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GEOLOGY

Sea Level in the Ordovician: Sharp Fluctuations in Subsidence Rates of the Siberian Craton Crust

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Most researchers relate rapid fluctuations in water depths of epicontinental sedimentary basins to eustatic sea level fluctuations [1 and others]. Of particular interest for oil-and-gas prospecting are third-order cycles or eustatic events 1–3 Ma long with amplitudes of 20 to 200 m. They are used as reference levels for interbasin correlation [2, 3, and others]. Using the data on low sedimentation rates in extremely shallow settings (≤10 m) of the eastern Baltic and East Siberia regions, it has been shown that third-order sea level fluctuations in the terminal Cambrian–Silurian did not exceed 10–20 m [4, 5]. At the same time, fluctuations in water depths up to 100–200 m over periods of 1–3 Ma long were characteristic of many epiplatformal sedimentary basins on many continents. Since the sea level was almost stable, such fluctuations indicate frequent crustal uplifts and subsidences in platforms. This is a quite unexpected result, since such areas are usually considered relatively calm in terms of tectonics.

Shallow-water Ordovician sections on ancient platforms are classical objects favorable for reconstructing eustatic events [6]. Some events with amplitudes up to 150–200 m were defined in these sections based on transgressions and regressions on different continents, primarily in North America (Fig. 1). The formation and degradation of large ice shields could be a primary factor responsible for such eustatic fluctuations. However, reliable evidence for glaciation in the Early–Middle Ordovician is lacking. Therefore, Ordovician transgressions and regressions require special consideration based on detailed data. Such data are available, for example, for Estonia [6, 7] and East Siberia [8–11]. Based on numerous faunal fossils, the geological sections in these regions have been subdivided in detail. Regional stratigraphic scales and facies models have also been developed [6–11].

In the terminal Cambrian, Ordovician, and Silurian, the North Estonian facies zone up to 300 km long and 40–45 km wide (Fig. 2) was marked by sedimentation above the base level of normal waves except for several episodes of short-term drainage. The zone was usually 10–15 m deep. The shelf with a low-angle slope was no deeper than 10 m. During 10–12 Ma of the terminal

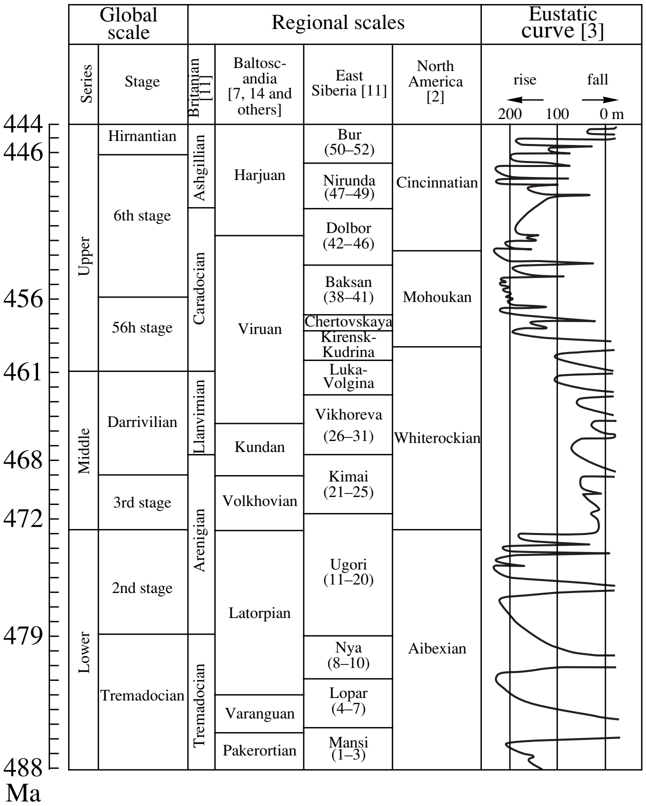

Fig. 1. Eustatic sea level fluctuations assumed for the Ordovician (modified after [3]).

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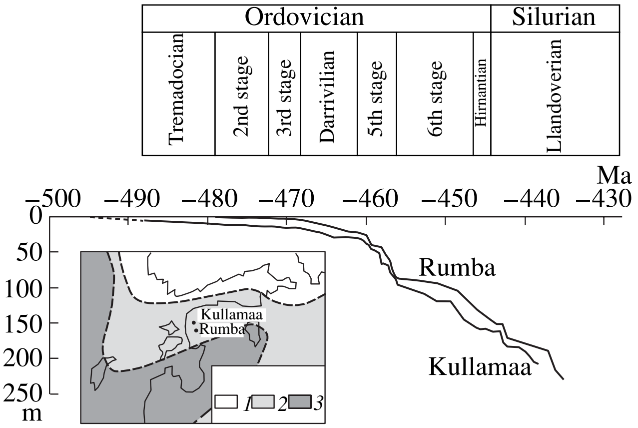

Fig. 2. Schematic distribution of facies zones in the eastern Baltic region during the Ordovician and sedimentation curves for the North Estonian zone (after [6, 7, and others]). (*1*) Land; (*2*) shoals with paleodepth shallower than ~10 m; (*3*) areas with the seafloor located below the base level of normal waves (~10 m).

Cambrian and Tremadocian, fine-grained sand and clay accumulated here at an extremely low sedimentation rate (Fig. 2). Shallow sedimentation settings are evident from the abundance of the brachiopod *Lingula* community, which is highly specialized and adapted to habitat on coastal shoals. During the subsequent 33-Ma-long (Arenigian–Ashgillian) period, mostly carbonate sediments were deposited in North Estonia. Numerous desiccation cracks, ripple structures, stromatolitic buildups and mats, and oolitic interbeds and small bioherms, as well as the highly condensed section [13], imply that the basin bottom was always located near sea level and intermittently drained during ebbs.

From the terminal Cambrian until the mid-Caradocian, the upper almost flat part of the shelf and semiclosed lagoons of the northwestern Siberian Craton (Fig. 3, inset) accumulated carbonates [8, 11]. The sections are largely composed of detrital and fine-grained limestones, primary (often gypsum-bearing) dolomites, dolomitic marls (domerites), stratiform and biohermal stromatolites, and oolitic and ooid limestones. Dolomites and domerites often contain desiccation cracks related to short-term draining of the tidal zone. The biota is characterized by low diversity (brachiopods, trilobites, and gastropods) and a dwarfish appearance. Such sediments are usually deposited near the shore above the base level of normal waves at depths of ≤10 m. In the terminal Cambrian to mid-Caradocian, shallow-water carbonate and terrigenous sediments also accumulated in the Irkutsk Amphitheater [9] and Lena facies zone [11] of the southern Siberian Craton. Judging from the character of sediments, they accumulated at extremely shallow depths ranging from ~10 m to a few meters.

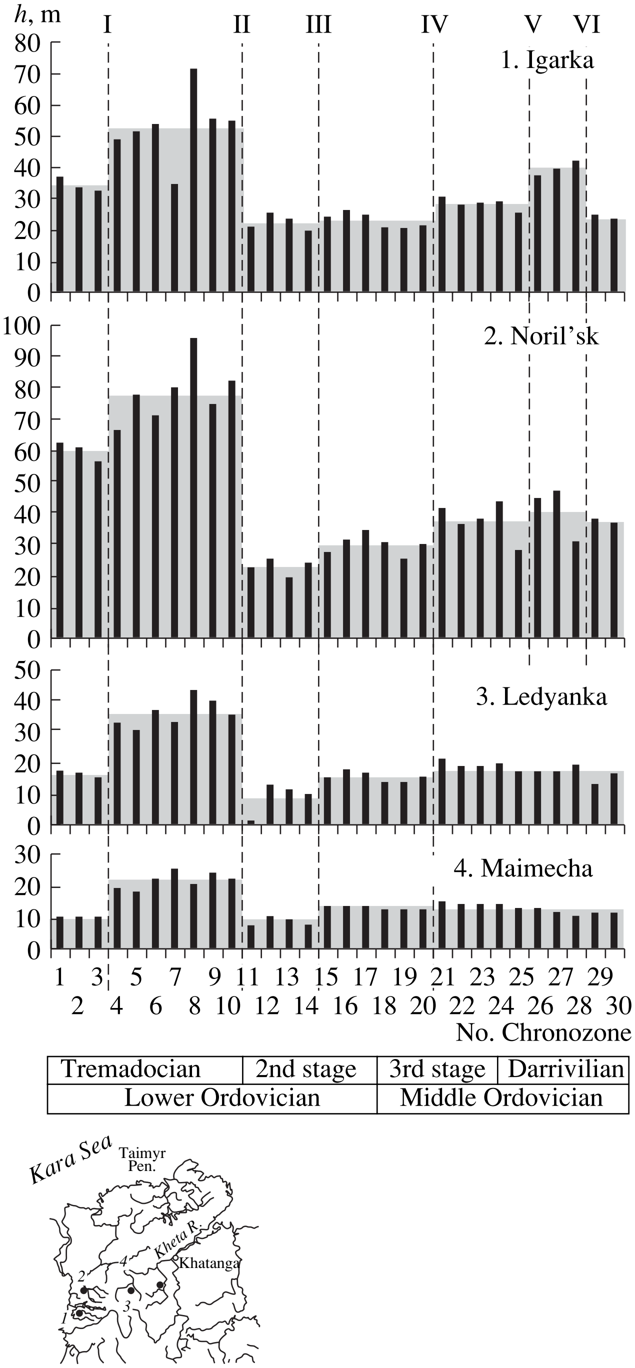

Fig. 3. Thicknesses of the first 30 Ordovician chronozones in areas 1–4 of East Siberia (after [11]). The light gray color indicates average values of the chronozone thickness in periods where their relative variations were insignificant. The inset demonstrates location of sections composed of extremely shallow-water terminal Cambrian–Middle Ordovician sediments in northwestern East Siberia: (*1*) Igarka; (*2*) Noril'sk; (*3*) Ledyanka; (*4*) Maimecha.

The Cambrian–Ordovician transition was presumably marked by a sea level fall of ≥100 m. This is the so-called *Acerocare* eustatic event that is considered the reference level for the Cambrian–Ordovician boundary [2]. In northern Estonia, this level corresponds to subaerial hiatus with erosion of a few meters of sediments.

On the southern shelf slope, the hiatus is missing. In northwestern East Siberia, in the stratotype section exposed along the Kulyumbe River [8] and in the sediments accumulated at a depth of ≤10 m in the southern part of the platform [10], the Cambrian–Ordovician transition is gradual. Hence, no significant global sea level fall took place at that time. Draining of northern Estonia could be caused by either a crustal uplift by ~10 m followed soon by a slight subsidence or a sea level fall of several meters. An additional subaerial hiatus is recorded in northern Estonia at the Tremadocian–Arenigian transition [6 and others]. At the same time, sedimentation was continuous at depths of ≤10 m in northwestern and southern East Siberia [9–11]. Hence, the short-term draining of northern Estonia was related to tectonic processes.

Hiatus and weak subaerial erosion also took place in northern Estonia during an approximately 1-Ma-long episode in the first half of the Caradocian [14]. The absence of a karst and even microkarst formation at this level indicates that the relative sea level fall was insignificant. This is also evident from the absence of a subaerial hiatus on the southern shelf slope. In the Caradocian, very shallow-water sedimentation took place in the southern and southeastern Siberian Craton [9, 10]. Hence, no substantial eustatic fluctuations occurred at that time and the draining of northern Estonia was caused by an insignificant short-term crustal uplift.

Glaciation of Gondwana in the Late Ordovician presumably caused significant sea level falls [2, 3, 12]. Their temporal distribution is uncertain. During the post-Caradocian time, northern Estonia retained extremely shallow-water settings. Hence, no glacioeustatic sea level falls took place here. The initial Hirnantian was marked by short-term draining of the study area [15] and the southern open shelf with depths of ~100 m. In the first half of the Hirnantian, open shelf settings were restored and extremely shallow-water sedimentation resumed in northern Estonia. These data indicate a sea level fall by ≥100 m in the initial Hirnantian, probably related to the Gondwana glaciation. In the second half of the Hirnantian, northern Estonia was again drained, while southern Estonia with water depths of ~100 m was characterized by extremely shallow-water sedimentation, which lasted approximately 1 Ma up to the end of the Hirnantian. Since the initial Silurian, northern Estonia was again flooded by the sea with water depths of ≥10 m and open shelf settings were restored in southern Estonia. These data suggest a new phase of the Gondwana glaciation in the second half of the Hirnantian with a sea level fall of ~100 m. Thus, the last 2-Ma-long interval of the Ordovician was marked by two phases of significant Gondwana glaciation separated by an approximately 1-Ma-long interglacial epoch. The first glaciation was characterized by the greater scale; the second one, by the longer duration (~1 Ma).

These data do not rule out significant short-term sea level falls during the Late Ordovician. However, they could not lead to notable erosion of older sediments. They could be related to glaciation phases with a duration of several tens of thousand years similar to those during the last Pleistocene glacial epoch.

The regional Ordovician chronostratigraphic scale elaborated for the northwestern Siberian Craton includes 52 units (chronozones) [11]. Figure 3 demonstrates the initial thickness h_{chz} of the lower 30 chronozones (25 Ma) compiled for areas 1–4 with account of subsequent compaction of extremely shallow-water sediments. At boundaries I–IV, h_{chz} values experience sharp fluctuations. Relative variations of h_{chz} are insignificant in the periods separated by these boundaries. For shallow-water settings, $h_{\mathrm{chz}} = vt_{\mathrm{chz}}$, where v is the crustal subsidence rate and t_{chz} is the chronozone span. The t_{chz} value is determined by rates of faunal variations on both regional and global scales. The crustal subsidence rate v in each area depends on its typical tectonic regime. In extremely shallow-water settings, v and t_{chz} values characterize two different processes and are independent. Therefore, in the intervals with insignificant relative variations in the chronozone thickness Δh_{chz} $(h_{\mathrm{chz}})_{\mathrm{aver}}$, both the crustal subsidence rate v and chronozone span t_{chz} also changed insignificantly. Figure 4 shows such intervals. Each interval includes one or several areas, where $\Delta h_{\mathrm{chz}}(h_{\mathrm{chz}})_{\mathrm{aver}}$ does not exceed 10%. In the Igarka area, the $\Delta h_{\mathrm{chz}}(h_{\mathrm{chz}})_{\mathrm{aver}}$ value is 9% for the interval of chronozones 11–20. Similarly slight variations in the Δh_{chz} $(h_{\mathrm{chz}})_{\mathrm{aver}}$ values are characteristic of the interval of chronozones 15–30 in the Maimecha River area. These intervals are overlapped during the epoch corresponding to chronozones 15–20. Hence, the t_{chz} value experienced insignificant variations during the entire period of chronozones 11–30.

At boundaries I (chronozones 3–4) and II (chronozones 10–11), sharp fluctuations in the h_{chz} value were recorded in all areas 1–4 (Fig. 3). Fluctuations in h_{chz} may be caused by variation in the crustal subsidence rate v at the constant chronozone span t_{chz} and variation in t_{chz} at the constant v value. Inasmuch as v and t_{chz} are independent values, their simultaneous variation, which could retain the chronozone thickness ($h_{\mathrm{chz}} = vt_{\mathrm{chz}}$), is unlikely. If the subsidence rate v is constant in each area, variations in the chronozone span t_{chz}, which are similar for all areas, should produce similar variations of the chronozone thickness. Let us estimate the h_{chz} variation at each boundary as a ratio between the average thickness of two subsequent chronozones $(h_{\mathrm{chz}})_2$ and the average thickness of the two preceding chronozones $(h_{\mathrm{chz}})_1$: $(h_{\mathrm{chz}})_2/(h_{\mathrm{chz}})_1$ (table). The significant scatter of this ratio implies that the crustal subsidence rate v, rather than chronozone span t_{chz}, changed at these boundaries. Moreover, these fluctuations varied substantially in different areas and they occurred during

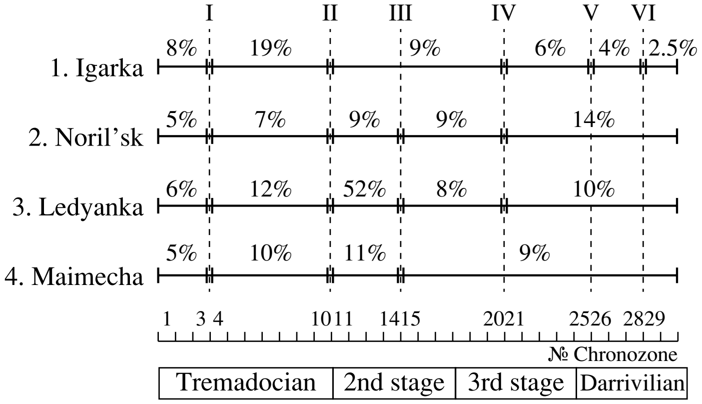

Fig. 4. Periods marked by insignificant relative variations in the thickness of Early and Middle Ordovician chronozones. For each period, the mean-square relative deviation (%) of chronozone thickness from its average value (shown by light gray color in Fig. 3) is given above the line.

very short periods that did not exceed the chronozone span t_{chz}.

Thus, the duration of chronozones during the interval of chronozones 1–30 (25 Ma) was approximately constant (average about 0.8 Ma), while the crustal subsidence rate experienced substantial variations. These variations in v were superimposed on the general crustal subsidence, which was more than 1 km over 25 Ma in areas 1 and 2. In extension-free areas of the lithosphere located away from convergent boundaries between lithospheric plates, such a subsidence required compaction of rocks in the lithosphere. In the cold Siberian Craton, it could only be provided by the phase transformation of gabbro into garnet granulites or eclogite in the lower crust.

In areas 1 and 2, where the total thickness of the first 30 chronozones is several times higher than in areas 3 and 4, h_{chz} fluctuations were also several times greater (Fig. 3). Hence, variations in the crustal subsidence rate were governed by fluctuations in the rate of eclogitization that was responsible for general subsidence. Eclogitization accelerates sharply in the presence of small volumes of water-bearing fluid. Since the crust of East Siberia was not uplifted at that time, mantle plumes capable of transporting fluids did not reach the lithosphere. Under such conditions, only the stressed state of the lithosphere could change rapidly and synchronously in separated areas. Therefore, it is conceivable that the eclogitization rate is highly dependent on the stress. Opening and closure of fissures accompanied by migration of fluids located under lithostatic pressure from one rock volume to another could serve as one of the responsible mechanisms. Fluctuations in the rate of fluid-catalyzed phase transformation within different rock volumes may provoke both acceleration and deceleration of subsidence.

Main boundaries (I–VI) marked by significant variations in the thickness of Tremadocian, Arenigian, and Llanvirnian chronozones in northwestern East Siberia. At each boundary, these variations are calculated for all areas as the ratio between the total thickness of the two subsequent and the two preceding chronozones. Location of areas is shown in the inset in Fig. 3.

Area	I	II	III	IV	V	VI
	Chronozone					
	3–4	9–10	14–15	20–21	25–26	28–29
1. Igarka	1.5	0.42	1.17	1.4	1.41	0.58
2. Noril'sk	1.24	0.3	1.34	1.4	1.28	0.97
3. Ledyanka	2	0.19	1.56	1.36	0.94	0.8
4. Maimecha	1.94	0.4	1.6	1.14	0.91	1.05

As follows from this study, significant sea level fluctuations in the Ordovician, except for the last 2 Ma, did not exceed ~20 m. Nevertheless, large regressions and transgressions occurred in many platform regions throughout the entire Ordovician. For example, several Early and Late Ordovician short-term regressions with subsequent transgressions occurred in North America (Fig. 1). The height of the platform relative to the sea level changed during these epochs by 100–200 m or more. Since the sea level was almost stable, these events indicate rapid crustal uplift and subsidence by ≥200 m. In the Middle Ordovician, North America was subjected to significant regression complicated by frequent transgressions with amplitudes of ~100 m. At the same time, epicontinental basins were drained in Australia, Argentina, and southern Anatolia [2]. Hence, rapid vertical movements of the same sign may be synchronous or quasi-synchronous on different continents. Precisely such events provided grounds for the concept of global eustatic sea level fluctuations. Synchronous manifestation of rapid crustal uplift and subsidence in different platforms is a new phenomenon. In order to establish the mechanism of these movements, we should carry out detailed studies of them in different regions and epochs.

Rapid fluctuations in sea depth in petroliferous basins were responsible for the formation of numerous stratigraphic traps with large reserves of oil and gas, for example, in the Achimovka sequence of West Siberia. Such traps also formed near ancient shorelines. Migration of shorelines over large distances is commonly attributed to synchronous and similar (in amplitude) sea level variations in all basins. Then, if we determine the value of sea level variation for one basin and know the angles of paleoslopes in any other basin, we can easily calculate the direction of their shoreline migration. Data reported in [4, 5] and the present communication suggest that significant third-order eustatic fluctuations in the Cambrian–Silurian (i.e., 126-Ma-long) history were manifested only during the 2-Ma-long episode of the Gondwana glaciation in the terminal Ordovician. Significant sea level fluctuations with a duration of 1–3 Ma were rather rare events during the major part of the Middle and Late Phanerozoic. Migration of shorelines of paleobasins was primarily related to the regional-scale crustal uplifts and subsidences. In this case, the search for nonstructural traps requires a new methodology.

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