 10–20 m sea-level fall under these conditions would cause subaerial exposure and erosion of the sea floor and a deposition gap, whereas a rapid ~10 m rise would result into flooding easily recognizable from faunal and sedimentologic evidence. However, the East Siberian Silurian sections do not bear any signature of these events. Therefore, 1–3 m. y. eustatic cycles there, if any, must have been very small. The sedimentation rate taken into account, the maximum magnitude of fluctuations that leave no traces in the sedimentary record could

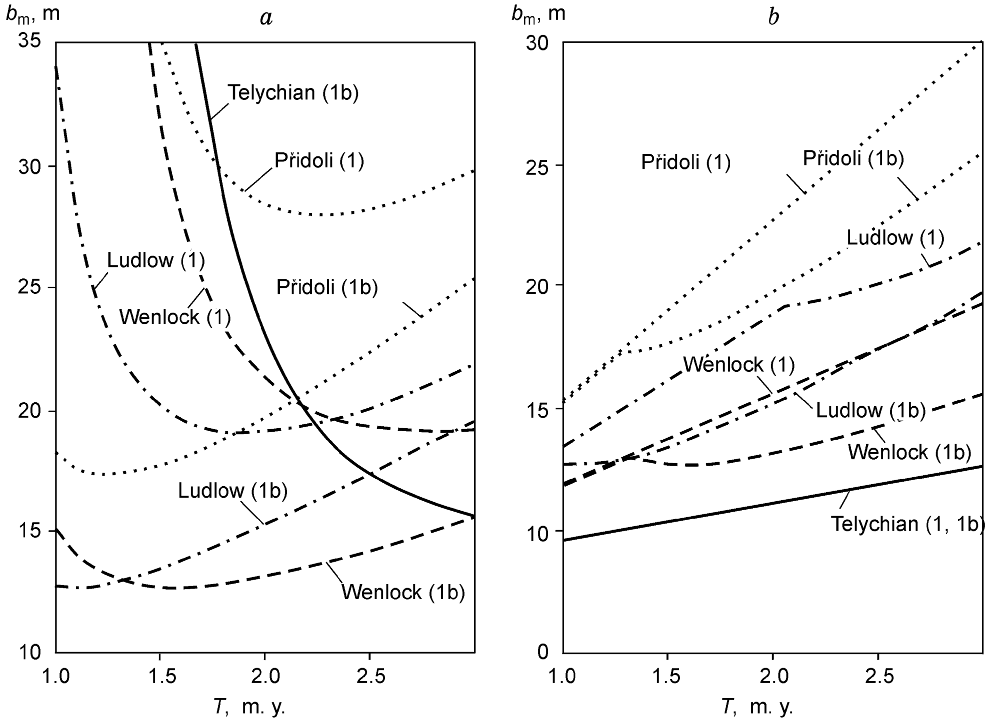


Fig. 16. Maximum magnitudes b_m (m) of eustatic events (see Fig. 13) in Telychian and Pridolian time: *a* — at observed structure of sedimentary section; *b* obtained using both criteria (absence of erosion, condition 1; complete section and smooth changes in chronozone thickness, condition 2). Labels on curves follow Fig. 12.

not exceed ~30 m, or less (~8–10 m) for some stages of the Silurian. These values are below or about the lower limit of the 20–100 m range suggested for the third-order cycles. Real Silurian eustatic fluctuations apparently were still smaller.

Although the Silurian eustasy was nearly stable, sea-depth changes reached ≥100 m (Fig. 2) and were thus most likely of tectonic origin. Therefore, the statistical approach yields averaged magnitudes of vertical crustal movements in randomly selected regions rather than eustatic curves. Our analysis showed that the absence of rapid large-scale eustatic fluctuations can be inferred from the evidence of slow deposition in peritidal environments instead of collecting numerous bathymetric data from many regions.

The same approach was used earlier [24, 25] to study sea level in Cambrian-earliest Ordovician southern Sweden, Lithuania, Australia, North America, etc., where brief asynchronous episodes of sea-depth changes in the absence of eustatic fluctuations above 10–20 m were attributed to rapid tectonic movements. The periods without rapid large-scale eustatic fluctuations in the earliest Paleozoic and Silurian time lasted in total about 70 m. y., which is 13% of the Phanerozoic. These results were obtained for sections randomly selected on the basis of data availability. Therefore, the sea level may have remained almost invariable over the greatest part of the Phanerozoic, and the earlier revealed eustatic events rather reflect regional-scale episodes of uplift and subsidence, except for the major glaciations.

The frequently alternating uplift and subsidence episodes that cause transgressions and regressions, including vertical crustal movements in East Siberia at the Ordovician/Silurian boundary, were largely discussed earlier [52]. Recent implications have mainly invoked eustasy to explain rapid sea-depth changes in continental basins, which, however, are most often of tectonic origin, as shown by this study and the results reported in [24, 25].

Rapid uplift and subsidence in cratonic areas is a specific type of tectonic movements which are responsible for the third-order sea-depth cycles and favor the formation of numerous oil and gas traps. The regions of recent crustal movements can be of high seismic hazard and are unsuitable for storage of nuclear waste. Thus investigation into the regularities and physical mechanisms of rapid vertical crustal movements is of scientific and practical interest.

We wish to thank Yu.I. Tesakov for numerous discussions.

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APPENDIX

I. Minimum magnitude of eustatic fluctuations with rapid regression detectable in continuous sedimentary sections

As noted above, the sediments deposited in peritidal environments in East Siberia did not experience significant erosion in the Silurian. Assume that crustal subsidence occurs at a constant rate $a(t/T) = a\tau$, where a is subsidence during a eustatic event T. Neglecting erosion, the duration of subaerial gaps for the events (Fig. 11, *a*) is

$$\Delta t_{\mathrm{sa}} = [(b - h_0)/(b + a)]T. \qquad \text{(A.I.1)}$$

Therefore, as follows from the condition (1), the gap is detectable to a 100% probability as a missing chronozone if the magnitude $b \geq b_{\mathrm{m}}$, where

$$b_{\mathrm{m}} = (h_0 + 2a\Delta t_{\mathrm{cz}}/T)\,(1 - 2\Delta t_{\mathrm{cz}}/T)^{-1}. \qquad \text{(A.I.2)}$$

Given (1b)

$$b_{\mathrm{m}} = (h_0 + a\Delta t_{\mathrm{cz}}/T)\,(1 - \Delta t_{\mathrm{cz}}/T)^{-1}. \qquad \text{(A.I.2)}$$

The magnitudes of (A.I.2) and (A.I. 2a) decrease with the duration T and increase with the initial water depth (h_0) and subsidence rate (a/T). Minimum b_{m} for each time span can be obtained for regions with the lowest mean subsidence rates.

Rhuddanian and Aeronian. Siliciclastic deposition in Rhuddanian and Aeronian time most likely occurred at $h_0 \sim 5$ m, occasionally at 10 m. Mean Δt_{cz} is 0.36 m. y. for the Rhuddanian and 0.61 m. y. for the Aeronian (Table 1). Mean sedimentation rates were the lowest in the Ilim region (6.8 km/m. y. in the Rhuddanian and 8.3 km/m. y. in the Aeronian). For these values, b_{m} curves are plotted in Fig. 12, *a* as T functions at T = 1–3 m. y., corresponding to third-order cycles (Tables 3, 4).

For the Rhuddanian, at h_0 = 5 m, b_{m} found as (A.I.2) at the condition (1) decreases from 30 m at T = 1.1 m. y. to 13 m at T = 3 m. y. For the Aeronian, b_{m} is 25–30 m only at T = 2.5–3 m. y. Now assume that h_0 = 10 m. As follows from Fig. 12, *a*, in the Rhuddanian b_{m} = 20–30 m within T = 2.5–3 m. y., whereas in the Aeronian, b_{m} is above 30 m throughout the cycle T = 1–3 m. y.

The condition (1) used in (A.I.2) is more rigorous as it requires that the interval corresponding to one chronozone were fully overlapped by a subaerial gap. At the less rigorous condition (1b), the magnitude of eustatic events (Fig. 11) can be hypothesized to a rather high probability to be within (A.I.2a) (see the respective curves for the Rhuddanian and Aeronian in Fig. 12, *a*). At h_0 = 5 m, b_{m} does not exceed 12 m in the Rhuddanian and 26 m in the Aeronian throughout the cycle T = 1–3 m. y. and decreases to 8 and 13 m, respectively at T = 3 m. y. At h_0 = 10 m, b_{m} is from 14 to 19 m in the Rhuddanian, and in the Aeronian it is below 30 m since T = 1.2 m. y. and as low as 19 m at T = 3 m. y.

Telychian-Pridolian. At that time the basin included a broad peritidal zone with water depths from 0 to 5 m. At h_0 = 5 m, z_0 = 3 m, according to the condition (3), erosion becomes visible at $b \geq b_{\mathrm{m}} = 8$ m. Δt_{cz} was the longest (1.1 m. y.) in the Telychian, when (A.I.2) yields $b_{\mathrm{m}} \geq 59$ m throughout the cycle T = 1–3 m. y. at a/T = 4.9 m/m. y. For the Telychian, b_{m} found as (A.I.2a) is as low as 16–30 m at T = 1.7–3 m. y. (Fig. 12, *b*). In the Wenlockian, $\Delta t_{\mathrm{cz}} = 0.45$ m. y., and at a/T = 11.9 m/m. y., b_{m} found as (A.I.2) is 30 m at T = 1.9 m. y. and 22 m at T = 3 m. y. (Fig. 12, *b*). At T = 1–3 m. y., (A.I.2a) yields b_{m} from 12 to 19 m. In the Ludlovian and Pridolian, Δt_{cz} are 0.31 and 0.4 m. y., respectively, and the mean subsidence rates are 17.2 and 22.9 m/m. y. In the Ludlovian, b_{m} = 20–30 m at T = 1.3–3 m. y. and in the Pridolian, $b_{\mathrm{m}} \geq 32$ m for T = 1–3 m. y. (Fig. 12, *b*). (A.I.2a) for T = 1–3 m. y. yields b_{m} = 12–15 m in the Ludlovian and b_{m} = 16–24 m in the Pridolian.

II. Minimum magnitude of eustatic fluctuations with slow regression detectable in continuous sedimentary sections

Consider a eustatic event (Fig. 13) of the form

$$\zeta_{\mathrm{eu}} = -b\,\sin^2(\pi\tau). \qquad \text{(A.II.1)}$$

where $\tau = t/T$ is normalized time, and $\tau = 0$ and $\tau = 1$ correspond to the beginning and the end of the event, respectively.

Rhuddanian and Aeronian. At that time, siliciclastic deposition in the absence of eustatic fluctuations in southern and southeastern East Siberia kept up with crustal subsidence at a slowly changing rate and the uplift of the crustal surface was $\zeta = -h_0$. Under this condition, the relative depth of the crustal surface below the sea level ($\zeta < 0$) is given by

$$\zeta_1 = -h_0 + b\sin^2(\pi\tau). \tag{A.II.2}$$

The falling water level reaches the sea floor ($\zeta = 0$) at time

$$\tau_1 = (1/\pi)\arcsin{(h_0/b)}^{1/2}. \tag{A.II.3}$$

From that time to the beginning of new transgression, the height of the crustal surface above sea level is controlled by eustatic fluctuations (A.II.1) and crustal subsidence at a constant rate $a(t/T) = a\tau$:

$$\zeta_2 = -h_w^0 + b\sin^2(\pi\tau) - a(\tau - \tau_1). \tag{A.II.4}$$

Denote the second root of (A.II.4) at $0 \le \tau \le 1$ as τ_2. At τ_2, after a subaerial gap, the crustal surface again reaches the sea level. The duration of the gap is $\tau_2 - \tau_1$. According to the condition (1), sediments of all chronozones are always present in the section at

$$(\tau_2 - \tau_1)T \le 2\Delta t_{\mathrm{cz}}. \tag{A.II.5}$$

As follows from the condition (1b), no abrupt changes in sediment thickness occurs between neighboring chronozones if

$$(\tau_2 - \tau_1)T \le \Delta t_{\mathrm{cz}}. \tag{A.II.5a}$$

The least b_{m} corresponding to (A.II.5) and (A.II.5a) for the Rhuddanian (a/T = 6.8 m/m. y.) and Aeronian (a/T = 8.3 m/m. y.) are plotted in Fig. 14, *a*. At the condition (1) and h_0 = 5 m, b_{m} found as (A.II.5) varies from 10 to 40 m, never exceeding 15 m at T = 1.4–3 m. y. in the Rhuddanian and is below 30 m since T = 2 m. y. in the Aeronian. At a greater initial depth (h_0 =10 m) at T = 1.4–3 m. y., b_{m} is from 12 to 20 m in the Rhuddanian and below 20 m only at $T \ge 2.4$ m. y. in the Aeronian. At the condition (1b), b_{m} found as (A.II.4a) are much lower. At h_0 = 5 m, within T = 1–3 m. y., b_{m} is 8–9 m in the Rhuddanian and from 10 to 22 m in the Aeronian, never exceeding 15 m at T = 1.2–3 m. y. At h_0 = 10 m, b_{m} vary from 10 to 14 m at T = 1–3 m. y. in the Rhuddanian and from 15 to 30 m at T = 1.1–3 m. y. in the Aeronian, never exceeding 20 m at T = 1.4–3 m. y.

Now we estimate b_{m} in the absence of significant erosion during subaerial gaps. This erosion occurs if the crust surface is at $\zeta_2 \ge z_0$ relative to the sea level:

$$\max(\zeta_2) \ge z_0. \tag{A.II.6}$$

The minimum b_{m} that satisfy this condition in the Rhuddanian and Aeronian at z_0 = 10 m and h_0 = 5 m and 10 m vary from 17 to 27 m (shown as T functions in Fig. 14, *b*).

Telychian-Pridolian. Assume that crustal subsidence (z_{t}) occurs at a constant rate $a(t/T) = a\tau$, and the mean rate of carbonate sedimentation ($dz_{\mathrm{dp}}/d\tau$) at shallow depths (≤5 m) is proportional to the water depth $-z$:

$$z_{\mathrm{t}} = -a\tau, \tag{A.II.7}$$

$$dz_{\mathrm{dp}}/d\tau = -(a/h_0)z. \tag{A.II.8}$$

The rate of tectonic subsidence (A.II.5) is $d\zeta_{\mathrm{t}}/d\tau = -a$. In the absence of eustatic fluctuations, $z = -h_0$, $dz_{\mathrm{dp}}/d\tau = a$, and $d\zeta_{\mathrm{t}}/d\tau + dz_{\mathrm{dp}}/d\tau = 0$ and subsidence is balanced by deposition. The rate of eustatic fluctuations is $d\zeta_{\mathrm{t}}/d\tau = -\pi b\sin 2\pi\tau$. When the crustal surface is below sea level, relative changes of its position are defined by $dz/d\tau = dz_{\mathrm{t}}/d\tau - dz_{\mathrm{eu}}/d\tau + dz_{\mathrm{dp}}/d\tau$. Taking into account (A.II.8),

$$dz/d\tau = -a + \pi b\sin 2\pi\tau - (a/h_0)z\,, \text{ at } z \le 0. \tag{A.II.9}$$

The solution to this equation at $z(0) = -h_0$ looks as (Fig. 15)

$$\zeta_3 = -h_0 + \{\pi b/[4\pi^2 + (a/h_0)^2]\}\ \{(a/h_0)\sin 2\pi\tau - 2\pi\cos 2\pi\tau +$$
$$2\pi\exp[-(a/h_0)\tau]\},\ \text{at}\ z \le 0. \qquad \text{(A.II.10)}$$

Let the falling water level reach the sea floor and deposition stop at the time τ_3. At low altitudes above sea level, erosion of carbonates is weak and can be neglected at moderate eustatic fluctuations. Then, the last term in the right side of (A.II.9) is zeroed, and the solution looks as (Fig. 15)

$$\zeta_4 = -a(\tau - \tau_3) - (b/2)\cos 2\pi\tau + (b/2)\cos 2\pi\tau_3,\ \text{at}\ \zeta > 0. \qquad \text{(A.II.11)}$$

Let the crustal surface again reach the sea level at the onset of new transgression at the time τ_4 (Fig. 15). Then, τ_4 is the second root of (A.II.11) at $0 \le \tau \le 1$. According to the condition (1), a section misses one chronozone anyway if

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

The less rigorous condition (1b) implying that the section misses one chronozone to a fairly high probability or the thickness of the latter is strongly reduced corresponds to

$$(\tau_4 - \tau_3)T \ge \Delta t_{cz}. \qquad \text{(A.II.12a)}$$

The least b_m values satisfying these conditions are plotted in Fig. 16, *a* as a function of T for the Telychian-Pridolian.

Subaerial gaps become notable when the maximum value ζ_4 reaches z_0 where erosional features form:

$$\max(z_2) = z_0. \qquad \text{(A.II.13)}$$

For Silurian carbonates in East Siberia, we can assume z_0 = 3 m and h_0 = 5 m. The magnitude b_m of events (Fig. 13) detectable from traces of erosion increases with the rate of tectonic subsidence. The most rigorous constraint on b_m can be obtained by selecting the least rates of carbonate deposition for each period in the Telychian-Pridolian span (Table 2): 4.9 m/m. y. for Telychian, 11.9 m/m. y. for Wenlockian, 17.2 m/m. y. for Ludlovian, and 22.9 m/m. y. for Pridolian. The b_m values found as (A.II.13) can be compared to those found through (A.II.12) and (A.II.12a) (Fig. 16, *a*). The least b_m values are plotted in Fig. 16, *b* as a function of T.

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