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The Origin of Paleozoic Terranes in Northeastern Asia: Geologic Evidence for Rifting of the Pericratonic Margin of the Siberian Paleocontinent and for Migration of Its Fragments

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Abstract—The paper provides an insight into the geodynamic history of the Northeast Asian terranes during the Paleozoic, focused on the stratigraphic, paleontological, and sedimentological data indicating that the Precambrian structures of early–middle Paleozoic age were originally part of the passive margin of the Siberian paleocontinent. The geological and paleontological data presented in the foregoing studies have shown the inherited geodynamic regime and synchronous sedimentation and magmatism on the passive continental margin and in most terranes before their separation from the Siberian paleocontinent in the late Paleozoic. The revealed significant differences in evolution between the Okhotsk and Omolon and other terranes give grounds to postulate that they rifted off the paleocontinent even earlier.

Keywords: orogenic belt; terranes; Paleozoic; tectonics; geodynamics; sedimentology; paleogeography; stratigraphy; northeastern Asia; Siberian paleocontinent

INTRODUCTION

This paper is an extension of the previous study of the authors (Kanygin et al., 2020), in which they provided paleontologic, sedimentologic, and stratigraphic evidence for the Paleozoic terranes of the Siberian paleocontinent (now geographically dispersed among the Mesozoic and Cenozoic tectonic blocks) as those that used to be parts of its passive margin located in the place of the present-day foldbelt. It was shown that subsequently the Paleozoic passive margin experienced breakup induced by rift development, triggering thereby the migration of its blocks to different locations. The research was focused on the Ordovician paleobiogeography of the area, inasmuch as the coeval deposits are most fully represented both in the platform and Paleozoic foldbelts. The well-studied major fauna groups from these sections allowed using the chorological analysis as the most effective method for paleogeographical reconstructions of the Siberian Platform foldbelts, which enabled identification of the spatial position evolution of its tectonic blocks (terranes) (Kanygin et al., 2019a,b). The previewed available geological data for the entire Paleozoic Era confirm that the early and middle Paleozoic epicontinental marine basins of the Siberian paleocontinent evolved together with its passive margin through the Paleozoic.

The present study specifically explored geologic data indicative of the Paleozoic geodynamic history of the Siberian Platform foldbelt terranes, particularizing different stages of their evolution in the early to middle Paleozoic tectonic framework of northeastern Asia. Apart from comparing the methods and results of palinspastic and paleogeographic reconstructions, the closing part of the paper discusses methodological problems of paleogeographic research stemming from the paradigm shift from fixism to mobilism.

BOUNDARIES OF THE SIBERIAN PALEOCONTINENT: THE PROBLEM OF GENETIC LINKS BETWEEN THE PLATFORM AND PALEOZOIC FOLDBELTS

Modeling of a possible genetic link between the Paleozoic terranes and the Siberian Platform, as well as changes in their spatial position through time, requires, in the first place, determining the boundaries of the Siberian paleocontinent in the Paleozoic Era.

Although the terms "platform", "craton", and "continent" (more precisely, "paleocontinent") are generally recognized as synonymous in modern paleotectonic and paleogeographic reconstructions, the approaches used for determinations of their boundaries may differ for different development

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stages. In its modern tectonic framework, the Siberian Platform is bounded by mixed-age foldbelts, in the place of which its late Precambrian and Paleozoic passive margins were located (Kosygin and Luchitskii, 1960; Parfenov and Prokopiev, 1993). The terms "pericratonic margin", or "miogeosynclinal margin", are commonly cited as equivalents for a passive margin (in respect to "craton"), and "shelf" for the concept of "continent (paleocontinent)". The craton (paleocontinent) boundaries are thus determined by the external constraints of these structures.

Kosygin et al. (1964) identified the North Asian craton within the Proterozoic boundaries, which in some works is recognized as a synonym for the Siberian Platform. However, these authors included two megastructures within its framework: the Siberian Platform itself and the present-day territory of the Verkhoyansk–Chukotka Foldbelt, which was interpreted as a system of uplifts and troughs of a subplatform or parageosyncline type.

Within the modern framework, the passive margin of the Siberian Platform (paleocontinent) appears in reduced dimensions and deformed by the folding and faulting processes driven by the post-Paleozoic tectonogenesis. Neoproterozoic and Paleozoic sediment records have been best preserved in the Sette-Daban Ridge and on the Taimyr Peninsula. The Sette-Daban Range area, which is presently a horst-anticlinal structure, has always been viewed as a marginal part of the Siberian paleobasin within the Siberian Platform. Integration of the Sette-Daban pericratonal sector into the intracratonic part of the Siberian Platform is marked by the Nel'kan–Kylakh tectonic suture, superposed by the folded framework of the horst-anticlinorium thrusting over the intracratonic part of the platform. The block structures descend stepwise eastward, toward the Mesozoides (Yanzhin-shin, 1983).

The Taimyr Foldbelt is separated from the rest of the Siberian Platform by the Yenisei–Khatanga trough along the junction zone (between the intra- and pericratonic parts of the platform) buried under a thick Mesozoic–Cenozoic sequences. The Paleozoic sedimentary sequences of the Taimyr Peninsula are divided into three structural–facies zones oriented roughly west–east, which are the most pronounced in the Ordovician and Silurian: southern (carbonate with benthic fauna), transitional, or mixed (mixed carbonate–siliciclastic sediments with benthic and planktonic fauna), and northern (mostly siliciclastic rocks with graptolites) (Sobolevskaya and Nekhorosheva, 2016a,b). The cross-section of these structural–facies zones exhibits facies change from the shelf with carbonate depositional environments through the transient zone into the proto-oceanic continental slope. As such, the successive order of biofacies indicates that the ocean–continent transition zones inheritably persisted throughout the Paleozoic Era (Pogrebitsky, 1971; Sobolevskaya and Kaban'kov, 2014; Sobolevskaya and Nekhorosheva, 2016a,b), which contradicts earlier results of the palinspastic reconstructions interpreting these structural–facies zones of Taimyr, together with the territory of the Severnaya Zemlya archipelago, as independent wandering terranes (Kara microcontinent) accreted to the Siberian continental margin only at the end of the Paleozoic (Zonenshain et al., 1990; Vernikovsky, 1996; Metelkin et al., 2005, 2015; Vernikovsky et al., 2013).

According to results of the earlier identifications (based on the geophysical survey conducted in the 1980s) of almost nondislocated Paleozoic sedimentary successions of platform affinity in the Fore-Yenisei sedimentary basin of the West Siberian geosyneclise (plate), the western boundary of the Siberian Platform was delineated along the transregional Yenisei fault. During the last few decades, the seismic reflection profiling has been focused on a series of sublatitudinal intersections of the territories adjacent to the Siberian Platform and the southwestern part of the syneclise drilled by four parametric wells. According to results of the comprehensive analysis of these data, the sediments proved to be of Vendian and Cambrian age, which was inferred from the commonality of paleogeographic environments and identical fauna and lithofacies throughout the whole profile. The established thickness gradient for coeval sediments at the fault boundary between the outcrop and buried successions of the platform is characteristic of pericratonal subsidence (Kontorovich et al., 1999; Filippov et al., 2014; Grazhdankin et al., 2015; Filippov, 2017).

The ancient Proterozoic to early Paleozoic orogens rimming the Siberian Platform along its southern, southeastern, and southwestern boundaries dramatically altered the pericratonal zone of the platform. Gordienko (2006) showed that the foldbelts of the platform are complex intracratonic assemblages composed of a collage of terranes genetically related to the cratons, island arcs, active continental margins, turbidite basins, and continental slopes, albeit not time-correlative.

In revealing relationships between Paleozoic terranes and the Siberian Platform, the pivotal role is played by the reconstruction of the junction zone with the Mesozoic Verkhoyansk–Chukotka Foldbelt, which is currently buried under the Verkhoyansk fold–thrust complex.

Parfenov and Prokopiev (1993) conducted an in-depth analysis of the data on the geologic structure of the Verkhoyansk fold–thrust system and adjacent territories of the platform, along with the Mesozoides of the Verkhoyansk–Chukotka Foldbelt. According to these authors, a passive margin of the platform that had existed since the late Precambrian in place of the Verkhoyansk fold–thrust system was significantly modified by the Middle–Late Devonian rifting processes. To give a more accurate representation of the fold geometry, they compiled structural profiles and reconstructed down-plunge projections for nine intersections within the West Verkhoyansk foldbelt, which is subdivided into the Kharaulakh, Orulgan, Kuranakh, and Barain segments, differing in structural features.

Late Precambrian and lower to middle Paleozoic carbonate deposits (Paleozoic) have been preserved in the West Verkhoyansk zone of the folded belt only as fragments. At the same time, late Precambrian and Cambrian rocks crop out on the day surface at the Kharaulakh Range. These Cambrian deposits host the rich trilobite assemblage which is also common in other areas of the Siberian Platform, such as Taimyr, Sette-Daban, and Kotelny Island. Paleozoic deposits of older age have been eroded in this area. Inextensive Upper Devonian and Carboniferous outcrops are known in the Orulgan segment. The presence of late Precambrian and early Paleozoic deposits in the Kuranakh segment is inferred from deep seismic sounding (DSS) data. Large limestone clasts containing Middle to Upper Devonian fauna were identified in the gypsum–anhydrite stock with basaltic fragments. The deposits confidently dated as Precambrian and Paleozoic (before the Carboniferous) are hitherto unknown in the Barain segment, adjacent to the Sette-Daban horst-anticlinorium in the southern part of the Verkhoyansk area.

Thus, this allows an inference that on the northern and southern flanks of the Verkhoyansk fold–thrust belt (in the Kharaulakh and Orulgan segments as well as on Sette-Daban) there are undeniable indications of the pre-existing passive (pericratonal or midshelf) margin of the paleocontinent. At the same time, the presence of a carbonate platform in two segments (Kurunakh and Barain) beneath the Verkhoyansk complex is only assumed. Given the revealed structural features of the kinematics of Paleozoic tectonic blocks drift and paleogeographic data discussed below, we can suggest the formation of the Verkhoyansk complex in the place of a trough or graben as a result of the late Paleozoic rifting of pericratonic terranes and migration of their fragments eastward.

GEODYNAMIC HISTORY OF TERRANES IN THE PALEOZOIC: EVIDENCE FOR THEIR GENETIC LINKS WITH THE SIBERIAN PALEOCONTINENT, BREAKUP, AND MIGRATION OF ITS PASSIVE MARGIN FRAGMENTS

Spatial position and tectonic and lithostratigraphic structures of terranes. Paleozoic structures are distinctly discriminated among the Mesozoides by fault (transform) boundaries, structural–formational features, and unusual spatial position in the form of spaced-apart blocks, with the Chukotka terrane being the farthest from the Siberian craton (about 2000 km away). In the predominantly carbonate composition of the rocks, enormous thicknesses (up to 20–30 km, inclusive of the upper Precambrian) in five- to tenfold excess of the coeval platform sediments, and specific sedimentary cycles, these tectonic blocks are almost equivalent to the pericratonic terranes of the Sette-Daban Range structural–facies zone (Fig. 1). The differences are observed only in the lithologic variability determined by the local tectonogeomorphic and depositional settings and by effects of the proximal zones of volcanic activity and rift development.

Paleozoic blocks differ strikingly from the gently folded Mesozoides both in structure and morphology, which is accentuated by the predominance of narrow-linear, brachiform, and box-type folding as well as intensity and large amplitudes of discontinuous faults (Gusev, 1979; Tretiakov, 1996). The unique "architecture" of these terranes is reflected in the figurative definitions describing them as "key-type structure" (Bulgakova, 1986) and "tectonic chunks" (Zonenshain et al., 1990). Levashov (1974) pointed out the step-block pattern of the Paleozoic Sette-Daban structures. Oksman (1998) marked the echelon-like location of narrow, roughly north-to-south oriented blocks in the Tas-Khayakhtakh Ridge.

The linear folding and west-to-east oriented folds common to all the Verkhoyansk–Chukotka Foldbelt terranes are discernible on the detailed maps of the Omulevka Mountains (Fig. 2). The cross-section through another place within the same massif illustrates their complex fold–thrust structure (Fig. 3).

The configurations of the boundaries of Paleozoic blocks provided in different schemes of tectonic zoning may differ significantly because of the masking effect of thrust and strike-slip sheets. Most numerous are the differences stemming from the delineation of Paleozoic structures in the central part of the Verkhoyansk–Chukotka Foldbelt. This part was recognized as the Kolyma Platform, Kolyma median massif, and the Kolyma–Omolon, or Omolon–Okhotsk, terrane; also, it was represented by the dispersed terranes: Omulevka, Fore-Kolyma, and Omolon. The Selennyakh and Tas-Khayakhtakh blocks are referred to in many works as the integrated Moma or Moma–Selennyakh block.

This paper considers the Selennyakh, Tas-Khayakhtakh, Omulevka, and Chukotka inliers as independent Paleozoic tectonic blocks having common genesis, judging from all the geologic and paleontologic evidence. In most modern plate-tectonic reconstructions, these are interpreted as microcontinents with different continental roots. The Kolyma–Omolon terrane group is usually seen as a superterrane that existed independently of the Siberian Platform (Parfenov, 2001). Some authors argue that the Omolon and Okhotsk terranes have a single structure. Their tectonic–stratigraphic framework (in particular, the morphologies of the folded structures are marked by the predominance of isometric forms, and the lithologies of Silurian and Devonian strata are dominated by siliciclastic sediments, compared to Ordovician rocks) appear, indeed, unique among the Paleozoic terranes. Figure 4 shows tectonostratigraphic columns for the Okhotsk and Omolon terranes with the geodynamic interpretation (Khanchuk, 2006), demonstrating striking differences in the Ordovician and post-Ordovician stages of evolution of these terranes. Analysis of their structural style bearing indications of the geologic structure of platform type served as the basis for their isolation (in the first tectonic zoning schemes for the Verkhoyansk–Chukotka Foldbelt) among the Mesozoides, as an independent Kolyma Platform and then the Kolyma median massif.

Most researchers believe the terranes proximal to the Siberian Platform (Selennyakh, Tas-Khayakhtakh, and Ok-

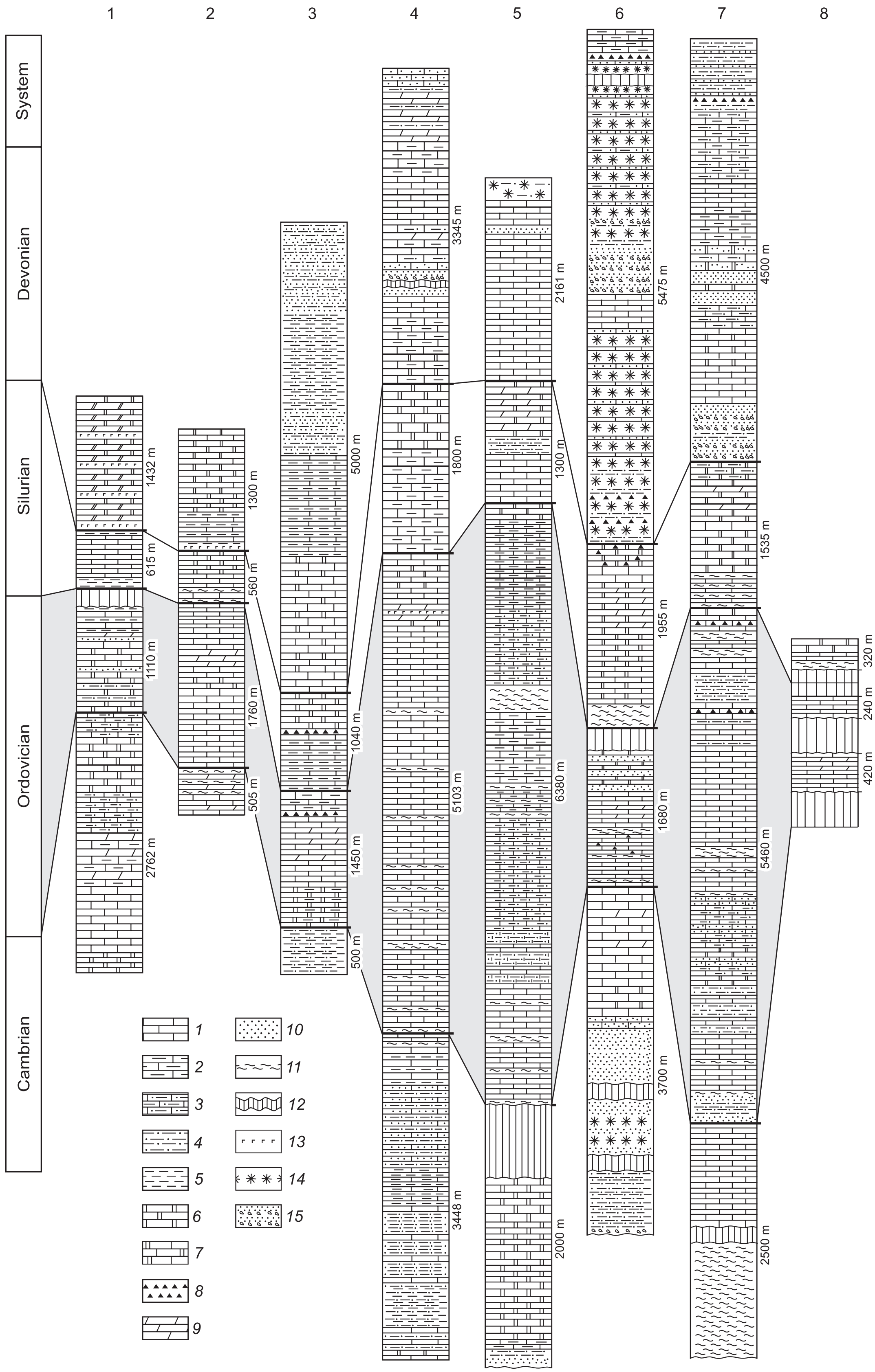

Fig. 1. Stratigraphic sections of Paleozoic sedimentary rocks and their correlation, Northeastern Asia. *1*, limestone; *2*, clayey limestone; *3*, silty limestone; *4*, siltstone; *5*, mudstone; *6*, dolomite; *7*, calcareous dolomite; *8*, silicification; *9*, marl; *10*, sandstone; *11*, shales; *12*, stratigraphic gap; *13*, gypsum bearing; *14*, volcanogenic rocks; *15*, conglomerate. Stratigraphic columns: 1, Siberian Platform; 2, Taimyr; 3, Kotelny Island; 4, Sette-Daban; 5, Kolyma; 6, Omolon terrane; 7, Selennyakh Range; 8, Chukchi Peninsula.

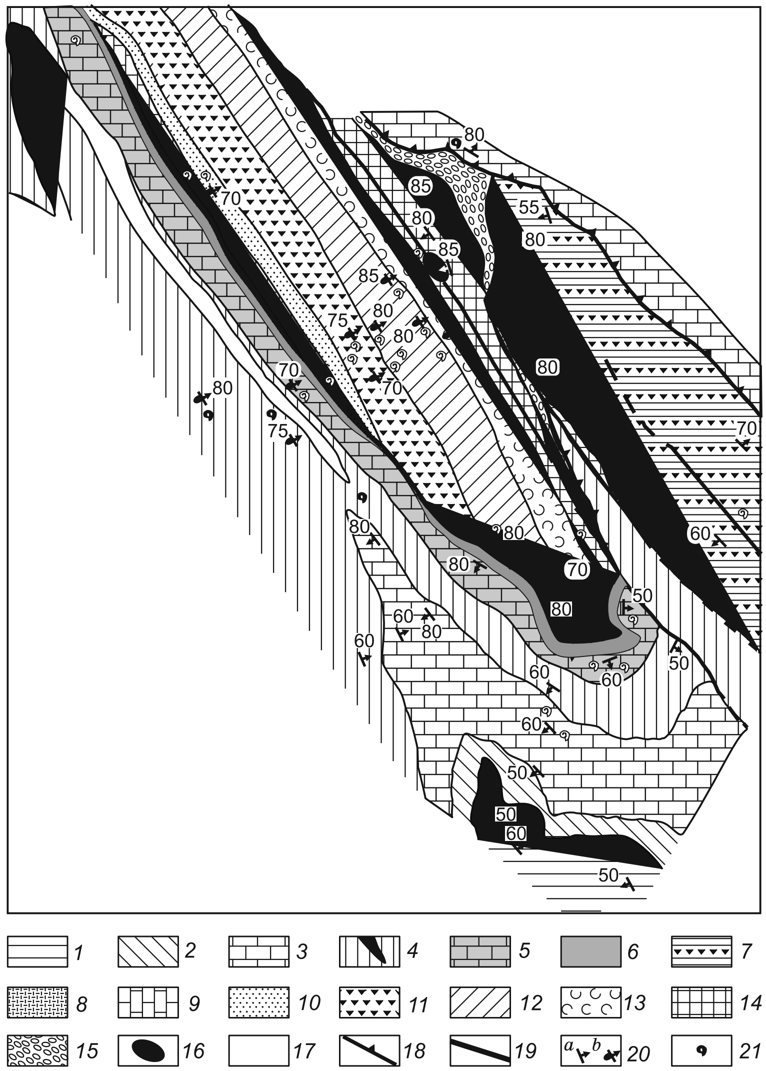

Fig. 2. Schematic geologic structure of the Serechen River basin in the Omulevka Mountains (Merzlyakov, 1971). *1*, *2*, lower Carboniferous: *1*, Tournaisian; *2*, Visean; *3–6*, Devonian: *3*, uppermost Eifelian Stage; *4*, middle Eifelian Stage; *5*, lowermost Eifelian Stage; *6*, lowermost Lower Devonian; *7*, undivided Ordovician rocks; *8–10*, Upper Ordovician, Serechen Sequence: *8*, trachytes; *9*, limestones; *10*, sandstones and tuffites; *11*, Lower–Middle Caradocian; *12*, Llandeilian Stage, Gorelyshev Sequence; *13*, Arenigian Stage, Biik Sequence; *14*, Cambrian(?)–lowermost Lower Ordovician, Ichen Sequence; *15*, Upper Riphean(?); *16*, granitoid intrusions; *17*, sheet intrusions and diabase dikes; *18*, thrusts; *19*, normal faults and strike-slip faults; *20*, dips and strikes (*a*, inclined stratification; *b*, overturned stratification); *21*, locations of fossil collection.

hotsk) to have been either a part of the platform's marginal part in the Paleozoic, or located in its proximity (Natapov and Surmilova, 1995; Oksman, 1998; Parfenov, 2001; Rodionov et al., 2007).

The Chukotka (Eskimo) terrane, ranked as the smallest in area (about 120 km^2) and the most remote from the Siberian paleocontinent, is geographically located on the Chukchi Peninsula, in the pinching-out zone of the Verkhoyansk–Chukotka Foldbelt, where it accreted to two megastructures (the Chukotka–Koryak volcanic belt and the Chukotka Foldbelt) to form what is commonly recognized as Arctida (or the Hyperborean Platform, after N.S. Shatsky). The Chukotka terrane plays a critical role in reconstructing the paleogeographic links between the Eurasian and North American continents in the Paleozoic owing to its placement on the geographic and evolutionary crossroads of these two continents, integrally with the adjacent Pacific and Arctic Oceans.

In all first-generation schemes of tectonic zoning (during the period of the geosynclinal theory dominance), the Paleozoic Chukotka inlier was interpreted as part of the Verkhoyansk–Chukotka Foldbelt structure. At the same time, in modern schemes compiled from the perspective of the lithospheric plate tectonics, this inlier has been included in the Chukotka Foldbelt, separated from the Verkhoyansk–Chukotka Foldbelt by the South Anyui suture zone (Sokolov, 2010). The age and geodynamic evolution of the tectonostratigraphic terranes within these two megastructures differ significantly.

The present-day geographic proximity of the Eurasian and North American continents and their postulated integra-

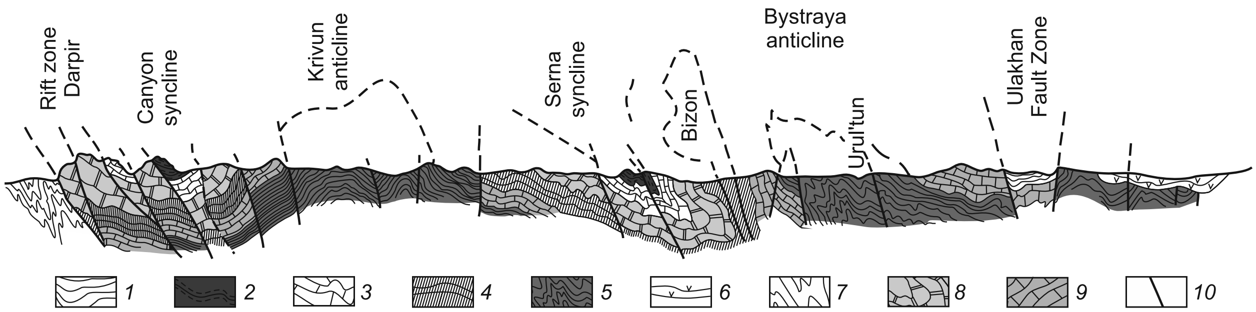

Fig. 3. Geologic profile of the Urul'tun block in the Omulevka Mountains (Merzlyakov, 1971). *1*, Neogene; *2*, Middle Devonian; *3*, Lower Devonian (Nelyudimaya Formation); *4*, lower Silurian (Kharkindzha and other formations); *5*, Krivun Formation; *6*, Upper Jurassic; *7*, Verkhoyansk complex; *8*, upper Silurian (Bizon and Mirnyi Formations); *9*, Darpir Formation; *10*, faults.

tion during the Precambrian into a single Asian–American craton (Sears and Price, 1978), supported by paleontologic evidence from the Paleozoic, indicate that a close paleogeographic relationship between the Chukchi Peninsula and Alaska existed at that time. The new reconstructions derived from the paleomagnetic data view this area as a single composite terrane isolated from both the paleocontinents (Metelkin et al., 2012; Chernova, 2017). However, a more reliable reconstruction of the geographic position of the Chukotka and Alaska terranes requires refining the correlation of depositional ages of the tectonostratigraphic complexes.

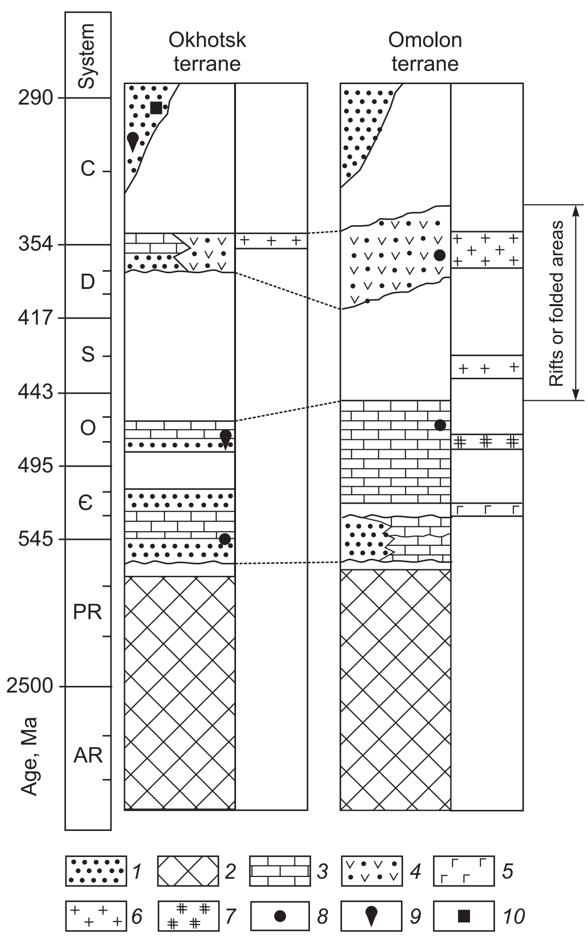

Fig. 4. Tectonostratigraphic columns of the Paleozoic strata of the Okhotsk and Omolon terranes (Khanchuk, 2006). *1*, shallow-water, marine, and terrigenous; *2*, Proterozoic or Archean basement; *3*, limestones; *4*, suprasubduction volcanic complexes; *5*, gabbro; *6*, suprasubduction granitoids; *7*, collisional granitoids; *8*, macrofauna; *9*, microfauna; *10*, flora.

The structures of Lyakhovsky, South Anyui, and Wrangel islands are commonly cited as typical tectonic–stratigraphic complexes bearing evidence of the Chukotka Foldbelt development. The most detailed tectonostratigraphic framework of this belt is best represented in the Wrangel Island sections (Tuchkova et al., 2018). The rich fauna records provided in this work, in the author's opinion, indicate its paleogeographic proximity to Northern Canada, beginning from the Carboniferous. However, the Paleozoic inlier of the Chukchi Peninsula appears exotic in this structure, since the early–middle Paleozoic age of its deposits is interpreted as antecedent in respect to the Chukotka Foldbelt structural evolution. At the same time, its lithology, fauna, and age are similar to those of Paleozoic terranes of the Verkhoyansk–Chukotka Foldbelt.

A detailed lithological description of the Chukotka terrane offered by M.M. Oradovskaya is based on the results of three field seasons (from 1966 through 1968; in 1968 attended by A.V. Kanygin) and was subsequently published in the collective monograph (Obut, 1977). It includes descriptions of brachiopods (M.M. Oradovskaya), ostracods (A.V. Kanygin), graptolites (A.M. Obut and N.V. Sennikov), corals (B.V. Preobrazhenskii), and stromatoporoids (V.G. Khromych) as well as identifications of other groups of fauna (trilobites, gastropods, and bryozoans), whose taxonomic composition indicates that this terrane belonged to the Siberian paleobiogeographic province.

The characterization of the Chukotka terrane was largely complemented by B. Natal'in et al. (1999). They divided it into two tectonic zones (Chegetun' and Tanatan) with Paleozoic successions which differ strikingly in terms of stratigraphic range, lithology, and geodynamic evolution. The Chegetun' zone, earlier described in great detail by M.M. Oradovskaya and colleagues, is represented by weak-

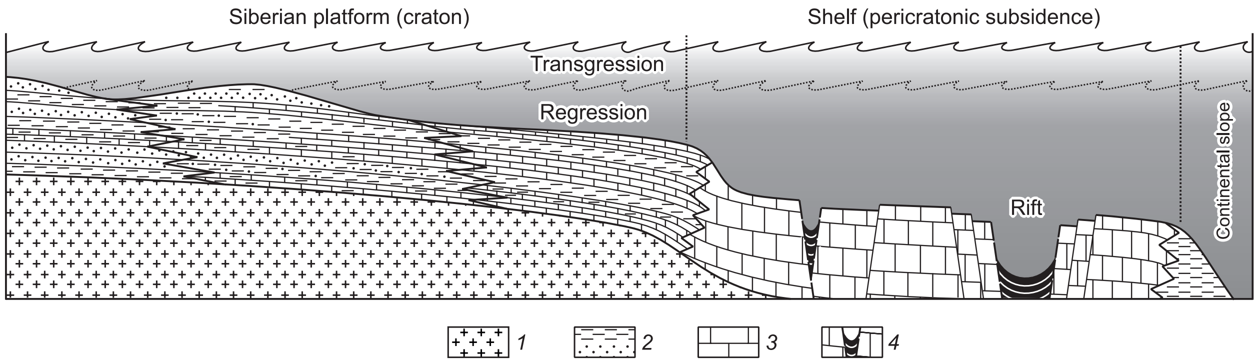

Fig. 5. Schematic bathymetric profile across the eastern margin of the Siberian paleocontinent in the Paleozoic. *1*, crystalline basement; *2*, terrigenous deposits; *3*, carbonate deposits; *4*, graptolite shales.

ly deformed Ordovician–Early Devonian shallow-water deposits of predominantly carbonate composition. The adjacent Tanatan zone consists of highly deformed and metamorphosed rocks (phyllites, thin limestones, and andesitic tuffs). The U–Pb zircon dates determined their Devonian age (375–365 Ma). The authors interpret this structure as the southern margin of the Bennett–Barrovia tectonic belt, extending from the New Siberian Islands as far as Northern Alaska and across it. This means that the tectonic joint between these zones overprinted on the South Anyui suture extension dissects the Chukchi Peninsula, marking the chronological and tectonic boundary between the adjacent megastructures (the Verkhoyansk–Chukotka Foldbelt and postulated Arctida paleocontinent). Thus, it has been established that the Paleozoic inlier of the Chukchi Peninsula is a collage of two multiple-age terranes belonging to different megastructures. As is the case with the other Verkhoyansk–Chukotka Foldbelt tectonic blocks of Paleozoic age, the Chegetun' block originally formed from the passive margin of the Siberian paleocontinent, whereas the tectonic–stratigraphic units of the Chukotka Foldbelt (or Bennett–Barrovia, after (Natal'in et al., 1999)) appear to have different origins.

Basin bathymetry and structural–facies zoning. The scheme in Fig. 5 represents the paleobasin bathymetric profile across its eastern margin. This allowed distinguishing three groups of structural–facies zones on the basis of bathymetric differentiation of paleogeographic environments, tectonic settings, geodynamic regime, and rates of sedimentation. The first group (intracratonic) is confined to the interior part of the epicontinental basin, which is delimited by the present-day boundaries of the Siberian Platform. This is the shallowest part of the basin, dominated by littoral bionomic facies across most of its territory, except for the deeper water zones of the affiliated Tunguska and Vilyui basins as well as regional Yenisei–Khatanga and Fore-Verkhoyansk troughs. An extensive deep-water basin formed during the early Cambrian in the northeastern part of the platform favored the deposition of black shales (the Kuonamka Formation), which by their composition are analogous to anoxic zone of the Domanic facies (Paleozoic strata) of the Russian (East European) Platform and Mesozoic bazhenites of the West Siberian basin. The relatively short-term deep-water sedimentation conditions succeeded by shallow-water carbonate environments in the middle Cambrian are indicative of the metastable oscillatory geodynamic behavior in the intracratonic parts against the backdrop of its unidirectionally subsiding passive margin. The predominantly shallow-water sedimentation regime persisted on the platform throughout the Paleozoic with the alternating basin deepening (transgressive phases) and its shallowing (regressive phases) to the extent of insular landmass showing up. The basin extent was progressively reducing throughout the Devonian, Carboniferous, and Permian, which terminated in the late Paleozoic, marked by the separation of freshwater lake basins from the marine basins and subsequent formation of an extensive land area (the Angarida paleocontinent) overgrown with subtropical vegetation (Malich, 1975).

The second group of structural–facies zones is confined to the marginal (pericratonic) terranes that rim the platform and, themselves, are a shelf of the paleocontinent dominated by sublittoral paleogeographic environments. This part of the paleobasin differs from the intracratonic structural–facies zones in a specific geodynamic regime of sedimentation, termed as "pericratonic sinking" by E.V. Pavlovsky (1959). The pericratonic sinking is defined as the long-term tectonic subsidence (spanning several geologic periods) of the Earth's crust along the ancient platform periphery, on the border with the adjacent coeval geosynclinal belt; along this boundary, the sedimentary platform cover dramatically increases in thickness (Petrov, 2011, p. 311). This characteristic is fully consistent with the concept of depositional patterns in the pericratonic part of the Siberian Platform, which are the most pronounced in the Sette-Daban and Taimyr sections. Given the continuous pericratonic subsidence characterized by steady-state sedimentation regime and metastable state of the basin intercratonal part, the gradient of depths remained sharp between these groups of structural–facies zones. The Paleozoic tectonic units (terranes) of the Verhoyansk–Chukotka Foldbelt and Kotelny Island can be reasonably attributed to the same group of structural–facies zones proceeding from similarity in their structure, origin, and commonly shared fauna associations.

The structural–facies zones of rifts represent a disparate category comprising deep-water, mainly terrigenous–volcanic, often siliceous rocks with sharply subordinate amounts of carbonate material. These tend to be confined to the terrane edges and are well identifiable within folded-thrust structures of Paleozoic blocks owing to characteristic indications of lithofacies and taphocoenoses with planktonic organisms (Kanygin et al., 2020). The events of Paleozoic rifting transpired only on the eastern margin of the paleocontinent, thereby predetermining its breakup and dispersal of its fragments.

The inherited nature and synchronicity of terrane evolution. The genetic affinity of all Paleozoic terranes with the Siberian Platform is corroborated by their inherited nature and synchronicity of their evolution. The stages of evolution of structural-formation complexes were studied by comparing their pivotal tectonic and evolutionary events which took place on the pericratonic margin of the Siberian paleocontinent and on the terranes. This comparison was based on the key sections (the Sette-Daban Ridge, Selennyakh Ridge, and Omulevka Mountains) exhibiting continuous sedimentary sequences and magmatic massifs from Riphean to lower Carboniferous.

Cambrian, Ordovician, Silurian, and Devonian deposits correspond to paleogeographic environments of the sublittoral zone of the shelf by their lithologic, mostly carbonate, composition, enormous thickness (up to 10 km), and similarity of benthic fauna associations. On the Omolon and Okhotsk uplifts, the relatively homogeneous Ordovician carbonate and terrigenous–carbonate facies pass into facies zones with exceedingly contrasting, predominantly coarse-grained siliciclastic sedimentation (sandstones, gravelites, and conglomerates). These zones have primarily local areal distribution, inasmuch as the composition of the pebble fraction indicates their transport from local provenance areas (Simakov and Shevchenko, 1967; Merzlyakov, 1971; Bulgakova, 1986; Oradovskaya, 1988). This facies differentiation attests to geodynamic activity within these tectonic blocks, which resulted in the origin of local uplifts.

In most of the structural–facies zones confined to the platform, its pericratonic margin, and terranes, the sedimentation evolution has shown a generally increasing trend both in the facies differentiation and in amounts of terrigenous–clastic material because of the sediment transport from local elevations.

The unidirectional nature and synchronicity of development of the entire paleobasin, including terranes, are evidenced by recognizable stratigraphic events. The Ordovician and Devonian rifting is well-proven by the paleontological data to be coeval. The graptolite zone at the Lower–Middle Ordovician boundary enabled precise dating of the onset of the Ordovician rifting (Obut and Sobolevskaya, 1972; Oradovskaya, 1988). Within the Siberian Platform, this time is marked by the onset of a new sedimentation cycle manifested in the change from predominantly carbonate to terrigenous–carbonate sedimentation accompanied by a sharp decrease in the rock mass thickness. This caused the explosive growth of the biodiversity of the pioneer fauna groups in the epicontinental seas of all the paleocontinents, including the Siberian paleocontinent. This global ecosystem restructuring on scales comparable to evolutionary implications of the appearance of stem-groups of skeletal hydrobionts on the phylogenetic tree in the early Cambrian is known as the Great Ordovician Biodiversification Event (Kanygin, 2008).

The later stage of rift development, which manifested itself more extensively and intensively, began in the Middle Devonian in the Fore-Verkhoyansk Trough of the Siberian Platform (Parfenov and Prokopiev, 1993), on the Sette-Daban Ridge (Levashov, 1974), and on the Paleozoic tectonic inliers of the Verkhoyansk–Chukotka Foldbelt (Bulgakova and Kolodeznikov, 1990; Karyakin et al., 2000). The red-colored and anhydrite–gypsum rocks appearing amidst predominantly carbonate deposits showed a good correlation with these stages of rifting events.

Based on the detailed comparison of lithostratigraphy and interpretation of the paleogeographic environments of the Selennyakh and Tas-Khayakhtakh blocks, V.S. Oksman (1998) demonstrated an almost completely coincident sequence of facies changes which revealed themselves either as episodes of carbonate–terrigenous and terrigenous–clastic lithologies appearing in carbonate deposits or as evidence of lagoon sedimentation (Fig. 6).

The periods of magmatism activation are also associated with the main stages of rift development, and they are largely responsible for preservation of amazingly sustainable uniformity of the trachybasalt and trachyandesite composition. Magmatism manifestations were primarily associated with rift depressions in the form of eruption-produced tuff material and outpourings of lava during underwater events. Volcanic activity increased dramatically in the Late Devonian and early Carboniferous, entailing the formation of thick trachybasalt and trachyandesite lava flows (Merzlyakov and Lychagin, 1973; Grinberg et al., 1981; Lychagin et al., 1989; Karyakin et al., 2000). Thus, remarkably thick pillow basalts were observed in the Moma–Selennyakh area (Selennyakh and Tas-Khayakhtakh) (Oksman, 1998).

Paleomagnetic data. The current state of paleomagnetic studies and the resulting palinspastic reconstructions of northeastern Asia are characterized by contradictory trends. First, note the multitude of alternative versions of paleotectonic reconstructions. This is quite understandable given the heterogeneous structure of this territory and the lack of reliable paleomagnetic data, especially for the folded structures rimming the Siberian Platform. Second, most publications on this topic are characterized by fairly poor coverage of geological information, which essentially amounts to paleomagnetic definitions, kinematic interpretations of boundary structures within the hypothetical motions of lithospheric

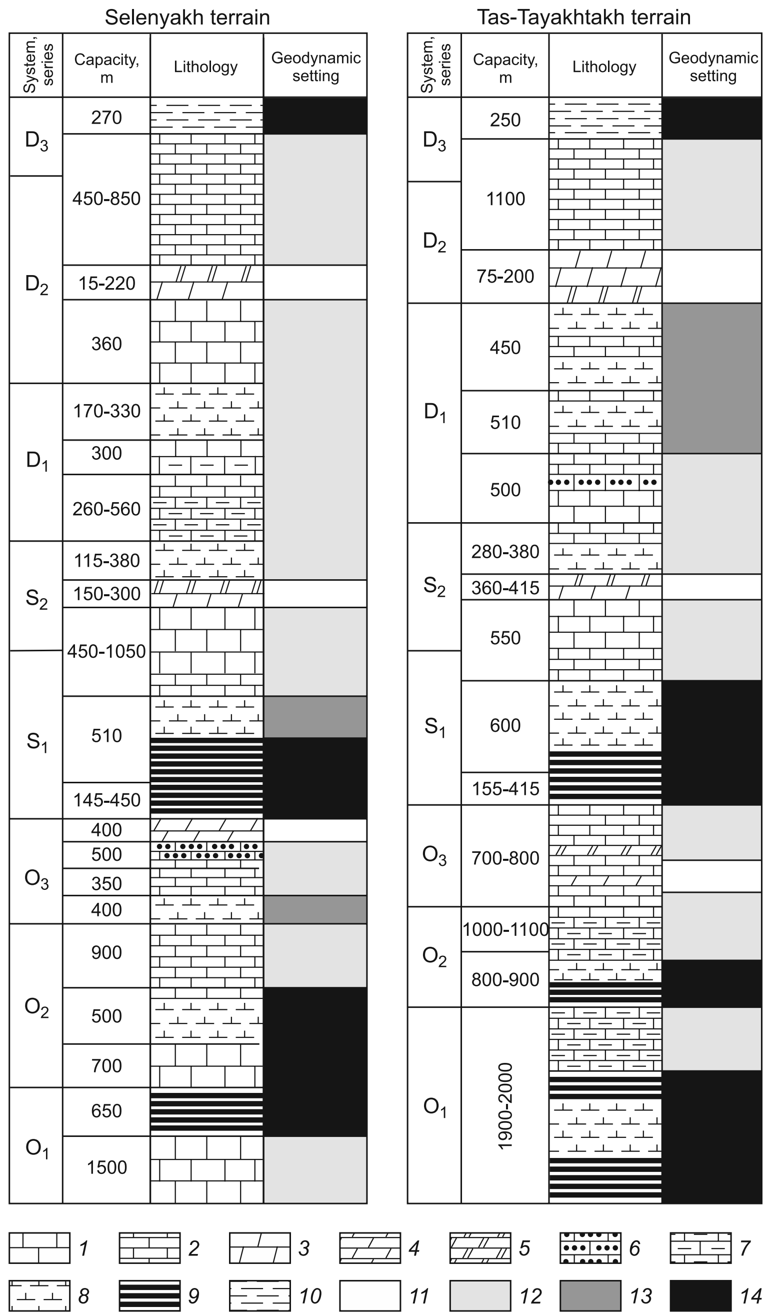

Fig. 6. Stratigraphic columns of lower to middle Paleozoic strata and geodynamic settings of their deposition. *1*, massive organogenic–clastic and brecciated limestones; *2*, layered and thinly laminated limestones; *3*, dolomites; *4*, layered and thinly laminated dolomites; *5*, gypsum and anhydrites; *6*, sandy limestones; *7*, clayey limestones; *8*, calcareous shales; *9*, interbedding of calcareous–argillaceous shales, argillaceous graptolitic shales, siltstones, and calcarenites; *10*, mudstones; *11*, lagoon; *12*, shelf; *13*, open sea; *14*, continental slope.

plates, and comparative data on the magnetic events supported by isotope-geochronological dating.

At the same time, both the sedimentary geology data (on lithofacies, paleontology, and structure of consedimentation), which characterize the paleogeographic history of each particular paleobasin and its biogeographic relations with other paleobasins, are largely ignored, albeit in the previous paleotectonic and paleogeographic reconstructions these, complemented by the endogenous geology data, were commonly used as basic inputs. As a result of such a one-sided approach to using the geological information, there is an increasing trend in the number of plate-tectonic reconstructions that yielded results contradicting the "prohibitive" sedimentary geology, in particular, paleobiogeographic data.

A detailed characterization of the level of paleomagnetic knowledge on the studied region is amply provided in the published literature (Neustroev et al., 1993; Sokolov et al., 1997; Parfenov, 2001; Veselovskiy et al., 2003; Rodionov et al., 2007; Metelkin et al., 2012). Many of these works noted early paleomagnetic data as scarce and having a low degree of reliability (before "the methodological and instrumental revolution" in paleomagnetology in the 1980s–1990s, after (Veselovskiy et al., 2003)), whereas novel laboratory methods for samples preparation allow eliminating the undesirable components and isolating the primary magnetization. Thus, early paleomagnetic measurements are found to be obsolete, inasmuch as that they do not measure up to modern requirements.

In the context of new criteria with respect to the territory of the Verkhoyansk–Chukotka Foldbelt, there appeared two collaborative studies on the paleomagnetism of the Tas-Khayakhtakh rocks with simultaneous detailed description and complete reconstruction of the evolution of geologic structures of the paleomagnetic testing sites (Neustroev et al., 1993; Rodionov et al., 2007). The first paper presents the results of three-year paleomagnetic studies of the Paleozoic rocks of the Tas-Khayakhtakh Ridge and their comparison with the available data on the Siberian Platform and the Omulevka (including the Arga-Tas block) and Omolon terranes. These data allowed an inference that, albeit all these terranes were in proximity to the Siberian Platform in the Paleozoic, they moved and rotated independently of each other along different trajectories. Note that the terranes most rapidly drifted (and probably asynchronously) in the post-Devonian time in the direction opposite to the platform to a distance of several thousand kilometers. At this time, the ocean whose width in the late Middle–early Late Jurassic exceeded 2500 km opened between the passive margin of the platform and the terranes. When analyzing the paleomagnetic data, the authors specified that, in the absence of integrated data on the Omulevka and Omolon terranes at that time, they relied mainly on their own data on the Tas-Khayakhtakh terrane.

The paper devoted to the paleomagnetic reconstruction of the paleogeographic positions of the Siberian Platform (the East Siberian Plate, after the authors' terminology) and the Tas-Khayakhtakh terrane from Ordovician to Carboniferous is of great interest specifically from the perspective of methodology (Rodionov et al., 2007). According to the determined geomagnetic pole coordinates and the unified kinematics of rotational motion of the platform and the Tas-Khayakhtakh terrane, these structures formed a single tectonic system from Middle Ordovician to Early Devonian (452–397 Ma). A dramatic change in the mutual position of the Tas-Khayakhtakh terrane and the platform occurred in the early Carboniferous (probably, in the Middle–Late Devonian).

In the conclusion, the authors provided very important methodological comments concerning (1) the need for more paleomagnetic determinations derived from at least several blocks, because the data obtained from one block have a substantial longitudinal error in its position; (2) the fact that individual paleomagnetic determinations generally have an error of 5–10° (confidence angles equivalent to the two-fold standard error), which should not be ignored; (3) the accuracy and correctness of stratigraphic correlations of the sections of tectonic structures are critical for validity and reliability of the reconstruction of mutual spatial position of the craton and terrane for each time slice of geochronological charts.

In fact, these comments indicate that the error sources in the paleomagnetic data interpretations are associated, in particular, with the adherence to the conditions of the sampling method and the reliability of their tectonic and stratigraphic ties. Inedequate paleomagnetic determinations also stem from the obscuring effect of remagnetization of sedimentary rocks, which can be established only in the case when obvious contradictions between such determinations and geological data occur (Stone et al., 1992; Pavlov et al., 2004). The degree of reliability of the determined coordinates of paleomagnetic pole positions is critical for achieving the best conformity of the available geological and paleomagnetic data (Metelkin et al., 2007).

These examples highlight the importance of geological (including paleobiogeographic) data for delimiting of the confidence intervals of paleomagnetic determinations. Hopefully, the progressive improvements in the paleomagnetic method, aided by the accumulation of sufficiently reliable paleomagnetic data for terranes, will provide more detail and insights to refine the proposed model of their origin.

Model of autochthonous development of Paleozoic terranes. In different versions of palinspastic reconstructions, Paleozoic tectonic blocks in the Mesozoides of northeastern Asia are interpreted as wandering allochthonous terranes, whose origin suggests allogeneity in relation to the Siberian Platform. The paleontologic and geologic evidence provided herewith and in the previous works (Kanygin et al., 2020) indicates that they were initially parts of the Siberian paleocontinent. The postulated boundaries of the Siberian paleocontinent prior to its separation from the eastern pericratonic margin (in modern coordinates) are shown in Fig. 7. The continuous process of sedimentation in the mode of compensated subsidence in the pericratonic belt throughout the Neoproterozoic and early and middle Paleozoic resulted in the formation of a massive carbonate plate, reaching in different areas 20 and even 30 km in thickness, according to the available data. The breakup of this plate can be compared with the iceberg calving from the edge of ice shelf and its subsequent drift driven by ocean currents and wind of variable directions.

The two known stages of the rifting activation (Ordovician and Middle Devonian) are believed to have predetermined the eastern margin separation from the paleocontinent, with the middle Carboniferous being the most likely time of the fragments rifting off the continental mass. The separated tectonic blocks drifted, most likely, during the late Paleozoic–early Mesozoic, which agrees well with some modern reconstructions using the paleomagnetic data (Neustroev et al., 1993; Rodionov et al., 2007).

In the Verkhoyansk–Chukotka Foldbelt, the terrane drift vector is oriented roughly west-to-east, which agrees well with the direction of seafloor spreading, expressed in the Pa-

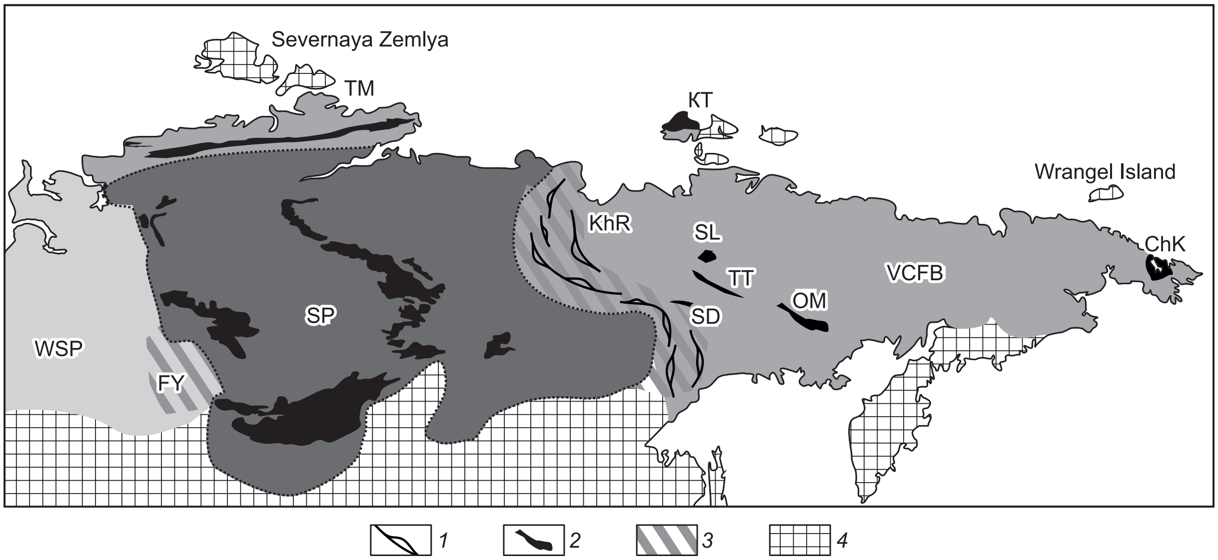

Fig. 7. Boundaries of the Siberian paleocontinent. *1*, rift; *2*, terranes; *3*, rifted passive margin of the paleocontinent before the breakup and dispersal of fragments; *4*, framing structures of the paleocontinent and Mesozoides. WSP, West Siberian Plate; FY, Fore-Yenisei sedimentary basin; TM, Taimyr folded area; SP, Siberian Platform; KhR, Kharaulakh; KT, Kotelny Island; SL, Selennyakh Range; TT, Tas-Tayakhtakh; SD, Sette-Daban; OM, Omulevka Mountains; VCFB, Verkhoyansk–Chukotka Foldbelt; ChK, Chukchi Peninsula.

leozoic as the processes of rifting and intensive faulting. The longer duration of the predominantly faulting events in the Paleozoic has been noted by many researchers (Chekhov, 2000). The spreading process is known to be inherited from the Proterozoic, when the North American continent became separated from the Eurasian continent, according to many researchers (Sears and Price, 1978).

This scenario is consistent with the opinion of a number of well-known paleontologists and geologists from Canada and the United States postulating that the Alexander terrane in Alaska may have a Russian origin (Blodgett et al., 2010). The correlation of Silurian and Devonian sections of this terrane and those of the Omulevka Mountains within the Verkhoyansk–Chukotka Foldbelt revealed similarities of their faunas, lithologic composition, and sediment thickness. Besides, their paleomagnetic data suggest that these terranes may have been located in close proximity to each other. Proceeding from the similarity of the Emsian fauna (Middle Devonian), the Siberian origin of the Farewell terrane of Alaska was suggested (Blodgett, 1998). The presence of endemic Alaskan–Siberian fauna in the Paleozoic was marked in a series of publications (Cocks and Torsvik, 2007; Torsvik and Cocks, 2017). In light of this hypothesis, it appears logical to conduct a comparative analysis of the paleontological and paleogeographic data on Paleozoic terranes of the Verkhoyansk–Chukotka Foldbelt and Alaska using most recent methods and datasets.

The most probable locus of the Verkhoyansk–Chukotka Foldbelt terranes separation from the margins of the paleocontinent is confined to the Verkhoyansk fold–thrust belt with the arcuate–concave central part. Specifically, no reliable evidence of older deposits has been found in this part of the belt overprinted by the late Paleozoic–Mesozoic Verkhoyansk sedimentary complex, unlike its southern and northern flanks. The appearance of the bending folds of the Verkhoyansk Belt and adjacent Verkhoyansk–Chukotka Foldbelt structures (the Kolyma loop) was interpreted from the standpoint of the terrane collage concept and attributed to deformation of the eastern margin of the Siberian Platform when the large Kolyma–Omolon terrane collided with it (Zonenshain et al., 1990).

The current geographic position of the Kotelny Island terrane, lying northward of the Siberian Platform determines the probable direction of its drifting along the sublongitudinal vector, i.e., orthogonal to the vector of the Verkhoyansk–Chukotka Foldbelt terrane motion. This direction is found to be congruent with the kinematics of tectonic movements of Taimyr and the northern part of the Verkhoyansk–Chukotka Foldbelt, where the orientation of the fault-and-folded structures sharply changes from W–E to N–S along the transregional tectonic suture. This suture was shown by N.V. Shatsky (1935) on one of the pioneering tectonic zoning schemes of northeastern Asia, who also delineated the southern boundary of the Hyperborean platform previously determined by him. Then, in slightly differing modifications, it was captured in the schemes of several authors. Presently, it is called the South Anyui suture zone.

The supposed locus of this terrane separation from the paleocontinent is pinpointed at the northeastern corner of the Kolyma loop, where in the modern tectonic framework the faulting orientation changes sharply from sublatitudinal to sublongitudinal. The original Tas-Khayakhtakh, Selennyakh, and Kotelny terranes probably formed as a single tectonic block. Because of the similarity in the geologic structure and spatial position of the Tas-Khayakhtakh and Selennyakh terranes, some researchers (Oksman, 1998) integrate them into a single Moma–Selennyakh tectonic zone. When compiling the actualized Ordovician chronostratigraphic chart for Northeastern Russia on the basis of uniformity of composition of lithofacies and fauna associations, M.M. Oradovskaya united all the three structures ranking as subzones into a single structural–facies zone (Koren' and Kotlyar, 2009).

The available paleontological and sedimentological data, however, do not allow us to confidently establish the timing of separation of the Okhotsk and Omolon terranes from the Siberian Platform. Like the other terranes, they are interpreted as part of its passive margin in the Ordovician. This is evidenced by the facies affinity and uniformity of thicknesses of predominantly carbonate deposits and by the brachiopod finds of the same species collected both on the other terranes and on the Siberian Platform (Oradovskaya, 1988). The level of paleontological study of these terranes is generally insufficient for elaboration of more profound inferences with greater certainty; rather, it allows only stating that, over the post-Ordovician time, paleogeographic environments on these terranes have changed dramatically, which therefore leaves the geodynamic history of the Okhotsk and Omolon terranes still poorly understood. The solution of the problem concerning their origin and evolution would be possible only in the context of the geologic evolution of the entire territory of northeastern Asia, on the basis of a comprehensive approach and application of different methods. Among them, the paleomagnetic method might become especially important if it is controlled by other methods, including the paleobiogeographic method.

DISCUSSION OF RESULTS: METHODOLOGICAL PROBLEMS OF THE PALEOGEOGRAPHIC RECONSTRUCTIONS WITH REGARD TO LITHOSPHERIC PLATE TECTONICS

The three historical and geologic stages (tectonic levels) distinguished in the geologic evolution of northeastern Asia and adjacent parts of the Arctic Ocean were named according to the geodynamic regime: (1) Pt_3–D_2, cratonic (intracratonic development of structures); (2) D_2?, C_1–J_2, oceanic (associated with the rift-to-drift transition); and (3) J_2–K, orogenic (accretion, structural transformation, and craton formation).

Each stage is characterized by its specific database and methods for its analysis. Thus, the studies of the cratonic stage (epicontinental basin developing as a whole) tend to be largely underlain by the methods of sedimentary geology (stratigraphy, bio- and lithofacies analysis, and fauna chorology), while petrological–petrochemical methods are used as complementary methods for obtaining proxy evidence of continental crust. The key parameters for reconstructions of the oceanic stage are petrologic and petrochemical indicators of marine depositional environments and deep geodynamic processes in combination with sedimentologic evidence of deep-water settings as well as paleomagnetic determinations of stratigraphic coordinates of the tectonic blocks. The orogenic stage is associated with collage of terranes and accounts for accumulating evidence on the continuous development of tectonic blocks as integrated structures. Therefore, the methods of morphostructural analysis become of paramount importance in reconstructions of this stage, since their results are applicable to identification and systematization of the structure–substance systems decoding, allowing us to uncover the information from geologic chronicles entangled by the tectonic processes.

A comparison of methods for palinspastic and paleobiogeographic reconstructions showed that the selected initial geological information and methodology for its analysis vary significantly. The terrane analysis method developed by geologists in the United States back in the 1980s on the example of the Cordillera Mountains and Alaska has become of reference value in developing paleotectonic and paleogeographic reconstructions of folded areas from the perspective of lithospheric plate tectonics. In Russia, the method was actively developed by L.M. Parfenov (on the example of the Verkhoyansk–Chukotka Foldbelt), who has formulated the key concepts and methodology for terrane analysis, consisting of the following major elements (Parfenov, 2001, p. 70): (1) Isolation of terranes and other formations either overlapping (sedimentary and sedimentary–volcanogenic) or "suturing" (igneous and metamorphic) them; (2) determination of the terrane boundaries and their types (thrust, strike-slip fault, and normal fault); (3) typification of terranes, as well as overlapping and "suturing" formations on the basis of the actualistic approach (isolation of island-arc formations, accretionary-wedge (subduction) complexes, active and passive continental margins, fragments of oceanic crust, etc., and formations associated with riftogenic magmatism, collision, subduction, etc.); (4) isolation and typification of postaccretion deformations (faults) emerging after the terranes accretion to the craton, which lead to the terranes breakup (dispersion); (5) analysis of paleobiogeographic and paleomagnetic data required for deducing the ancestry of terranes.

It follows from these successive steps that the structural and tectonic data characterizing the final stage of geodynamic evolution of a foldbelt are used as the primary information, i.e., acting as the top-down analysis. This approach, therefore, excludes the stratigraphic and lithological data, which would otherwise allow characterizing the paleogeographic settings in the initial stage of the basin evolution and their chronological changes according to the biostratigraphic data. Involvement of both paleontological and paleomagnetic data is commonly required only at the final stage of the terrane analysis. In practice, priority is given to paleomagnetic determinations, while no or very limited paleogeographic data (and only in those cases where there is no controversy with the paleomagnetic data) are used in the majority of palinspastic reconstructions.

The terrane and paleogeography approaches should be used as complementing each other, in particular, when the differences in the "evolutionary leaps" of folded areas are taken into account, since their integration requires involving more complete geologic and paleontologic evidence. The paleobiogeographic reconstruction methods based on the available adequate paleontological and sedimentological data allow establishing the initial position of tectonostratigraphic complexes, with simultaneous testing of the paleomagnetic data reliability. The multitude of mutually exclusive versions of palinspastic reconstructions is associated not only with the insufficient development of actual models of lithospheric plate tectonics, as many experts think, but also with the limited use of the entire complex of old and new methods of paleogeography.

The tectonic data analysis carried out for Northeastern Russia by a group of renowned experts in tectonism and paleomagnetism (Sokolov et al., 1997) resulted in their collaborative paper, which includes the "Challenges and Uncertainties" section, illustrated with many examples of controversy between palinspastic reconstructions and the geological and paleontological data. The authors of the paper express their concerns about an urgent need to develop new-generation geodynamic reconstructions based on the synthesis of marine and terrestrial geologic evidence. Marine geological studies without doubt play the pivotal role, primarily in substantiation of actualistic models of the paleogeodynamic reconstructions of the oceanic lithosphere. At the same time, it is obvious that the enormous data pool allowing us to justify more reliable reconstructions is contained in the geological chronicles of the Earth's sedimentary envelope, or "the stratosphere", specifically, as paleontological and sedimentological records, which have thus far been largely underestimated.

CONCLUSIONS

(1) The comparative analysis of stratigraphic, paleontological, and sedimentological data on the Siberian Platform, Taimyr foldbelt, Sette-Daban horst-anticlinorium, Paleozoic terranes of the Verkhoyansk–Chukotka Foldbelt (Selennyakh, Tas-Khayakhtakh, Omulevka, and Chukotka), and Kotelny Island showed that throughout the Cambrian, Ordovician, Silurian, and Devonian they belonged in the Siberian paleocontinent, which accommodated a predominantly shallow marine basin;

(2) Paleozoic terranes (including the Taimyr and Sette-Daban terranes) formed the passive continental margin in the place of the present-day Verkhoyansk fold–thrust system. The common origin of the presently geographically dispersed fragments of the passive continental margin is evidenced not only by commonality in the composition of all groups of benthic fauna and identical geodynamic regime of sedimentation (continuous compensated sedimentation under pericratonic subsidence), but also by the unidirectional and synchronous nature of geologic processes (composition and thickness of sedimentary strata, tectogenesis, nature of volcanism, and episodes of rifting);

(3) The period from Late Devonian to early Carboniferous, marked by the drastically changed geodynamic regime in the territory of the Verkhoyansk–Chukotka Foldbelt and adjacent offshore parts of the Arctic Ocean, appears the most likely time of the terrane separation from the Siberian paleocontinent;

(4) The transitional stage in the tectonic evolution of northeastern Asia and adjacent parts of the Arctic Ocean (C_1–J_2) is time-correlative with regional pivotal geologic events (large-scale manifestations of intrusive trap magmatism in the Siberian Platform and the closure of the Uralian paleoocean surrounding it from the west), drastic global tectonic restructuring of the lithosphere (the supercontinent Rodinia II breakup with subsequent amalgamation of its parts into new configurations), and a major global extinction of marine and terrestrial biota;

(5) The Chukotka terrane being part of the passive margin of the Siberian paleocontinent in the Paleozoic (through the Middle Devonian) contradicts the palinspastic reconstructions, which depict Chukotka and Alaska at this geologic time as accreted microplates separated from the Siberian and North American paleocontinents. However, the available paleontological and lithological-facies data leave no doubt about the existence of close paleogeographic links between the Siberia and Alaska terranes in the mid-Paleozoic;

(6) The position of the Verkhoyansk–Chukotka Foldbelt terranes relative to the passive margin of the Siberian paleocontinent in the Paleozoic rules out their being accreted to the North American lithospheric plate, as has been postulated by many researchers (Churkin, 1972; Kogan et al., 1998; Cocks and Torsvik, 2007).

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