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Position of the Siberian Platform and Adjacent Cratonic Terranes in the Paleozoic from Paleontological and Geological Evidence

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Abstract—The comprehensive chorological analyses of benthic and planktonic faunal groups, the reconstruction of paleogeography, and the delineation and correlation of the same-type biofacies and geographic ranges of the fauna suggest that the Paleozoic tectonic blocks of the Verkhoyansk–Chukotka foldbelt (Tas-Khayakhtakh, Selennyakh, Omulevka, Omolon, Okhotsk, and Chukchi inliers) and Kotel'nyi Island originated in the same epicontinental sea basin of the Siberian paleocontinent, being parts of its passive margin located at the place of the recent foldbelt. We provide a rationale for paleontological, sedimentary, and morphometric diagnostic characteristics of rift zones in complex thrust-folded structures. A rift development, with activation phases in the Ordovician and Devonian, is found to have preceded the break-up of the passive margin in the late Paleozoic.

Keywords: foldbelt, terranes, Paleozoic, tectonics, sedimentology, paleogeography, stratigraphy, chorology, Northeastern Asia, Siberian paleocontinent

INTRODUCTION

The studied territory comprises four adjacent (in modern coordinates) regions, the Siberian Platform, Verkhoyansk–Chukotka foldbelt, Taimyr, and associated islands in the Arctic Ocean that are disparate in tectonic structure and geodynamic history, but have been regarded as fragments of the Arctida (Hyperborea) paleocontinent. Due to their geological characteristics, a good coverage by stratigraphic, tectonic, sedimentological and paleontological studies, a diversity of interpretations of the geological history from various conceptual perspectives, these territories form a unique geological testing ground for comparison and evaluation of the accuracy of alternative paleotectonic and paleogeographic reconstructions using both traditional and novel approaches. A number of alternative models have been published with regards to the nature of Paleozoic blocks in the Northeastern Asia Mesozoides and their genetic links with the Siberian Platform from the perspective of both fixism and mobilism theories. The different interpretations are manifested in the observed diversity of terminology used to describe these structural elements that have been variously referred to as anticlinal structures within a geosyncline; horst anticlines; Paleozoic tectonic blocks; inliers of the basement; relict massifs; marginal uplifts; relict older foldbelts; tectonic blocks; nuclei of earlier or continental consolidation; rigid continental massifs; mid-massifs (including small, with exception of the Kolyma Massif); microcontinents (selectively); terranes of different genesis.

Compared to typical geosynclinal regions, the geological structure of the Verkhoyansk–Chukotka foldbelt is characterised by the presence of dissociated Paleozoic blocks having platform affinities and surrounded by Mesozoic foldbelts. To explain this phenomenon, various models of the heterogeneous structure have been suggested, with the Kolyma, Kolyma–Yukagirian and Hyperborean platforms (or transitional type platforms such as Kolyma Mid-Massif) surrounded by the Mesozoides. In addition, different concepts of tectonic phase development of this specific type megastructure have been brought forward, including an epicratonic geosyncline; a mobile platform; a para-platform; a marginal marine type of the Earth Crust intermediate between the oceanic and continental crust.

From the perspective of mobilism theory, all these models became obsolete as incompatible with the theoretic statements of plate tectonics. The short life of the interpretations of these tectonic units is a warning signal that some of the "inconvenient facts" can be dismissed a priori if they contradict the established paradigm. Such criteria of validity, for example, have been applied by Parfenov et al. (2003, p. 8) in their statement: "A model should not only satisfy geological data, but comply with conceptual principles" in that "the fundamentals of Earth's evolution and orogen development,

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beginning at least from the late Precambrian to our time are determined by the plate tectonics concept". This approach probably facilitates the evolution of methods and the classification of geological data at early stages of conceptualisation; however, a canonisation of the antecedently established limits of factual data interpretation leads to the selective use of both the geological information and analytical methods and, eventually to the corporative isolation of research and the exclusion of "antiquated" methods.

In view of the novel understanding of Earth's geographic and geodynamic history, the paleomagnetic method became of paramount importance for paleogeographic and paleotectonic reconstructions because it enables identification of the spatial position, in geographic coordinates, of lithospheric plates and their elements. In addition to paleomagnetic studies, almost every recent palinspastic reconstruction is also based on petrological and petrochemical data and their isotope geochemical dating, as well as kinematic interpretations of fold-and-thrust structures and geometry of tectonic sutures. Furthermore, traditional paleogeographic approaches centered around paleontological and lithofacies data are seldom and usually very superficially applied. These data are particularly important for folded regions and can be used for establishing allochthonous or autochthonous nature of the terranes, as well as dynamics and kinematics of their development in a stratigraphic order. Comparison between palinspastic and paleobiogeographic reconstructions often reveals striking discrepancies between the spatial position of the terranes determined from paleomagnetic and paleontological (chorological) data.

In this contribution we suggest a hypothesis for the origin of Paleozoic blocks of Northeastern Asia based on the analysis of tectonostratigraphic, paleontological, and lithofacies data against geological evidence characterising paleogeographic and paleogeodynamic settings as an alternative to the existing palispastic reconstructions. The term "terrane" is herein used in a narrow sense as synonymous to "Paleozoic massif" with no specific reference to either genetic classifications of these structural elements or existing models of tectonic demarkation of the foldbelt.

CHOROLOGY OF THE BENTHIC FAUNA: PALEONTOLOGICAL EVIDENCE OF THE COMMON ORIGIN OF THE SIBERIAN PLATFORM AND THE PALEOZOIC TERRANES IN THE SAME EPICONTINENTAL SEA BASIN

The term "chorology" is currently seldom used in paleogeographic typification of paleontological data because it has erroneously become synonymous with the term "biogeography". Biogeography in the strict sense refers to cartographic delineation and description of biochories of different rank, determination of their spatial position and connections between them based on chorological analysis; i.e., study of the taxonomic composition of the biotas, the ecology of the faunal and floral associations, the routes and mechanisms of migration of the associated species. According to the well-established definition, the chorology "studies patterns of spatial distribution of biotas (from Greek χῶρος, khōros, «place, space»; and -λογία, -logia, «word, thought, principle» (Petrov, 2012). The chorology constitutes the basic procedure in biogeography. The semantic difference between these two concepts is the same as between geography and geodesy; i.e., between the objective and the solution.

Compared to schematic paleobiogeographic generalisations of the paleontological data, the chorological analysis demands for higher standards of source data quality that characterise paleogeographic conditions of faunal occurrence within the entire paleobasin. Therefore, representative and comparable data are required from different structural facies zones of the basin for faunal groups that could be used as reliable proxies for paleogeographic settings and intrabasinal migration routes of the biocoenoses; i.e., groups that are characterised by specific ecological properties, population size, biodiversity, and taxonomic rank.

Province is regarded as the principal operative unit of biogeographic demarcation corresponding to a specific sedimentary basin. The relative monotony of faunal associations at species and genus level, as well as a degree of endemism are major diagnostic characteristics of the province. The stability of species-level ecological specialisation in the ecosystem is rigidly bound with the specific environmental conditions of the species that ensures the importance of this species as the main proxy of paleogeographic settings. Different species of the same genus represent a combination of closely related albeit disparate ecological specialisations; distribution areas of genera therefore comprise a larger spectrum of environmental conditions. Heuristic possibilities of family-level faunal associations are of limited value for paleogeographic demarcation of specific paleobasins; however, such analysis is important in phylogenetic reconstructions and in the studies of patterns of high-rank taxa evolution particularly in establishing the ancestral forms, their original location and the sequence of branches divergence.

Paleontological and geological data accumulated for the Ordovician Period are particularly detailed in the entire Paleozoic history of Northeastern Asia because the Ordovician strata, apart from the Siberian Platform, are well exposed in all the Paleozoic blocks in folded structures, are abundantly fossiliferous, are characterised by well-defined lithofacies and bathymetry differentiation of the paleobasin, geodynamic proxies such as specific tectonic dislocations and paleovolcanism. Comparative studies of paleontological and geological data from the underlying (upper Precambrian and Cambrian) and the overlying (Silurian, Devonian, Carboniferous) strata against the reference Ordovician stratigraphic interval allows common features to be established in the paleogeographic and paleotectonic evolution of the territory during these periods.

Figure 1 represents composite Ordovician sections in the folded framework of the Siberian Platform (along its passive

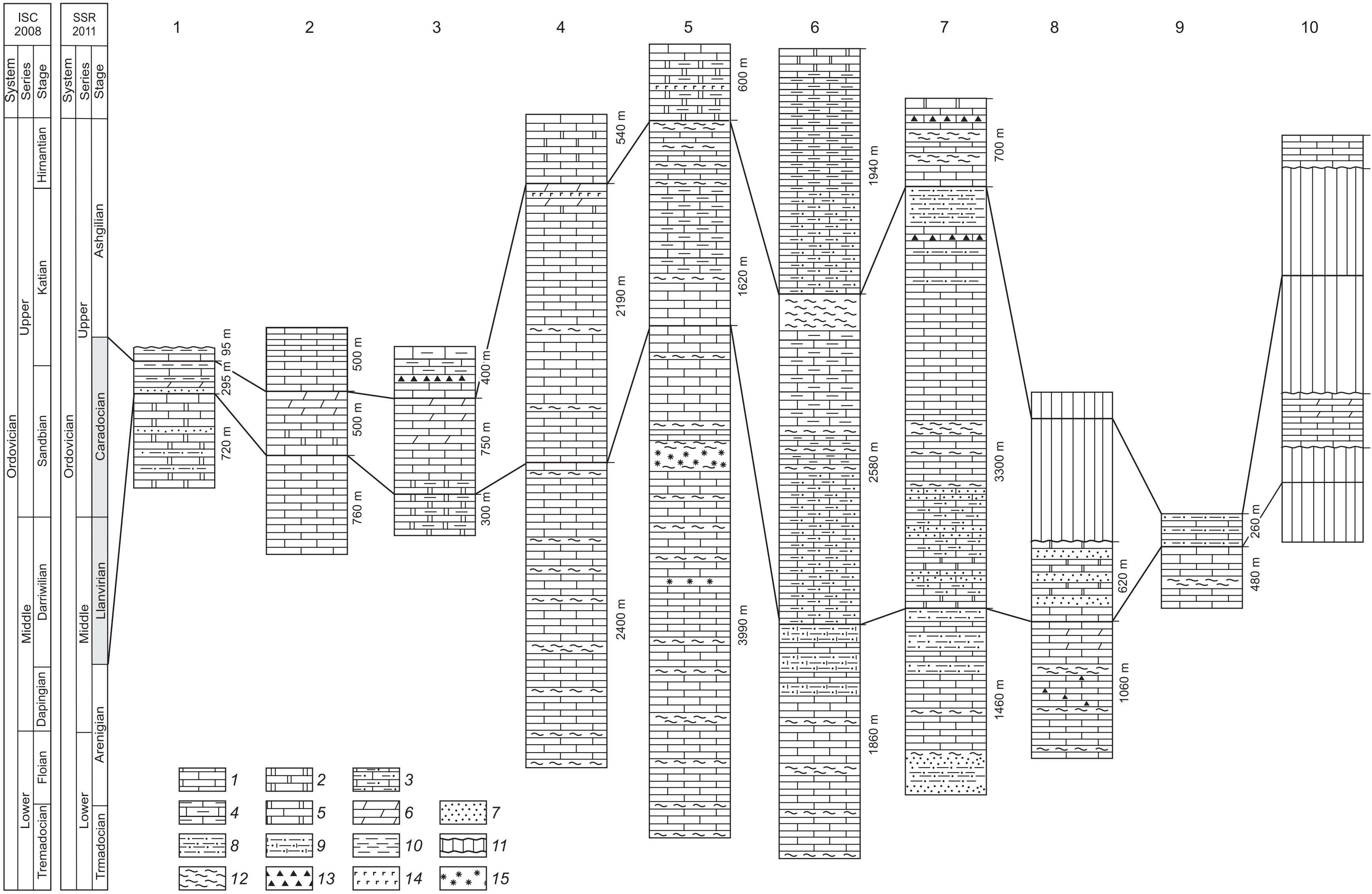

Fig. 1. Ordovician stratigraphic sections of the Siberian Platform (the reference section along the Kulyumbe River), the passive margin (Taimyr Peninsula and Sette-Daban Ranges), and the terranes. 1, Siberian Platform; 2, Taimyr Peninsula; 3, Kotel'nyi Island; 4, Sette-Daban Ranges; 5, Tas-Tayakhtakh; 6, Selennyakh Ranges; 7, Omulevka Uplift; 8, Omolon terrane; 9, Okhotsk terrane; 10, Chukotka Peninsula. Legend, see Fig. 3.

margin and in terranes) and their correlation with one of the most complete sections of the platform (the Kulyumbe Basin). The sea basin that extended across almost the entire platform (apart from the Anabar Shield and Yenisey Ridge) was represented by shallow-water facies dominated by carbonates. The bathymetric layout of the basin was determined by the configuration of inherited depressions, the Tunguska and Vilyui syneclises as well as the Yenisey–Khatanga and Fore-Verkhoyansk troughs. Within these depressions, the Ordovician is covered by younger strata and penetrated by boreholes along the flanks. Outside of the depressions, the Ordovician is covered by Quaternary deposits only and crops out in river valleys (Fig. 2). Locally the Ordovician is missing in Paleozoic stratigraphic successions; however, it is present as xenoliths in kimberlite pipes and contains well-preserved conodont fossils (Tarabukin et al., 1999).

At least 14 structural facies zone have been proposed in the regional stratigraphic scheme of the Siberian Platform (Kanygin et al., 2016). Figure 3 provides principal reference sections that characterise facies bathymetric differentiation of the basin. Correlation of the sections between the platform and the adjacent Verkhoyansk–Chukotka foldbelt and Arctic Ocean (Kotel'nyi Island) reveals marked differences in the thickness and composition of coeval strata reflecting disparate geodynamic conditions of sedimentation. On the platform, the sedimentary body was formed in a tectonic oscillation mode, with marked transgressive-regressive cyclicity (Kanygin et al., 2007; Dronov et al., 2009) so that carbonate deposition alternated with carbonate-siliciclastic deposition during regressive phases, with occasional exposition, evaporite and predominantly siliciclastic red-bed formation.

Deposition on the passive margin of the platform (Taimyr Peninsula and Sette-Daban Ranges) took place in a continuous subsidence mode (pericratonic subsidence), therefore the thickness of the coeval strata is many times greater than that of the platform. The strata are also different in composition represented on the passive margin by mostly monotonous limestones, with minor fine-grained material. This suggests a substantial distance from the source of terrigenous material in this facies zone. Deposition on the carbonate platform and in the Paleozoic terranes was characterised by an equilibrium between the subsidence and the sedimentation. Paleogeographic settings in this zone were stable during the entire Ordovician and corresponded to a subtidal bionomic zone. Composition of the faunal associations was similarly stable during the regressive-transgressive cycles. Paleogeographic settings in the interior parts of the basin, in contrast, differed significantly both laterally and in the stratigraphic succession of the transgressive and regressive phases in the basin evolution. In terms of bionomic types, they corresponded to subtidal, intertidal, and supratidal zones of the basin. In the light of marked variations in ecological conditions of the fauna, most of the taxonomic groups (brachiopods, trilobites, bryozoans, crinoids, etc.) were eliminated, whereas ostracod communities persisted although changed almost completely both in the taxonomic composition and in the ecotypes to comply with new conditions. The manifest distinction of the ecotype is best expressed in the Kirensk-Kudrino Regional Stage of the Siberian Platform (Kanygin, 1974). Despite the paleogeographic differences during the regressive phases, there is no evidence of any significant barriers to free dispersal of benthic fauna during transgressive phases because paleogeographic conditions appear to be uniform across the entire basin, with predominance of subtidal settings. As a result, the Ordovician strata can be reliably correlated across the

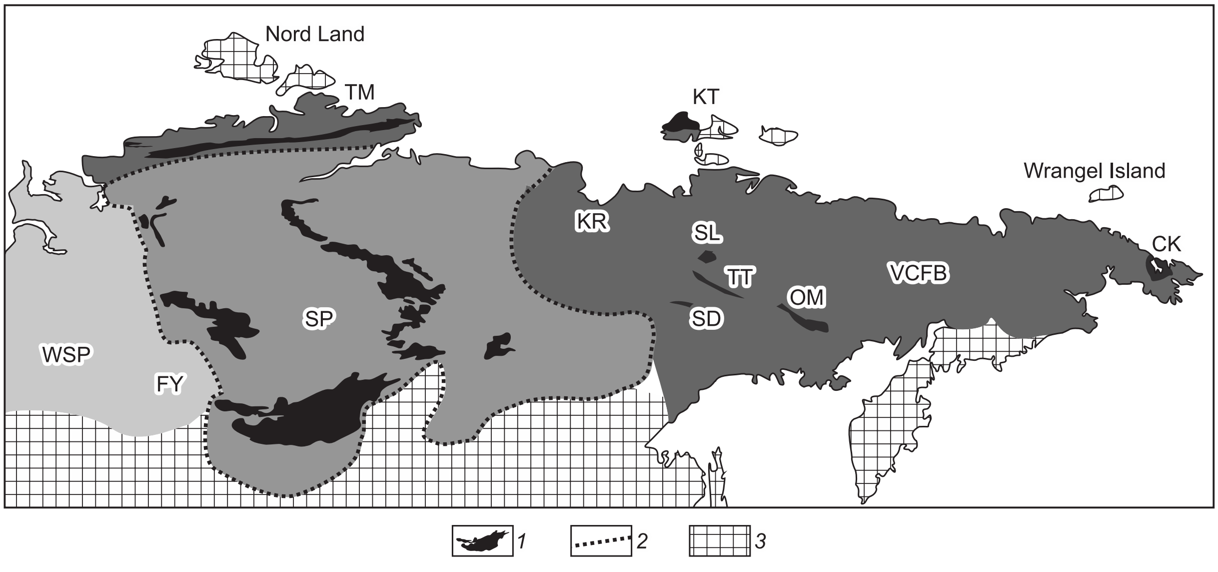

Fig. 2. Ordovician outcrops on the Siberian Platform and in the adjacent foldbelts. Abbreviations: TT, Tas-Tayakhtakh; OM, Omulevka Ranges; SL, Selennyakh Ranges; KR, Kharaulakh Ranges; CK, Chukotka Peninsula; TM, Taimyr foldbelt; KT, Kotel'nyi Island; VCFB, Verkhoyansk–Chukotka foldbelt; SP, Siberian Platform; WSP, West Siberian Plate; FY, Fore-Yenisey Sedimentary Basin.

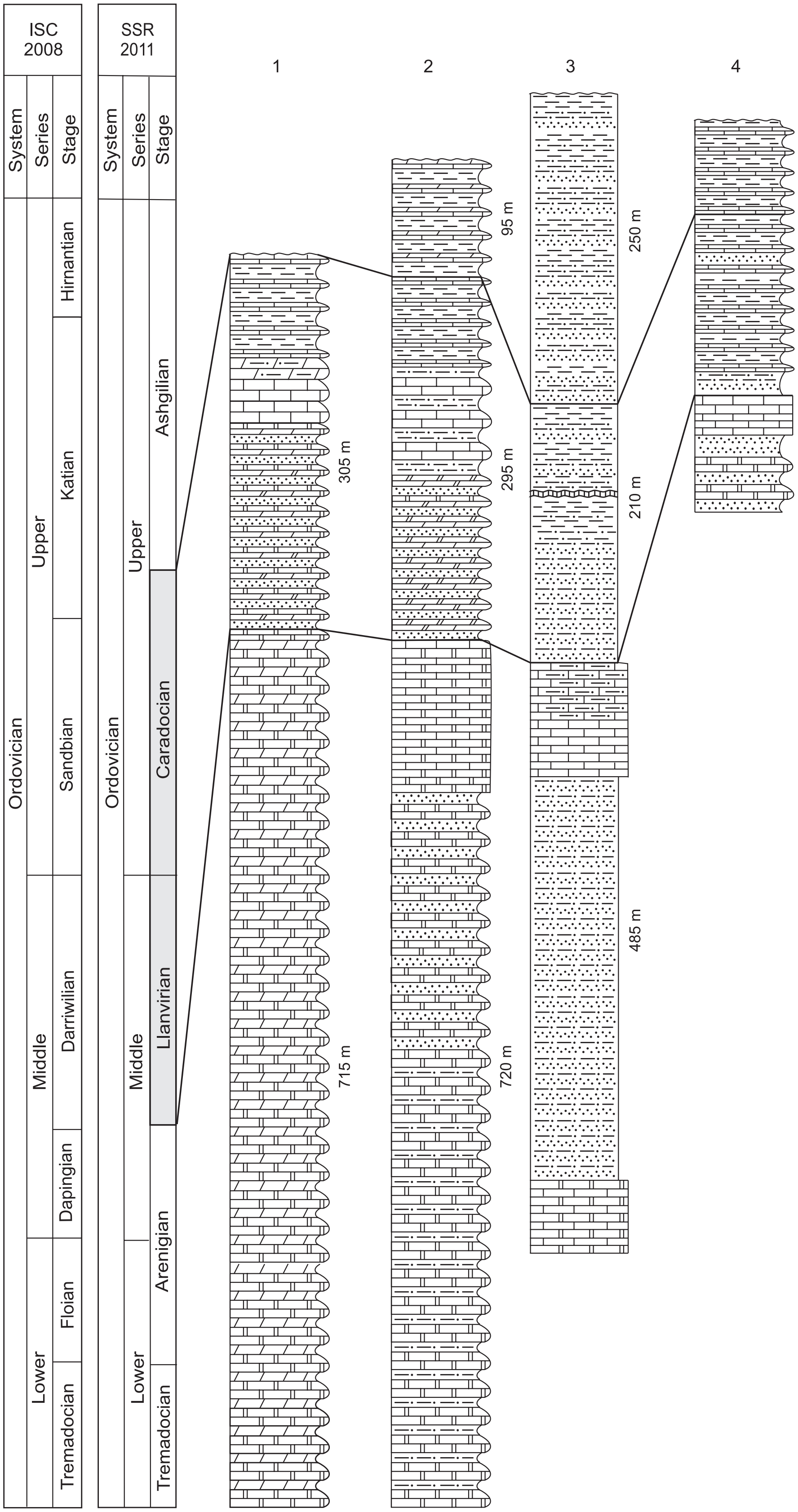

Fig. 3. Ordovician reference sections of different structural facies zones of the Siberian Platform. Legend: 1, Kulyumbe River; 2, Chiridinskaya 1 Borehole (Moyero Structural Facies Zone); 3, Angara River; 4, Gaindinskaya 3 Borehole (Southern Tunguska Structural Facies Zone).

entire platform and folded structures for this stratigraphic interval (Table 1).

All regions of the studied territory are characterised by benthic fauna (brachiopods, trilobites, ostracods, and to a lesser degree corals, bryozoans, crinoids, stromatoporoids) that has been featured in numerous summary reports on paleontology and stratigraphy of the Siberian Platform (Kanygin et al., 2007), Kotel'nyi Island (Nekhorosheva and Sobolevskaya, 2018), Taimyr Peninsula (Sobolevskaya, 2003), Verkhoyansk–Chukotka foldbelt (Balashov et al., 1968; Oradovskaya, 1988), as well as in a new edition of regional stratigraphic schemes for the Siberian Platform (Kanygin et al., 2017) and Taimyr Peninsula (Sobolevskaya and Nekhorosheva, 2016). The state of knowledge in paleontological information of specific regions of the Northeastern Asia has been summarised by Kanygin et al. (2019).

The isolation of the epicontinental sea basin of the Siberian Platform was isolated from other paleobasins in the Ordovician and Silurian had long been appreciated based on taxonomic studies of brachiopods and associated fauna (Nikiforova and Andreeva, 1961). The benthic fauna in this palaeobasin was shown to be highly endemic. Apart from the Siberian Platform, the identified Siberian paleobiogeographic province included the Taimyr Peninsula and Kotel'nyi Island, that by that time had yielded common brachiopod and bryozoan species. In the first paleogeographic scheme for the Ordovician of Northeastern Asia (Sokolov, 1960), the entire territory was shown as covered with a network of interconnected sea basins that were shallow-water in the platform part and relatively deep-water in place of the foldbelts. The platform and the foldbelts were geographically connected based on their relatively invariable position next to each other in the geological past, and on lithofacies similarity.

Palaeontological evidence for common paleogeography for the Siberian Platform and the Verkhoyansk–Chukotka paleobasins was collected following the discovery and study of the previously unknown Ordovician ostracod fauna of the Verkhoyansk–Chukotka foldbelt that allowed a correlation at composite stratotype level between the distant sections of the Sette-Daban, Selennyakh, and Omulevka ranges and of the Chukotka Peninsula (Kanygin, 1965, 1967, 1971, 1977), as well as establishing of stratigraphic markers for correlation between the Middle Ordovician of the Siberian Platform and the Verkhoyansk–Chukotka Foldbelt and with the Ordovician of the Standard Global Chronostratigraphic Chart based on ostracod and graptolite associations (Sidyachenko and Kanygin, 1965a,b). This conclusion was corroborated by data that accumulated during geological surveying starting from late 1950s on other massive faunal groups such as brachiopods, trilobites, bryozoans, corals, gastropods, crinoids, conodonts.

The current state of paleontological and stratigraphic knowledge on the Paleozoic of Northeastern Asia, specifically on the Middle–Upper Ordovician being the most reliable datum level, provides the ground for a paleobiogeographic demarcation for that period within the novel information and procedural framework. Sections of the Siberian Platform have been correlated with the Standard Global Chronostratigraphic Chart for the Ordovician based on paleontological and lithofacies data at a level of fractional stratigraphic units, the regional stages, as well as certain datum levels (Table 1). We conducted a classification of species composition for each of the benthic group, the ostracods, brachiopods, and trilobites, according to published sources and our records resulted from several years of field and laboratory work on sections of the Siberian Platform, Taimyr Peninsula, Sette-Daban, Selennyakh, and Omulevka ranges, Kotel'nyi Island and Chukotka Peninsula (Table 2). To date, as many as 260 ostracod species, 70 brachiopod species, and over 60 trilobite species have been described from the Middle and Upper Ordovician of these territories. All the ostracod species appear to be endemic; i.e. have never been accounted outside of this paleobasin. At least 90% of the brachiopod and trilobite species are endemic to this particular paleobasin.

Chorological analysis of the faunal associations have been conducted at a level of larger stratigraphic intervals; i.e., the Upper and Middles series of the Ordovician System when the general faunal characteristics are most profound. The structure and qualitative composition of ostracod, brachiopod, and trilobite species associations has been illustrated in a form of cyclograms (Fig. 4). The central ring of each cyclogram shows the total number of species, whereas the outer ring and the adjacent data chart depict the number of species shared with other regions shown to scale. The total number of species for the Siberian Platform has been given as a cumulative value because there has been a relative uniformity of species composition across different structural and facies regions; numbers along the lines connecting different regions of the studied territory correspond to the quantity of species shared between these regions. It is interesting that there is a pattern of same species dominance (occasionally represented by a counterpart species of the same genus representing a similar morphotype) for almost all of the discrete areas of the foldbelts and of the continuous areas of the Siberian Platform. A similarly broad distribution of same-type communities has been corroborated by the data from other benthic faunal groups (bryozoans, tabulate corals, rugose corals, crinoids) that are characterised by same species occurring both on the platform and in the adjacent folded regions. The uniformity of species composition across benthic biocoenoses within a large territory of the Northeastern Asia is here regarded as a chorological phenomenon. Today, biotopes of benthic faunal communities, specifically of small-sized organisms such as ostracods inhabiting relatively shallow-marine (both intertidal and subtidal) bionomic zones mostly have a mosaic topographic structure and are smaller in dimensions. The only modern analogue of benthic biocoenoses having similarly broad dispersal and uniform species composition would be the abyssal zone of the World Ocean. The uniformity of taxonomic composition of the fauna in this specific bionomic zone is

Table 1. Middle and Upper Ordovician correlation for the Siberian Platform and adjacent foldbelts

ISC 2008				Correlation of Ordovician deposits in Northeast Asia							
System	Series	Stage	Geochronological dating, Ma	Siberian Platform	Taimyr	North-East of Russia					
				horizon	horizon	horizon	Formations				
							Sette-Daban Range	Selennyakh Range	Kotel'nyi Island	Omulevka Range	Chukotka Peninsula
Ordovician	Upper	Himantian	445.2		**Barkova** Limestones are grey and dark-grey micro- to medium-grained and pelitomorphic, siliceous-clayey, carbonate-bearing-clayey slates and mudstones **30-600 m**	**Terekhtyakh**	**Baran'y Lobiki** Dominantly limestones, in the upper part dolomitized, with interlayers of calcaroues-clayey slates **270-550 m**	**Balgikakchan**	**Terekhtyakh** Limestones, pelitomorphic, clayey, organogenic-clastic Limestones interbedded with silica **230-400 m**	**Omuka** Dolomitic siltstones and marls Limestones, silty, interbedded with clayey-calcareous-silty slates Calcareous siltstones with interlayers of clayey limestones, silty-calcareous-clayey slates and tuffogenic sandstones **~ 300 m**	**Chrgitun** Bluish-grey platy limestone, black reefogenic limestones with silicified organogenic nodules **205-240 m**
		Katian	453.0	**Bur (br)** Interbedding of grey limestones and greenish-grey mudstones and siltstones **5-60 m**				**Sakyndzhe** Limestones, clayey, pelitomorphic Limestones, clayey, pelitomorphic, organogenic, silty **470-980 m**			
				Nirunda (nr) Red-colored mudstoness and siltstones **8-100 m**							
				Dolbor (dl) Grey-colored limestones, siltstones and marls **16,5-110 m**		**Padun**		**Nalchan** Limestones, pelitomorphic, interbedded with organogenic limestones and calcareous-clayey slates **190-220 m**			
		Sandbian	458.4	**Baksan (bk)** Rhythmic interbedding of green-colored mudstones and grey, sometimes lilac-grey organogenic limestones **14,5-210 m**	**Tolmacheva** Grey and greenish-grey limestones are clayey and dolomitized, with layers of multi-colored organogenic-clastic limestones, calcareous marls and mudstones **60-430 m**	**Kharkindzha**	**Gichinsky** Dolomites, marls, gypsum, tohopekaliga **120-140 m**	**Syachan** Interbedding of limestones and calcareous-clayey slates Slates, calcareous-clayey **180 m**	**Malodiring-Ayan** Limestones, clayey, pseudo-oolitic, organogenic-clastic, dolomitic marls Limestones and clayey limestones **500-750 m**	**Kharkindzha** Black clayey and calcareous-clayey slates with interlayers of sandy-clayey limestones **~ 300 m**	
				Chertovskoy (ch) Grey siltstones and mudstones interbedded with sandstones and organogenic clastic limestones **3-63 m**			**Kulon** Limestones are dark grey, flagged, dolomitized with rare layers of shale and organogenic limestones **~ 600 m**	**Kalychan** Limestones, dark -grey, pelitomorphic, clayey, less frequently organogenic-clastic **900-1250 m**			**Isseten** Yellowish-grey, undulating-layered organogenic limestones, pelitomorphic limestones, yellow flaggy marls Ash-grey massive dolomitized limestones and dolomites, dolomitic breccias **430-540 m**
	Middle	Darriwilian	467.3	**Kirensk-Kudrino (k-k)** Grey, greenish- and brownish-grey siltstones with limestones and marl concretions **0,6-210 m**	**Engelgard** Grey and dark-grey limestones with interlayers of clayey, dolomitized and organogenic-clastic and oolitic lithologies. **10-700 m**	**Lachug**	**Labystakh** Thin layering of limestones and lime-clay shales Pelitomorphic limestones are organogenic-clastic, silty, oolitic with layers of green clay shales **~ 1000 m**	**Volchiy** Calcareous-clayey slates, interbedded with clayey, organogenic-clastic limestones, marls and dolomites **350-400 m**		**Darpir** Limestones, massive, sandy-clayey, dominantly thin-platy in the upper part. **500-800 m**	
				Volgino (vl) Grey and variegated siltstones, mudstones, marls and limestines **1-80 m**						**Krivun** Dark-grey pelitomorphic clay and sandy limestones and calcareous-clay shales **600-750 m**	
				Muktei (mk) Rhythmic interbedding of thin-terrigenous and carbonate, often detritic rocks **1,5-60 m**	**Toll** Limestones, dark- and greenish-grey with interlayers of black carbon-bearing-clayey slates and lenses of breccia conglomerates Greenish-grey dolomitic marls interbedded with grey clayey limestones and black graptolitic slates **90-550 m**	**Elgenchak**		**Taryn-Yurakh** Limestones, silty, organogenic-clastic, with calcareous siltstone interlayers **500-750 m**	**Ayan** Clayey dolomites and dolomitic limestones **250-300 m**	**Uochak** Limestones, grey, sandy, with thin interlayers of calcareous-clayey and clayey slates **~ 1000 m**	
		Dapingian	470.0	**Vikhorev (vh)** Variegated, dominantly terrigenous sediments **5-200 m**		**Khiti**	**Sakyryr** Grey and dark grey siltstone limestones, with layers of clastic limestones **400-900 m**	**Unga** Interbedding of calcareous siltstone, mudstones and calcareous limestones **315-560 m**			
				Kimai (k)							

Table 2. Middle and Upper Ordovician dominant faunal groups on the Siberian Platform and in the adjacent foldbelts

Locations Species	Siberian Platform	Taimyr Peninsula	Selennyakh Range	Omulevka Range	Sette-Daban Range	Kotel'nyi Island	Chukotka Peninsula
Trilobites O_2							
Biolgina sibirica	▨	▨					
Prodalmanitina nikolaevi	▨		▨	▨			
Pseudomera weberi	▨	▨	▨	▨			
Omulovia mira	▨		▨	▨			
Ampyx borealicus	▨	▨					
Calliops armatus	▨	▨	▨				
Ceraurinella biformis	▨	▨					
Homotelus obtusus	▨	▨					
Lichas kuckersiana	▨	▨					
Lonchodomas parvulus	▨	▨					
Remopleurides loneicostatus	▨	▨					
Eorobergia bipunctata			▨	▨			
Carolinites sibiricus			▨	▨			
Pliomers ficheri asiatica			▨		▨		
Pliomerellus jacuticus			▨	▨			
Ceraurinus sp.			▨				▨
Illaenus sp.			▨		▨		▨
Ceraurinella frequens			▨	▨	▨		
Bathurellus nonnulus		▨		▨			
Apatokephalus globosus			▨	▨			
Pliomera fischeri asiatica			▨	▨			
Calyptaulax senior			▨	▨			
Trilobites O_3							
Isalaux bifolius	▨	▨					
Isalaux stricta	▨	▨				▨	
Ceraurinus icarus	▨	▨	▨		▨	▨	
Monorakos mutabilis	▨	▨	▨	▨			
Monorakos planiusculus	▨	▨					
Ceratevenkaspis armata	▨	▨					
Isotelus maximus sibiricus	▨	▨				▨	
Evenkaspis sibirica	▨	▨				▨	
Carinopyge ensifera	▨	▨					
Carinopyge spinifera	▨	▨					
Evenkaspis nikiforovae	▨	▨					
Evenkaspis tchunensis	▨					▨	
Monorakos magnus	▨	▨					
Ceratevenkaspis taymiricus	▨	▨					
Carinopyge abscisa	▨	▨					
Isotelus robustus	▨	▨					
Stenopareia avus	▨	▨					
Ceratevenkaspis parnaicus	▨	▨					
Biolgina maximovae			▨	▨			

(*continued on next page*)

Table 2 (*continued*)

Locations Species	Siberian Platform	Taimyr Peninsula	Selennyakh Range	Omulevka Range	Sette-Daban Range	Kotel'nyi Island	Chukotka Peninsula
Bathyurellus nordicus			▨	▨			
Monorakos consimilis	▨	▨					
Thaleops recctangularis			▨				
Calliops maximovae			▨		▨		
Illaenus sp.			▨		▨		▨
Ceraurinella frequens			▨	▨	▨		
Monorakos sp.					▨		▨
Calyptaulax aff. maximovae			▨				▨
Amphilichas cf. atarvus		▨		▨			
Bumastus sibiricus	▨	▨					
Evenkaspis galeata	▨	▨					
Brachiopods O_2							
Atelelasma pergrinum	▨	▨		▨			▨
Hesperorthis ignicula	▨		▨	▨			
Hesperorthis brachiophorus	▨			▨			▨
Sowerbiella negritus			▨	▨			
Evenkina anabarensis	▨	▨	▨		▨		
Platymena amara	▨	▨	▨	▨			▨
Strophomena simplex	▨			▨			
Multicostella maaki	▨	▨					
Cuparius ovalis				▨	▨		
Polytoechia russkaja			▨		▨		
Eremotoechia yasachnaensis				▨	▨		
Xenelasmella jacutensis			▨	▨	▨		
Brachiopods O_3							
Mimella panna	▨	▨	▨	▨	▨	▨	▨
Evenkina convexidorsata			▨		▨		
Atelelasma carinatum	▨	▨	▨			▨	▨
Triplesia sibirica	▨	▨	▨			▨	
Valcourea aff. transversa			▨	▨			
Rostricallula raymondi nana	▨		▨		▨		
Rostricellula transversa	▨	▨		▨		▨	▨
R. tumidula verchojanica			▨		▨		
Titanambonites planum			▨				
Leptellina carinata	▨	▨					
Glyptorthis pulchra	▨					▨	
Triplesia dolborica	▨	▨					
Oepikina kalytschanica			▨	▨	▨		▨
Oepikina tojoni	▨	▨					
Maakina parvuliformis	▨		▨			▨	
Rostricellula subrostrata	▨	▨			▨		
Hesperorthis austrlis	▨			▨			
Hesperorthis tricenaria	▨	▨			▨	▨	

(*continued on next page*)

Table 2 (*continued*)

Locations Species	Siberian Platform	Taimyr Peninsula	Selennyakh Range	Omulevka Range	Sette-Daban Range	Kotel'nyi Island	Chukotka Peninsula
Hesperorthis evenkiensis	▨	▨			▨		
Boreadorthis asiatica	▨	▨					
Strophomena lethea	▨	▨				▨	
Bellimurina paucicostata	▨	▨					
Oxoplecia asiatica	▨			▨			
Sowerbyella sladensis			▨	▨			
Ptychoglyptus bellarugosus			▨	▨			
Eospirigerina mavrae			▨		▨		
Triplesia protea				▨	▨		
Oepikina gibbosa	▨	▨				▨	
Evenkorhynchia tenuicostata	▨				▨		
Strophomena mangazeica	▨	▨					
Ostracods O_2							
Ginella primitiformis	▨				▨		
Hallatina chanae	▨				▨		
Egorovella (E.) defecta	▨		▨	▨			
Egorovella (E.) cuneata	▨		▨	▨			
Sibiritella rara	▨		▨	▨			
Primitiella parvula	▨			▨			
Bodenia longiscula	▨	▨					
Martinssonopsis multifaria	▨	▨			▨		
Coelochilina patibilis	▨	▨	▨				
Soanella maslovi	▨	▨	▨	▨			
Egorovellina operosa		▨	▨				
Egorovella (E.) captiosa		▨		▨	▨		
Egorovella (E.) alicostata			▨	▨			
Eochilina (E.) indistincta			▨	▨			
Eochilina (E.) proxima			▨	▨			
Ungiella lituata			▨	▨			
Ungiella tumida			▨	▨			
Leperditella anteritumida			▨	▨			
Leperditella symmetrica			▨	▨			
Eochilina (Sibirichilina) tubericostata			▨	▨			
Hallatina orlovi			▨	▨	▨		
Eochilina (E.) scrobiculata			▨		▨		
Sibiritella furcata			▨		▨		
Bolbinella lecta			▨		▨		
Cherskiella beyrichonica			▨		▨		
Egorovella (E.) ventrilobata			▨		▨		
Eochilina (E.) elata			▨		▨		
Hallatina dentata	▨		▨	▨	▨		
Scutumella caliginosa	▨		▨	▨			
Sibiritella costata	▨		▨	▨			

(*continued on next page*)

Table 2 (*continued*)

Locations Species	Siberian Platform	Taimyr Peninsula	Selennyakh Range	Omulevka Range	Sette-Daban Range	Kotel’nyi Island	Chukotka Peninsula
Ostracods O_3							
Eochilina (E.) tumefacta	■						
Aparchitella procera	■						
Dogoriella sulcata	■						■
Sigmobolbina bucera	■						■
Tsitrites gloriosus	■		■				
Bodenia remota	■		■				
Coelochilina formosa	■		■				■
Egorovella (E.) captiosa	■	■	■		■		■
Egorovella (E.) admirabilis	■	■	■		■		
Bolbinella cumulata	■	■			■	■	■
Coelochilina laccochilinoides	■	■	■		■	■	■
Martinssonopsis multifaria	■	■	■		■	■	■
Bodenia aspera	■	■			■	■	
Eochilina (E.) convexa	■	■	■		■	■	
Soanella ampla	■	■	■			■	
Coelochilina modesta	■	■	■			■	
Jonesites confusus	■	■				■	
Jonesites obliquus	■	■				■	
Parajonesites notabilis	■	■				■	
Paraschmidtella bipunctata	■	■				■	
Planusella bicornis	■	■				■	
Aparchitella magna	■	■				■	
Aechminia subcuspidata	■	■					
Dolborella coalita	■	■					
Tergumella angulata			■		■		
Cherskiella bigibba				■	■		
Cherskiella inflata				■	■		
Fuscinulina pectinata				■	■		
Coelochilina sibirica	■					■	
Euprimitia helenae	■					■	
Grammolomatella valdari	■					■	
Reticulochilina dedalea	■					■	
Sobolitella rimmae	■					■	
Bodenia longiscula		■	■		■		■
Chegetella chegitunica		■					■
Coelochilina aculeata		■			■	■	
Coelochilina patibilis		■				■	
Egorovella (E.) dorsilobata		■	■			■	■
Hesslandella irinae		■				■	
Grammolomatella mesosibirica	■	■					
Pentagonochilina marinae	■	■					
Primitia perpusila	■	■					

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Table 2 (*continued*)

Locations Species	Siberian Platform	Taimyr Peninsula	Selennyakh Range	Omulevka Range	Sette-Daban Range	Kotel'nyi Island	Chukotka Peninsula
Pseudoplanusella tricornuta	■	■					
Coelochilina camptotropa	■					■	
Hesslandites ventritumidus		■	■		■	■	
Insolitella insolita		■				■	
Coelochilina plana						■	■
Eochilina (E.) obtusa						■	■
Tvaerenella clivosa			■		■	■	■
Coelochilina grumosa			■				■
Coelochilina magnifica			■				■
Egorovella (E.) parva			■				■
Hallatina chanae			■		■		■
Levisulculus ornatus					■		■

explained by the relatively low biodiversity, the absence of competition for the living space and nutrient resources, the stability of physical, chemical and coenotic conditions, and the uniformity of the trophic base. The globally distributed benthic ostracod species, when the range of a species (or a group of closely related species) is almost identical to the area of an ocean, serve as an illustrative example (Benson, 1975).

The free dispersal of same-type benthic fauna associations across the large area of Ordovician waters corresponding to the neritic zone is here explained as a combination of three factors (Kanygin, 2001, 2008; Kanygin et al., 2018): (1) the global expansion of pioneer taxonomic groups (i.e., ostracods, brachiopods) with novel ecological specialisations and adaptive resources; (2) the incipient stage of biotic barrier formation by sessile organisms such as corals, bryozoans, stromatoporoids, crinoids (i.e., living space fragmentation by biohermal buildups); and (3) the absence of physical geographic barriers between the Siberian Platform, the pericratonic periphery, and the terranes. The latter factor is of paramount importance for determining the real boundaries of the Siberian epicontinental basin that in the Paleozoic excluded the modern-day territory of the Paleozoic terrane distribution.

In terms of ecological space, the Ordovician benthic zone included only the shallow epicontinental marine realm that reached its maximum area over the entire Phanerozoic history (Ronov, 1993; Morrow et al., 1996). Deeper waters were anoxic and therefore prevented dispersal of the benthos. This stage of marine ecosystem evolution was accompanied by a predominantly autochthonous taxonomic composition of the biochores of epicontinental sea basins at species and genus level. Among the faunal groups, ostracods were thought to have achieved the highest numerical abundance, morphological disparity, taxonomic diversity, population densities, and levels of ecological specialisation. The Middle Ordovician explosion of ostracod diversity (along with other pioneer groups of filter-feeding organisms such as corals, bryozoans, crinoids, stromatoporoids, and new orders of inarticulate brachiopods) defines the start of a new stage in marine ecosystem evolution characterised by an increase in the rate of competition for nutrient resources and living space. As small-sized organisms with various nutritional adaptations and finely subdivided ecological niches, the ostracods could link together different food chains and ensure the level of biodiversity exceeding that of macrofauna. This can be exemplified by Lake Baikal where over 200 ostracod species coexist in adjacent environmentally similar habitats, with little if any spatial isolation, due to specialised feeding systems (Mazepova, 1990).

Ostracods are unique in terms of taphonomy. Their calcareous or chitinous valves having complex ultrastructure can be well preserved in carbonates and carbonate-cemented siliciclastic rocks. Due to their relatively short life cycle involving 8–9 periods of shedding, ostracods have both adult and juvenile exoskeleton (except for weakly calcified larval valves) preserved in taphocoenoses. The age structure of the ostracod fossil assemblages suggests high population densities in biocoenoses and an autochthonous preservation in taphocoenoses allowing ontogenetic and phylogenetic reconstructions for each species (Fig. 5).

A phylogenetic tree of the endemic family Cherskiellidae (Kanygin, 1967) is represented by inadaptive forms (Fig. 6); i.e., their valves possess characteristic morphological features that are manifested in a reduced form and often disappear in successive evolutionary lineages. Shvarts (1980) referred to such taxa as evolutionary monsters; we prefer the term "evolutionary ephemerae" because these species appear early in the evolution of a particular group and quickly become extinct. The most archaic members of the family Cherskiellidae represented by the genus *Cherskiella* emerged at the end of the Early Ordovician, but became dominant taxa only by the Middle Ordovician. Due to their clear diag-

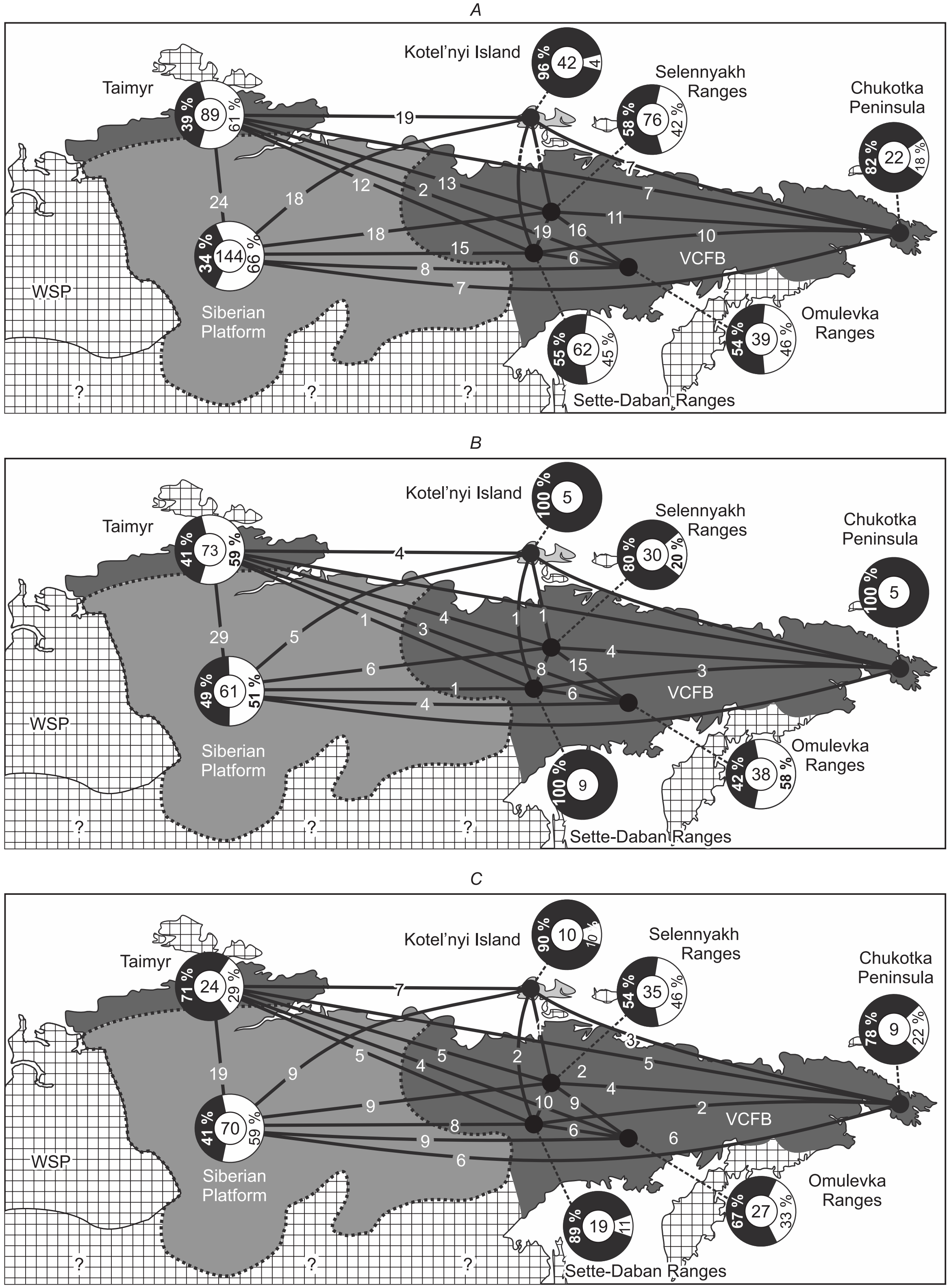

Fig. 4. Quantitative composition, structure, and distribution of species associations within the dominant Ordovician faunal groups of the Siberian Platform. *A*, Ostracods, *B*, Trilobites, *C*, Brachiopods.
The central ring of each cyclogram shows the total number of species, whereas the outer ring depicts, in percentage terms, the number of local species shared with other regions of the Siberian Province (right); numbers along the lines connecting different regions of the studied territory correspond to quantity of species shared between these regions.

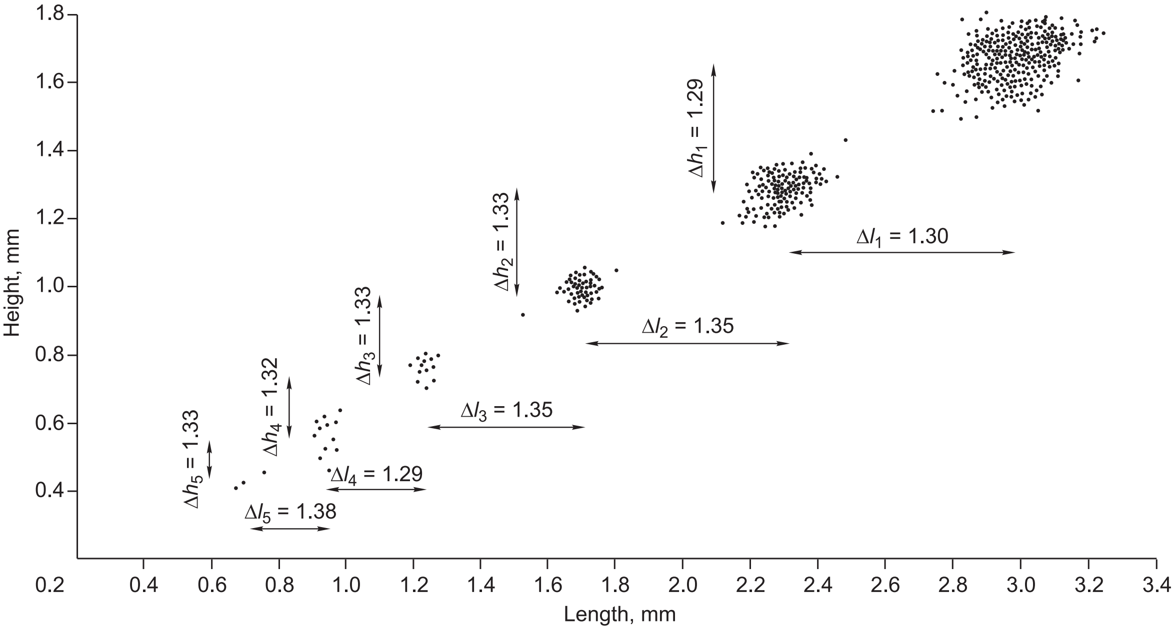

Fig. 5. Age structure of the Egorovella dorsilobata population from an autochthonous taphocoenosis (Kolychan Formation of the Selennyakh Range). Δl_1, Δl_2, Δl_1, Δl_3, Δl_4, and Δl_5 refer to elongation factor; Δh_1, Δh_2, Δh_1, Δh_3, Δh_4, and Δh_5 refer to elevation factor of the shell in ontogeny (Kanygin, 1967).

nostic characters, diversity at species level, and ubiquitous distribution, this family has been a reliable chronostratigraphic marker and an indicator of intra- and interregional paleobiogeographic links. An autochthonous origin of this family is an important additional argument in favour of the common origin of the Paleozoic terranes in the same epicontinental sea basin of the Siberian palaeocontinent.

To summarise, the paleontological data establish an isolation of the Siberian epicontinental paleobasin during the Paleozoic from other paleobasins by deep waters (oceanic basins). In addition, the paleontological data can be used to estimate the relative position of the Siberian paleocontinent and correct for the contradictory paleomagnetic data. Several authors recognised close paleobiogeographic links between the Northeastern Asia and Alaska as well as other regions of North America mostly at a level of high-rank taxa, but partially based on distribution of certain species and genera (Chugaeva, 1973; Rozman, 1977; Oradovskaya,

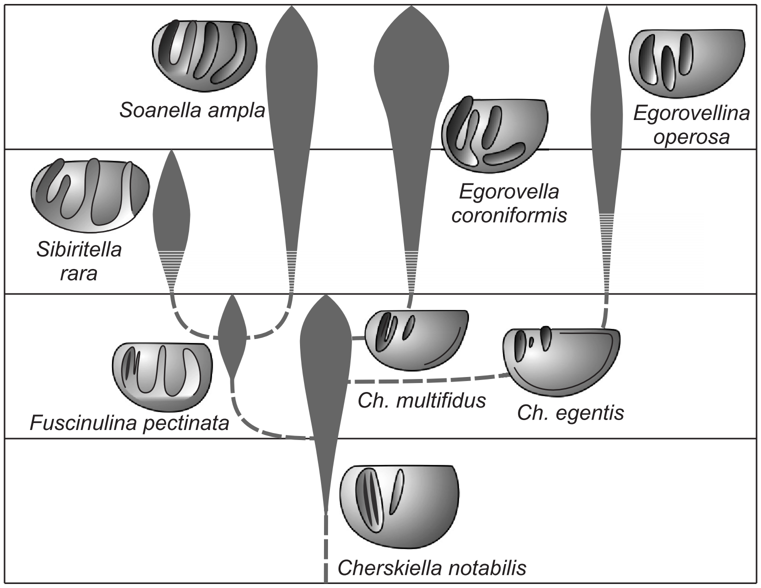

Fig. 6. Genetic links between species of the genera of the Cherskiellidae Family. Legend: 1, Cherskiella notabilis; 2, Cherskiella multifidus; 3, Cherskiella egentis; 4, Egorovella corniformis; 5, Egorovella operose; 6, Fucsinulina pectinate; 7, Sibiritella rara; 8, Soanella ampla (Kanygin, 1967).

1988; Blodgett, 1998; Cocks and Torsvik, 2007; Blodget et al., 2010; Torsvik and Cocks, 2017). Comparative taxonomic analysis of the Ordovician dominant faunal groups (brachiopods, trilobites, ostracods, and conodonts) revealed no common species and genera between Siberia and Balto-Scandia, whereas the common families all have different stratigraphic ranges. The two regions, nevertheless, are characterised by almost identical patterns of biodiversity changes and transgression-regression cycles reflecting eustatic variations (Fig. 7). The Baltic paleocontinent therefore was located relatively far from the Siberian paleocontinent compared to North America (Dronov et al., 2009; Kanygin et al., 2010).

CHOROLOGY AND TAPHOCOENOSES OF THE PLANKTON FAUNA: PALEONTOLOGICAL AND SEDIMENTOLOGICAL EVIDENCE OF THE RIFT BREAKUP OF SIBERIAN PALEOCONTINENT

Data on the age and distribution of graptolite shales can be important diagnostic proxies for deep-water depositional environments and for paleogeographic reconstructions. The Ordovician witnessed the evolution of first Phanerozoic-style zoopelagic system due to a massive appearance of the specialised plankton (chitinozoans, graptolites, radiolarians), a manifold expansion of the meroplankton (larval stages of benthic organisms), and an explosive biodiversification of nektonic organisms (conodonts, nautiloids). The available reconstructions suggest that the living space of these organisms was restricted to the epipelagic zone because of the anoxic conditions at deeper levels. Although graptolites were one of the most abundant group of nektonic organisms, they are extremely rare in shallow-water facies because of their poor fossilisation potential due to rigidity of their chitinous skeleton; therefore fossil graptolites are usually found in deep-water sediments subject to little if any bioturbation and hydrodynamic wave activity.

A deep-water origin of the graptolite shales in the Verkhoyansk–Chukotka foldbelt has been demonstrated by a comparison between the thickness of graptolitic black shales associated with deep fault zones and the thickness of carbonate facies hosting benthic fossil faunas (Kanygin, 1973) (Fig. 8). Additional evidence has been provided by vesicles in occasional trachybasalts interstratified with the graptolitic shales (Merzlyakov and Lychagin, 1973). Graptolitic shales cropping out in the Paleozoic terranes of the Omulevka Ranges, the pre-Kolyma area, and the Selennyakh Ranges mark rift zones that can be traced in complex folded structures based on diagnostic lithofacies.

Comparative lithological studies of the Ordovician strata in the east of Siberian Platform and all the major blocks of the Verkhoyansk–Chukotka foldbelt (except for Chukotka) has resulted in a detailed description of the lithofacies and reconstructions of the palaeobathymetry (Bulgakova, 1986). The territory of the Verkhoyansk–Chukotka foldbelt was characterised as an extended shelf of the Siberian Platform "dissected by deep narrow steep-flanked trough basins" referred to as grabens (Bulgakova, 1986). These structures were regarded as precursors of post-Paleozoic synclinoriums developed following a shift from a platform to a geosyncline tectonic regime. The depth of these troughs was estimated based on reference bathymetric marks defined by variation in the ratio of carbonate and terrigenous content in the sediment by analogy with modern oceanic sediments. The carbonate deformation zone is thought to correspond to the depth of 3.5–5.0 km; the carbonate dissolution zone is thought to be restricted to the depth of 4.5–5.0 km (carbonate compensation depth). These reference marks are only a relative, not a direct estimate of the water depth in the troughs (Bulgakova, 1986); nevertheless, the lithofacies, the associated zooplankton taphocoenoses, and the sedimentation patterns all argue for deep-water settings. The maximum water depth in these troughs is estimated to be at least 2000 m based on three independent proxies.

These troughs are infilled with predominantly terrigenous rocks of variable granulometric composition (shales and siltstones, occasionally with sandstone, gravelstone and rare gravelstone/conglomerate interbeds) and carbonate content (in a form of calcareous cement or carbonate interbeds), quite unlike the adjacent predominantly carbonate shallow marine facies zones. The terrigenous strata are characterised by high content of clay minerals and carbonaceous matter, are often pyritised, and appear to be significantly condensed compared to carbonate facies. In addition, the terrigenous strata host volcanic tuffs, tuffites, and tephroids of homogenous trachybasalt and trachyandesite composition, with interbeds of coarse grained volcanogenic material such as bombs, lapilli, scoria, and glass fragments. Some of the outcrops of these Ordovician and Devonian morphostructures yielded trachybasalt and trachyandesite lavas with evidence of subaqueous eruption (Merzlyakov and Lychagin, 1973; Lychagin et al., 1989; Karyakin et al., 2000). Structural features in the rocks suggest a slope gradient. The clastic material was deposited from suspension and as fine particle fallout, as well as rock fall, subaqueous slumps, and turbidity flows; as a result, along with graded rhythmites, the successions include olistoliths, roll-up structures, microfolded intervals, mixtites and other gravity-induced displaced lithified sediments both as interbeds and packages. These structures suggest a seismic activity and an increasing gravity load in stratified complexes leading to slope failure and dislocation down the slope. For this reason the sedimentary successions in addition to planktonic fauna yielded shelly fossils from adjacent shallow-marine biofacies. It is a specific type of marine taphocoenoses that can form only in deep-water settings. Furthermore, Bulgakova (1986) mentions a co-occurrence of graptolites and radiolarians; these are condensed shales representing extremely low rates of sedimentation away from the sources of terrigenous materi-

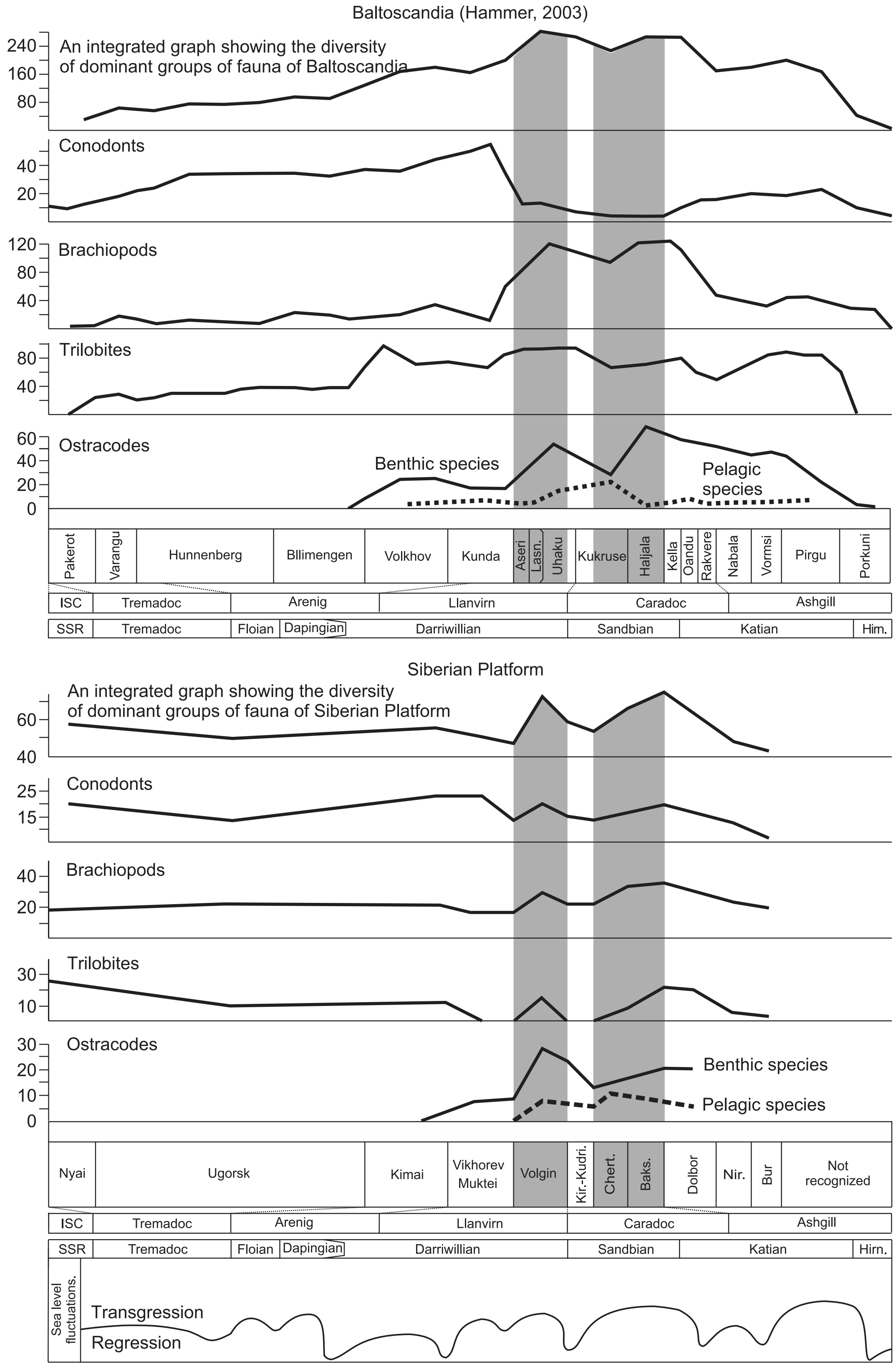

Fig. 7. Comparison between diversity graphs of dominant faunal groups for the Siberia and Baltica paleocontinents (Dronov et al., 2009).

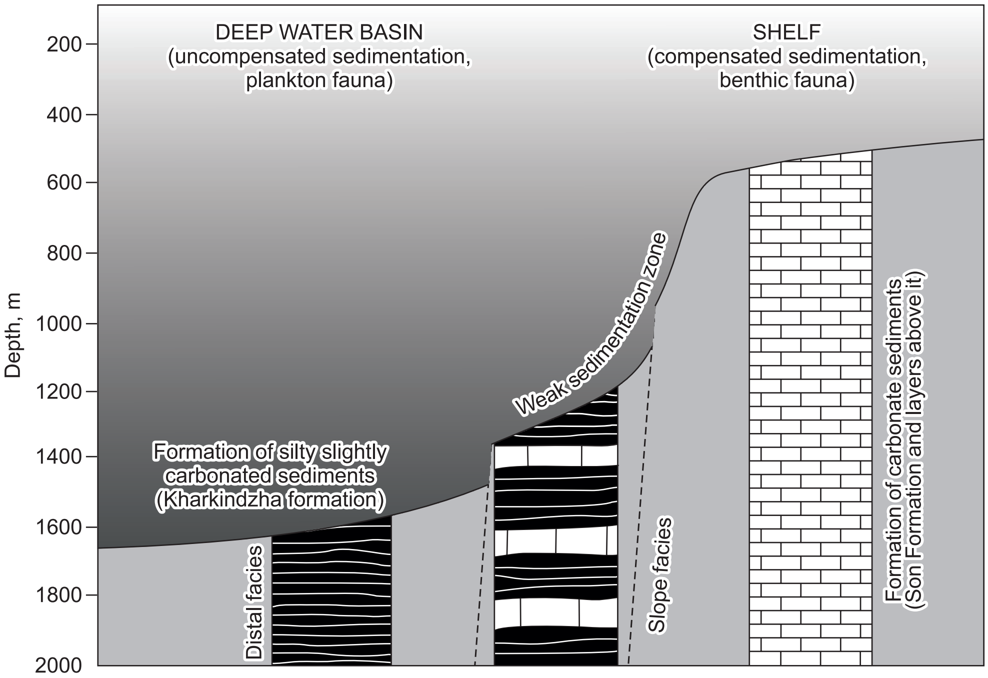

Fig. 8. Bathymetric profile along the transition from shallow marine carbonate facies to deep-water terrigenous facies (Omulevka Range, Kharkandzha River Basin) (Kanygin, 1973).

al. The concentration of radiolarian tests can reach rock-forming quantities leading to deposition of radiolarian cherts; however, poor preservation precludes the use of radiolarians in stratigraphy.

The graptolite-radiolarian taphocoenoses in association with certain lithofacies serve as a reliable proxy of rift-related zones in complex Paleozoic fold-and-thrust blocks. Graptolites mark the onset of rifting and the beginning of deposition of the terrigenous successions hosting the fossil plankton. The oldest fossil graptolites in the studied sections in the Omulevka and Selennyakh Ranges and in the Polovinny Kamen, pre-Kolyma area are Late Arenigian in age after the British Ordovician standard scale (Sobolevskaya, 1970; Obut and Sobolevskaya, 1972), and correspond to the Dapingian Stage in the Standard Global Chronostratigraphic Scale. Biofacies of the rift zones yielded abundant graptolite associations suggesting correlation with lowermost the Middle Ordovician to the lower Silurian.

The second phase of the rifting is best manifested in the Middle Devonian (Bulgakova and Kolodeznikov, 1990; Parfenov and Prokopiev, 1993). It was comprehensively studied in the Sette-Daban and Selennyakh Ranges (Levashov, 1974) where the rift structure is morphologically well expressed and contains a characteristic conodont biofacies of Famennian–Tournaisian age (Karyakin et al., 2000). In terms of the terrigenous volcanic composition, the stratification of packages with contrasting granulometric characteristics and carbonate content, as well the structural features these rocks are indistinguishable from the Ordovician and Silurian rift-related lithofacies. The volcanics of the Selennyakh Rift are referred to as a differentiated basalt series based on petrochemical analyses. Their geochemical speciation corresponds to a continental tholeiitic series suggesting a continental crust rifting. The widespread late Paleozoic rifting in the Verkhoyansk–Chukotka foldbelt resulted in the breakup of the eastern margin of the Siberian Craton and opening of the Oimyakon Ocean (Parfenov, 1995).

The evidence for two phases of rifting in the Paleozoic blocks surrounded by Mesozoic formations of the Verkhoyansk–Chukotka foldbelt is a compelling argument for a protracted crustal stretching associated with the breakup and fragmentation of the Siberian paleocontinental margin. In terms of geosyncline concept, the deep-water terrigenous and volcanic facies were interpreted as a eugeocyncline affected by vertical crust movements (Shilo et al., 1973; Merzlyakov, 1986). The available geological data suggest that the separated fragments migrated a different distance from the paleocontinent pericratonic margin.

Geological data suggesting the common origin of the terranes within the Siberian paleocontinent, the breakup of the passive margin, and the separation of the fragments will be dealt with in our second contribution.

CONCLUSION

Paleontological, stratigraphic, and sedimentological data all suggest that the patchwork of Paleozoic terranes separated from the Siberian Platform and surrounded by Mesozoic and Cenozoic formations of the Verkhoyansk–Chukotka foldbelt originally composed the passive margin of the platform. This conclusion is in conflict with the available palinspastic reconstructions based on paleomagnetic data. Furthermore, the existence of an Ordovician composite paleocontinent, the Siberia–Arctida–Baltica agglomerate has been suggested by detrital zircon spectra (Shatsillo et al., 2017); however, the chorology of the fauna and the comparison of the biota between the Siberian and Baltoscanian epeiric marine basins rule out the existence of such a supercontinent. By the same token, a North American (Fujita, 1978), Australian (Zonenshain et al., 1990), or Sino-Korean (Bulin, 1989) origin of these terranes can also be excluded. Palinspastic reconstructions depicting wandering Paleozoic terranes spatially isolated from the Siberian paleocontinent, are also not in line with the paleontological data. In our second contribution, we discuss the geodynamic history of the Siberian palaeocontinent passive margin taking into account the origin of Paleozoic terranes and the synchroneity in their development up until the late Paleozoic.

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