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The Permian of the Verkhoyansk–Okhotsk region, NE Russia

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Abstract

This report summarizes data on the Permian deposits of the Verkhoyansk–Okhotsk region (tectonics, paleogeography, fauna, flora and stratigraphy). The Verkhoyansk–Okhotsk region covers the area of the Verkhoyansk fold-and-thrust belt. The Permian deposits of this region were formed on the passive continental margin of the Angarida Continent, the ancient Siberian Continent, situated within the Siberian Platform. This continental margin developed as the result of continental break-up in the Late Precambrian. Late Precambrian to Jurassic (including Permian) sediments were deposited on a passive margin with a continental shelf extending out into an ocean towards the northeast. During the Permian, exclusively terrigenous sediments were deposited over a vast territory in the Verkhoyansk paleobasin forming part of this continental margin. The Permian deposits are divided into six regional stratigraphic units ranked as horizons (=regional stages), which in turn are subdivided into faunal zones and beds serving as the basis for intra-regional correlation. In the Late Jurassic–Cretaceous the continental margin sediments were converted into a foreland fold-and-thrust belt due to the collision of the Siberian Platform with the Kolyma–Omolon and Okhotsk continental blocks.

Keywords: Permian; Verkhoyansk–Okhotsk region; Stratigraphy; Biostratigraphy; Brachiopods; Ammonoids; Bivalve; Angarida continent

1. Introduction

The Permian rock succession in the Verkhoyansk–Okhotsk region attracts considerable interest because it represents a continuous, stratigraphically complete, and well-exposed section with a simple geological structure. The Permian sections are composed predominantly of marine facies that yield goniatites, brachiopods, and bivalves. Regional stratigraphic units are unambiguously correlated with stages of the East European Permian timescale. The Verkhoyansk–Okhotsk region is the key region for solving the main stratigraphic problems of Permian of Siberia.

2. Outline of the geologic structure

The Verkhoyansk–Okhotsk region lies in the Lena–Yana drainage basin covering the N–S Verkhoyansk fold-and-thrust belt. The Permian deposits of this region were formed on the passive continental margin of the Angarida (or Siberian) Continent which had developed by continental break-up in the Late Precambrian. Late Precambrian to Jurassic (including Permian) sediments formed a continental shelf extending out into an ocean towards the northeast. The Kolyma–Omolon Superterrane and the Okhotsk Terrane lay on the eastern side of this ocean. Sometime during the Jurassic this ocean began to close by subduction under the Kolyma–Omolon Superterrane and the Okhotsk Terrane. In the Cretaceous these terranes collided with the eastern margin of the Angarida Continent and the continental margin sediments (including the Permian) were thrust westwards over the margin of the Angarida Continent.

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This collision was completed by the Late Cretaceous. As a result of this collision the continental margin sediments, including the Permian, form a foreland fold-and-thrust belt, thrust over the margin of the Angarida Continent. Two zones, foreland and hinterland, are recognized within the N–S Verkhoyansk fold-thrust belt (Fig. 1).

Large linear folds with open hinges extending for 100–250 km or more and 25–50 km wide are typical of the foreland. The folds are generally asymmetrical, with a western vergence. Gentle anticlines and synclines, with axial plunges in both directions (periclines), are predominant in the hinterland. In the lower reaches of the Aldan River, there is a bend in the western part of the foreland to an E–W trend, separating the Verkhoyansk fold-thrust belt into the West Verkhoyansk and South Verkhoyansk domains.

Terrigenous, terrigenous-carbonate and carbonate shelf deposits of Late Precambrian, Early Paleozoic and Middle Paleozoic age crop out in the western part of the domain, along the boundary with the Siberian Platform. These deposits pass eastwards into terrigenous Late Paleozoic and Mesozoic shelf strata. Carboniferous deposits forming an anticlinal core occupy the central part of the West Verkhoyansk domain, whereas the Permian dominates in the east passing further eastwards into Triassic and Jurassic rocks. Folding in the West Verkhoyansk domain was due to the accretion of the Kolyma–Omolon Superterrane. The commencement of folding has been dated as Late Jurassic (Parfenov and Prokopyev, 1993), beginning in the east, successively spreading westwards and ending in the Late Cretaceous with the formation of frontal thrust systems along boundary of the Siberian Platform (Prokopyev, 1998; Prokopyev et al., 2001, and others).

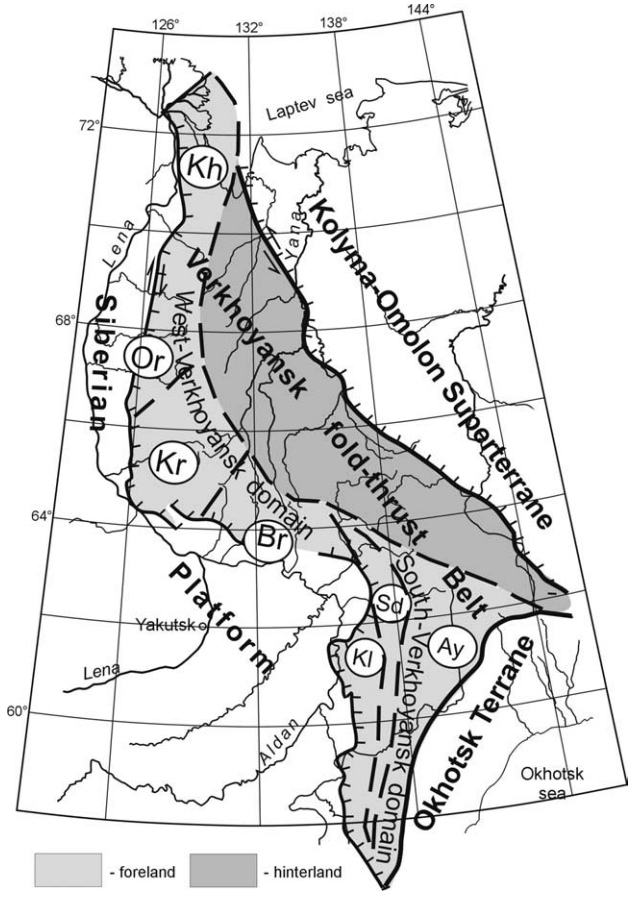

Fig. 1. Tectonic scheme of the Verkhoyansk fold-and-thrust belt. Segments of the West-Verkhoyansk domain: Kh—Kharalaulakhian, Or—Orulganian, Kr—Kuranakhian, Br—Baraian. Segments of South-Verkhoyansk domain: Kl—Killakhian, Sd—Sette-Dabanian, Ay—Allakh-Yunian.

The West Verkhoyansk domain is subdivided into the Kharaulakhian, Orulganian, Kuranakhian and Baraian segments (Fig. 1) which differ from each other in structural features. The Kharaulakhian segment is situated in the northern part of the domain. Relatively deep-water terrigenous turbidites of Carboniferous age occur in the axial part and transgressively overlap Cambrian and Silurian shelf carbonate deposits. Permian turbidites, represented mainly by interbedded mudstones, siltstones and sandstones make up the western and eastern parts of the segment, and concordantly lie on the Carboniferous marine deposits.

The Orulganian segment is formed of Carboniferous and Permian shallow-water marine, littoral-marine, deltaic and alluvial deposits. The Carboniferous occupies the core of a west-vergent asymmetrical anticlinorium and the Permian occurs on its limbs, forming N–S (320°–350°), narrow (2–3 to 5–10 km) and rather extended (40–50 km) folds. On the western limb of the anticlinorium Early Carboniferous terrigenous deposits transgressively overlap Devonian and earliest Carboniferous marine carbonate-terrigenous deposits. On the eastern limb, the basal horizon of the Early Carboniferous deposits is buried and its stratigraphic relationship with the underlying formations of the carbonate complex is obscure.

The Kuranakh segment is in the center of the West Verkhoyansk domain, where the belt begins to curve and change its strike to E–W (Fig. 1). Carboniferous and Permian sediments are of the same type as in the Orulganian segment. The internal zone of the Kuranakh segment is dominated by large (up to several kilometers across) box anticlines with intervening tight synclines (2–5 km), commonly accompanied by steep overthrusts. Westward-vergent structures in the west change to eastward-vergent structures in the east. The outer zone is dominated by fine-scale structures with shallow-dipping thrusts and narrow box ramp anticlines of Triassic and Jurassic, and broad synclines formed in Upper Jurassic and Lower Cretaceous rocks.

The inner zone of the Baraian segment is composed mainly of Carboniferous and Permian shallow marine deposits. Fold structures extend E–W with N–S-vergence and axes oriented at an acute angle to the general strike of the segment. In plan view, the folds and accompanied steep thrusts are arranged en echelon. Steep frontal monoclines with southern limbs dipping at 50°–70°, also arranged en echelon. The en-echelon arrangement of the folds within the segment implies that the structures were formed under conditions of sinistral transpression.

Three tectonic segments (Kyllakhian, Sette-Dabanian, and Allakh-Yunian) are distinguished in the South Verkhoyansk domain (Fig. 1), all of which extend from north to south

throughout the domain. They are made up of rocks of various compositions and display different styles of deformation (Prokopyev, 1989). Of the above segments, only the Allakh-Yunian segment, corresponding to the South Verkhoyansk synclinorium, contains Carboniferous, Permian, Triassic and Jurassic rocks. These are chiefly marine and littoral-marine deposits of the same type as in the West Verkhoyansk domain to the north. The axial part of the South Verkoyansk domain is occupied by Carboniferous rocks, and farther eastward the domain changes to predominantly Permian deposits, which are overlain concordantly by Triassic and Jurassic marine sediments. The western part of the Allakh-Yunian segment is characterized by compressed folds, accompanied with steep overthrusts, and with cleavage parallel to their east-vergent axial planes (Prokopyev, 1989). The folding in the South Verkhoyansk domain was produced by the accretion of the Okhotsk massif (terrane) to the Angarida (Siberian) Continent in the Late Jurassic. Here also the folding migrated from east to west towards the platform and ended in the Late Cretaceous.

3. The Permian of the Verkhoyansk–Okhotsk region

3.1. Paleogeographic setting

The Permian sediments of the Verkhoyansk–Okhotsk region were deposited in a vast sedimentary basin near the margin of the Angarida Continent, at that time the largest continent of the Northern Hemisphere (Klets, 2004). The sedimentary basin began to fill in the Carboniferous after Tournaisian–Visean rifting, but the Permian was characterized by low relief with widely developed shallow-water facies. This sedimentary facies was developed by successive eastward and northward prograding submarine fans (Budnikov, 1984; Parfenov and Kuzmin, 2001). In the Permian exclusively terrigenous sediments were deposited in the Verkhoyansk paleobasin over a vast territory from the mouth of the Lena River to the Sea of Okhotsk (Fig. 2). The main provenance for the sediments was the Angarida Continent. For this reason the Verkhoyansk–Okhotsk Basin is considered to be a separate region, with its own regional subdivisions, and distinct from the Kolyma–Omolon Superterrane. The sedimentary sequence is distinguished by a regular (cyclic) structure formed on a passive continental margin. The cyclic nature of the sedimentation, characterized by mesocycles, is generally regarded as due to the migration of the shoreline of the paleobasin in response to changes in sea-level (Fig. 3; Budnikov, 1988).

More than 40 years ago, the cyclic regularity was taken as the basis of a stratigraphic scheme for the Late Paleozoic deposits of the Verkhoyansk region by many authors (Andrianov, 1966, 1975, 1985; Menner et al., 1970; Abramov et al., 1973; Abramov, 1974; Abramov and Grigorieva, 1988; Solomina, 1997). The boundaries between the cycles are often associated with drastic changes in the diversity, composition and types of the dominant fauna. In general, the lower part of each mesocycle consists mainly of siltstones with marine fossils such as brachiopods and ammonoids, whereas the upper

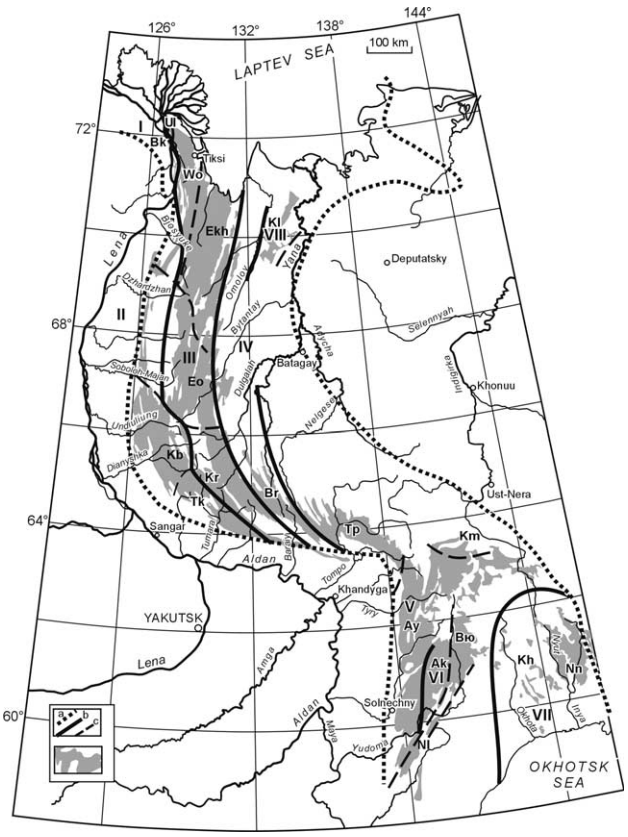

Fig. 2. Distribution of Permian deposits in the Verkhoyansk–Okhotsk region. In boxes: Boundaries: (a) Verkhoyansk–Okhotsk region; (b) structural-facies zones, (c) subzones; Shading—Permian outcrops. Structural-facies zones: I—Bulkur-Olenekian, II—West-Verkhoyanian, III—Central-Verkhoyanian, IV—East-Verkhoyanian, V—South-Verkhoyanian, VI—Yudoma-Majian, VII—Okhotian, VIII—Yana-Indigirkian; subzones: Bk—Bulkurian, Wo—West-Orulganian, Tk—Tukulanian, Kb—Kobichanian, Ul—Ust-Lenian, Wkh—West-Kharaulakhian, Ekh—East-Kharaulakhian, Eo—East-Orulganian, Kr—Kuranakhian, Br—Baraian, Tp—Tomponian, Ay—Allakh-Yunian, Km—Kobyuminian, Ak—Akachanian, Vy—Verkhneyudomian, Nl—Nyulikian, Kh—Kukhtuiian, Nn—Nyut-Nilgisigian, Kl—Kularian.

part consists of littoral-marine and littoral-continental, mainly sandy rocks, containing a predominantly bivalve fauna. In addition, fossil floras occur locally (Budnikov et al., 1997; Klets et al., 2001b; Kutygin et al., 2002; and others).

3.2. Lower and upper boundaries of the Permian

Permian deposits are abundant throughout the Verkhoyansk–Okhotsk region, where they rest concordantly upon Upper Carboniferous deposits of the Kygyltassian Horizon which contains the brachiopods *Jakutoproductus protoverchoyanicus* Kaschirzev, *J. expositus* Ganelin, *Cancrinella grandis* Solomina, *Pterospirifer terechovi* Zavodowsky, *Jakutochonetes tachanensis* Klets and *Attenuatella omolonensis* Zavodowsky and a flora of *Angaropteridium cardiopteroides* (Schmalhauzen), *Angaridium finale* Neuburg, *Cordaites latifolius* (Neuburg), *Rufloria theodorii* (Tschirkova and Zalesskiy), *R. derzavinii* (Neuburg), *R. tschirkovae* Zalesskiy, *Evenkiella zamiopteroidea* Radczenko, *E. schortonotensis* Gorelova, *Ginkgophyllum vsevolodii* Zalesskiy, *Samaropsis*

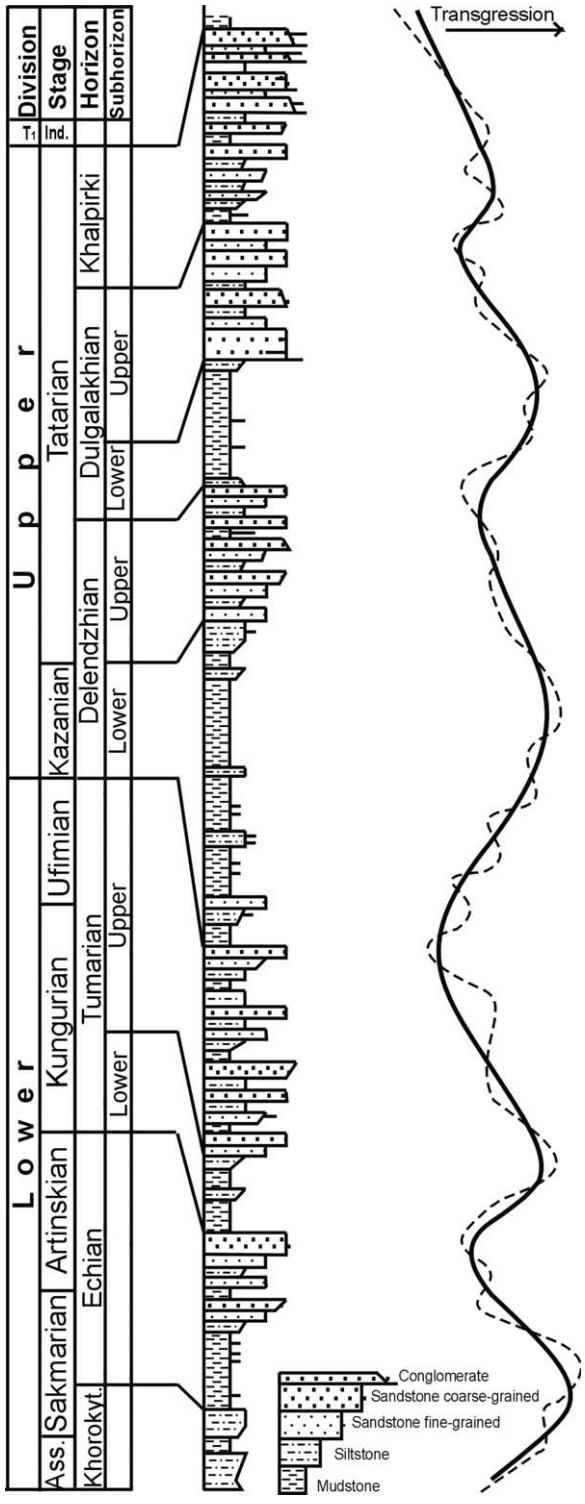

Fig. 3. The type Permian rock succession in the Verkhoyansk–Okhotsk Region. Solid line = major cycles; dashed line = minor cycles.

auriculata Neuburg, *S. pauxilla* Zalesskiy, *S. patula* Zalesskiy, *S. tscheremitchiensis* Suchov, *S. euryptera* Suchov and *Cardiocarpus krivljakiensis* Suchov. This flora is typical of the Alykaevian Horizon in the Kuznetsk Basin (south of West Siberia) (Danilov and Budnikov, 1989).

According to the resolution of the Russian Stratigraphic Interdepartmental Stratigraphic Committee (Zhamoida et al., 1992), the Permian system is divided into two epochs. The Lower Permian is subdivided into the Asselian, Sakmarian, Artinskian and Kungurian Stages, and the Upper Permian into the Ufimian, Kazanian and Tatarian Stages. In the Verkhoyansk–Okhotsk region the boundaries and extent of these stages are rather conventional. However, recent findings of Uralian elements in the Verkhoyansk region and of once-endemic Verkhoyansk forms beyond the Verkhoyansk region, in particular in the Urals, provided new support for recognizing the Artinskian, Kungurian and Kazanian stages in the region.

The location of the lower boundary of the Permian in the Verkhoyansk–Okhotsk region is still debatable. Until recently the boundary was marked by the change from the brachiopod group *Verkhojania cheraskowi* to the group *Jakutoproductus verkhojanicus*. After the species abundance of the genus *Jakutoproductus* was refined, many authors (Abramov and Grigorieva, 1988; Solomina, 1997) suggest drawing this boundary at the base of the *Jakutoproductus protoverkhojanicus* Zone, which would correspond to the boundary between the Baraian and Setlandian Horizons (Klets et al., 2001a). The Third Stratigraphic Meeting on the Precambrian, Paleozoic and Mesozoic of Northeastern Russia (4–6 December 2002) came to a decision, based chiefly on the stratigraphic distribution of ammonoids (Andrianov, 1985; Kutygin et al., 2002), that the lower boundary of the Permian in the Verkhoyansk–Okhotsk region should lie at the base of the Khorokytian Horizon. The boundary between the Lower and Upper Permian matches the base of the Roadian Stage of North America and is one of the most distinctive and persistent biostratigraphic benchmarks in NE Asia (Kotlyar, 1997).The upper boundary of the Permian runs through the top of the Khalpirki Horizon, above which lie deposits with Early Triassic invertebrates.

3.3. Biostratigraphy

The Permian deposits of the Verkhoyansk–Okhotsk region are divided into six regional stratigraphic units ranked as 'horizons' (=regional stages), which are in turn subdivided into faunal zones and beds, serving as a base for intra-regional correlations (Tables 1 and 2).

3.3.1. The Khorokytian Horizon

The type locality is the section of the Khorokyt Formation on the Delendzha River opposite the mouth of the Khorokyt Brook. Within the Verkhoyansk–Okhotsk region the thickness of the horizon varies from 250 to 400 m. According to brachiopods and ammonoids, the *Jakutoproductus verchoyanicus–Spirelytha fredericksi* Zone and beds with *Bulunites mezhvilki* have been recognized, respectively, within this horizon. The brachiopods are characteristic of the lower Permian of Taimyr (Ustritsky and Chernyak, 1963) and also the Kolyma–Omolon region (Ganelin, 1984, 1990). The *Jakutoproductus verchoyanicus* Zone has also been recognized in the Jungle Creek Formation of Northern Yukon Territory (Shi and Waterhouse, 1996). The Asselian–Early Sakmarian age of the Khorokytian Horizon is inferred from the coexistence of the ammonoid genera *Bulunites*, *Juresanites*

Table 1
Brachiopod and goniatite zones and key species of regional stratigraphic units

Division	Stage	Horizon	Subhorizon	Brachiopod Zones	Goniatite Zones	Faunal complexes: Brachiopods	Faunal complexes: Goniatites
				Regional stratigraphic units			
Upper	Tatarian	Khalpirki		**Crassispirifer monumentalis**		*Biplatyconcha lungersgauzeni*, *Grantonia grandis*, *Marginalosia? magna*, *Crassispirifer monumentalis*, *Strophalosia sibirica*	
		Dulgalakhian	Upper	**Cancrinelloides obrutschevi-C. curvatus**		*Cancrinelloides obrutschewi*, *C. curvatus*, *Strophalosia grandis*, *S. sibirica*, *Beecheria* aff. *chivatschense*, *Windhamia gijigensis*, *Brachythyrina sibirica*, *Biplatyconcha lungersgauzeni*, *Grantonia grandis*, *Spitzbergenia snjatkovi*	
			Lower				
		Delendzhian	Upper	**Tumarinia zavodowskyi**		*Cancrinelloides juregensis*, *Strophalosia sibirica*, *Tumarinia zavodowskyi* , *T. ganelini*, *Brachythyrina sibirica*, *Baitugania boguchanica*, *Waagenoconcha wimani*	
	Kazanian		Lower	**Terrakea**	**Sverdrupites baraiensis**	*Waagenoconcha wimani*, *Terrakea belokhini*, *T. korkodonensis*, *Megousia yakutica*, *Tumarinia orientalis*, *T. ganelini*	*Sverdrupites baraiensis*, *S. amundseni*, *Daubichites* sp.
				Mongolosia russiensis	**Sverdrupites harkeri**	*Mongolosia russiensis*, *M. morenkovi*, *Spitzbergenia gracilis*, *Tumarinia ganelini*, *Jakutochonetes orulganicus*, *Yakovlevia mammatiformis*	*Sverdrupites harkeri*, *Pseudosverdrupites budnikovi* , *Popanoceras subtumarense*
	Ufim.	Tumarian	Upper	**Kolymaella ogonerensis**		*Kolymaella ogonerensis*	
Lower	Kungurian			**Megousia kuliki**	**Epijuresanites musalitini**	*Megousia kuliki*, *Striapustula koninckiana*, *Neotumarinia barajensis*, *Rhynchopora variabilis*	*Epijuresanites musalitini*, *Tumaroceras kashirzevi*
			Lower	**Anidanthus aagardi**	**Tumaroceras yakutorum**	*Anidanthus aagardi*, *Labuella kolymaensis*, *"Cancrinella" janischewskiana*	*Tumaroceras yakutorum*, *T. volkodavi*, *Paratumaroceras ruzhencevi*, *Popanoceras tumarense*, *Neouddenites andrianovi*
	Artinskian	Echian					*Paratumaroceras?* sp. nov. *Paragastrioceras* sp.
				Jakutoproductus burgaliensis - Spirelytha kislakovi	**Eotumaroceras subyakutorum**	*Jakutoproductus burgaliensis*, *Waagenoconcha wimani*, *Tomiopsis taimyrensis*, *Spirelytha kislakovi*	*Eotumaroceras subyakutorum*, *Paragastrioceras kirghizorum*, *P.* aff. *ellipsoidale*, *P.? tuberculatum*, *Uraloceras popowi*, *U. evencorum*
				Jakutoproductus rugosus - Alispiriferella gydanensis	**Eotumaroceras endybalense**	*Jakutoproductus rugosus*, *Anidanthus megensis*, *Neospirifer subfasciger*, *Kjutepia alata*, *Neochonetes brama*, *Alispiriferella gydanensis*	*Eotumaroceras endybalense*, *Paragastrioceras ? tuberculatum*
	Sakmarian				**Uraloceras subsimense**		*Neoshumardites hyperboreus*, *Metalegoceras crenatum*, *Agathiceras verkhoyanicum*; *Uraloceras subsimense*, *Andrianovia bogoslovskyi*, *Metapronorites angustus*
	Asselian	Khorokytian		**Jakutoproductus verchoyanicus - Spirelytha fredericksi**	**Bulunites mezhvilki**	*Jakutoproductus verchoyanicus*, *Jakutoproductus crassus*, *J. parenensis*, *Anidanthus boikowi*, *Neochonetes brama*, *Quinquenella pseudobrama*	*Bulunites mezhvilki*, *Eoasianites ? menneri*, *Juresanites ? maximovae*, *Agathiceras verkhoyanicum*

and *Tabantalites* in the Tuorasis Formation in the lower reaches of the Lena River.

Biostratigraphic assemblages with bivalves are hard to recognize within the Khorokytian Horizon in the Verkhoyansk–Okhotsk region, despite the presence of many bivalve species typical of the bivalve zones of the Kolyma–Omolon region. For example, the index species of the lower bivalve zone, *Palaeoneilo parenica* Biakov, occurs in sections

Table 2
Bivalve and floral complexes (assemblages) of regional stratigraphic units

Division	Stage	Horizon	Subhorizon	Brachiopod Zones	Bivalve	Flora
					Regional stratigraphic units	
					Faunal and floristic complexes	
Upper	Tatarian	Khalpirki		**Crassispirifer monumentalis**	Upperkhalpirki complex - *Polidevcia magna, Maitaia quadrata, Intomodesma costatum, I. bicarinatum, I. turgidum, Myonia gibbosa, M. bicarinata, Streblochondria ? corrugata, Vnigripecten volucer* Lowerkhalpirki complex - *Maitaia* cf. *tenkensis, Atomodesma variabile, Polidevcia* ex gr. *zabaikalica , Streblopteria levis*	*Cordaites gracilentus, C. gorelovae, C. khalfinii, Ñ. angustifolius, C. clercii, C. incisus, C. platyphyllus, Rufloria* sp., *Crassinervia* cf. *pentagonata, Lepeophyllum rotundatum, L. actaeonnelloides, L. kostomanovii, Nephropsis tomiensis, N. schmalhausenii, Samaropsis erunakovensis, Tungussocarpus tychtensis*
		Dulgalakhian	Upper	**Cancrinelloides obrutschevi-curvatus**	In upper part - *Maitaia bella, Streblopteria* cf. *levis, Myonia longa, Wilkingia bulcurensis*	
			Lower		In lower part - *Polidevcia* ex gr. *ovata, Cunavella etheridgeiformis, Myonia elata, Wilkingia bulkurensis*	*Cordaites gracilentus, Rufloria brevifolia, Samaropsis iljinskiensis*
	Kazanian	Delendzhian	Upper	**Tumarinia zavodowskyi**	*Kolymia multiformis, K. pergamenti, K. nikolajewi, Maitaia lenaensis, Kolymia verchojanika, Oriocrassatella elongata, Myonia* ex gr. *komiensis, Myonia bulkurensis*	*Salairia longifolia, Uscatia conferta, Phyllotheca turnaensis, Cordaites candalepensis, C. kusnetskianus, Rufloria brevifolia, Crassinervia primitiva, Cr. kuznetskiana, Cr. meyenii, Cladostrobus lutuginii, Samaropsis ampuliformis, Tungussocarpus tychtensis, T. budnikovii, T. rotundatus, Skokia elongata, Sylvella elongata*
			Lower	**Terrakea**	*Kolymia* ex gr. *simkini, K. irregularis, K.* cf. *plicata, K. kasanenkoi, Kolymia* ex gr. *angusta*	*Uskatia conferta, Paracalamites angustus, Cordaites singularis, Rufloria derzavinii, Crassinervia primitiva, Cr. kuznetskiana, Samaropsis danilovii, Tungussocarpus* sp.
				Mongolosia russiensis	*Polidevcia omolonica, Aphanaia stepanovi, Kolymia simkini, K.* ex gr. *yurii, Kolymia inoceramiformis, K. aurita, Aviculopecten kolymaensis*	
	Ufim.	Tumarian	Upper	**Kolymaella ogonerensis**		*Zamiopteris glossopteroides, Cordaites latifolius, Ñ. singularis, Rufloria derzavinii, Crassinervia tunguscana, Cr. primitiva, Cr. gorlovskiana, Cr. angusta, Nephropsis integerrima, N. rhomboidea, Vojnovskyia* sp., *Samaropsis triqetraeformis, S. prokopievskiensis, S. pseudoelegans, S. skokii, S. danilovii, S. stricta, S. elegans, Bardocarpus* sp., *Skokia elongata, Sylvella alata, Carpolithus* sp.
				Megousia kuliki	*Aphanaia andrianovi, Aphanaia* cf. *ganelini, A. popowi, Parallelodon striatus, Polidevcia undosa, Aviculopecten kolymaensis, Undopecten keyserlingi, Astartella multicostata, A. permocarbonica, Solemya solikamica*	
	Kungurian		Lower	**Anidanthus aagardi**		*Phyllopitys heeri, Paracalamites vicinalis, Zamiopteris* sp., *Cordaites latifolius, C. singularis, Rufloria derzavinii, R. rasskasovae, Crassinervia kuznetskiana, Nephropsis integerrima, N. rhomboidea, Samaropsis skokii, S. khalfinii, S. neuburgii* cf. *bungurica, S. triqetraeformis, Skokia elongata, Sylvella* sp.
Lower	Artinskian	Echian			*Aphanaia lima, A. borlichi, A. formosa, Astartella multicostata, P. undosa, Aviculopecten* cf. *mutabilis, Aviculopecten mutabilis, Lithophaga gigantea, Praeundulomya urbajtisae*	
				Jakutoproductus burgaliensis - Spirelytha kislakovi		
				Jakutoproductus rugosus - Alispiriferella gydanensis		
	Sakmarian					
	Asselian	Khorokytian		**Jakutoproductus verchoyanicus - Spirelytha fredericksi**	*Nuculopsis* cf. *postolegi, Polidevcia* cf. *kolyvanica, Myophossa* cf. *subarbithrata*	*Phyllopitys* sp., *Angaropteridium cardiopteroides, Angaridium finale, Glottophyllum primaevum, Cordaites singularis, Rufloria theodorii, R. derzavinii, Ginkgophyllum primaevus, Samaropsis pauxilla, S. auriculata*

of the Dzhuptagin Formation of the South Verkhoyansk subregion, and another typical species of this zone, *Sanguinolites lukjanovae* Muromzeva, has also been described from the Megen Formation of the West Verkhoyansk subregion. *Merismopteria permiana* (Kulikov) is the index species of the bivalve zone of the Ogoner Horizon of the Kolyma–Omolon region, which also occurs in the North Verkhoyansk subregion, from the mouth of the Lena River (Kulikov, 1967).

At the top of the Khorokytian Horizon there are *Polidevcia* cf. *kolyvanica* Muromzeva, *Nuculopsis* cf. *postolegi* Biakov and *Myophossa* cf. *subarbithrata* (Dickins) (Kutygin et al., 2002), which are also found in the Oroch and Ogoner Horizons of the Kolyma–Omolon region. In addition, Muromzeva and Guskov (1984) have reported *Aviculopecten mutabilis* Licharew, *Lithophaga gigantea* (Stuckenberg) and *Praeundulomya urbajtisae* Muromzeva from the lower part of the Lower Permian in the Verkhoyansk region. The Verkhoyansk region also yields species that are absent from the Kolyma–Omolon region, but nevertheless are present in other parts of the Boreal biogeographic area (in the Urals, in the north of Russian Platform), e.g. *Acanthopecten licharewi* (Fredericks); there are also species endemic to the Verkhoyansk region: *Wilkingia verchojanika* (Muromzeva) (South and West Verkhoyansk subregions) and *Verchojanogramyssia*? *saphronovi* Muromzeva (West Verkhoyansk subregion).

The flora of the Khorokytian Horizon is typical of the lower part of the Burguklin Horizon of the Siberian Platform and the lower part of the Promezhutochny Horizon of the Kuznetsk Basin (south of West Siberia) (Danilov and Budnikov, 1989; Durante, 1996).

3.3.2. The Echian Horizon

The Echian Horizon at the type locality (Endybal and Echiy Rivers) comprises the Endybal–Echiy, Mysov, and Khabakh Formations. Its thickness in the study area ranges from 850 to 1200 m, and includes the brachiopod *Jakutoproductus rugosus–Alispiriferella gydanensis* and *Jakutoproductus burgaliensis–Spirelytha kislakovi* Zones. Brachiopods of these zones have been known from the coeval deposits of Taimyr, Kolyma–Omolon region, and Transbaikalia (Ustritsky and Chernyak, 1963; Kotlyar and Popeko, 1967; Ganelin, 1984, 1990). Ammonoid zones corresponding to these brachiopod zones are the *Uraloceras subsimense* and *Eotumaroceras endybalense* zones and the *Eotumaroceras subyakutorum* zone, respectively. The last two ammonoid zones contain species typical of the Aktastinan Substage, or for the Baigendzhinian Substage of the Artinskian Stage in the Urals.

Bivalves are found at the top of the Echian Horizon. On the basis of specific *Inoceramus*-like bivalves such as *Aphanaia lima* (Lutkevich and Lobanova), *A.* aff. *lima* (Lutkevich and Lobanova) and *A. borlichi* (Astafieva), the *Aphanaia lima* Zone can be correlated with the upper half of the Koargychan Horizon (Lower Permian) in the Kolyma–Omolon region (Ganelin et al., 2003). In addition to the above-mentioned bivalves, there are species of a wider stratigraphic range—*Polidevcia* cf. *undosa* (Muromzeva) and *Aviculopecten* cf. *mutabilis* Licharew. The West Verkhoyansk endemics are *Aphanaia aenigma* Astafieva and, probably, a new species *Wilkingia*? sp., as well as *Aphanaia formosa* Astafieva, which also occurs in North Verkhoyansk region (Northern Kharaulakh). A.Biakov (in Kutygin et al., 2002) believes that *Aphanaia lima* and the *Eotumaroceras* fauna characterize the post-*Jakutoproductus* stratigraphic interval.

The floral assemblages of the Khabakh Formation and its equivalents (uppermost Echian Horizon) are typical of the bottom of the Upper Burguklin Subhorizon of the Siberian Platform and the Ishanov Horizon of the Kuznetsk Basin (Durante and Izrailev, 1977; Danilov and Budnikov, 1989; Durante, 1996; and others). Conventionally, the upper (regressive) part of the Echian Horizon is compared with the uppermost Artinskian Stage (Kutygin et al., 2002).

3.3.3. The Tumarian Horizon

This horizon is recognized in the basin of the Tumara River to encompass the Orol, Takamkyt and Kadachan Formations (Menner et al., 1970; Andrianov, 1975). In the Verkhoyansk–Okhotsk region the thickness of the horizon varies from 210 to 750 m, reaching a maximum thickness of 3300 m in the East Kharaulakh subzone of the Central Verkhoyansk zone.

Brachiopod beds with *Anidanthus aagardi*, *Megousia kuliki* and *Kolymaella ogonerensis* are recognized within the horizon as well as beds with the ammonoids: *Tumaroceras yakutorum* and *Epijuresanites musalitini*. The brachiopod species of the horizon have been found not only in coeval deposits of Taimyr and Kolyma–Omolon regions, but also in the Kungurian Stage of the Urals. The ammonoidean fauna indicates a Kungurian age for the Tumara deposits. Additional support for this age assignment also comes from remains of the species *Baraioceras stepanovi* Andrianov, found in the alluvium of the Imtan'ya Brook (Baraiy basin) in the outcrop area of the Tumara Formation. This species is close to the Kungurian *Paragastrioceras kungurense* (Mirskaya). The bivalve fauna of the Tumarian Horizon corresponds to the *Aphanaia andrianovi* Zone of the lower half of the Khalala Horizon in the Kolyma–Omolon region. In the West Verkhoyansk subregion, the Tumarian Horizon contains *Aphanaia andrianovi* (Muromzeva and Kusnezov), *Aphanaia* cf. *ganelini* Biakov, *Praekolymia*, gen. & sp. nov., *Polidevcia undosa* (Muromzeva), *Parallelodon striatus* (Schlotheim), *Aviculopecten kolymaensis* Maslennikov, *Undopecten keyserlingi* (Stuckenberg) (also found in the North Verkhoyansk subregion), *Pyramus*? ex gr. *bonus* (Lutkevich and Lobanova), *Astartella multicostata Dembskaya, Permophorus* sp., *Streblochondria* ex gr. *krasnoufimskensis* (Fredericks) and *Solemya* cf. *biarmica* Verneil. These species also occur in the sections of the Kolyma–Omolon region. Such species as *Aphanaia* sp. nov., *A. triangula* Astafieva, *Pyramus* sp. and *Myonia* sp., are endemic to the West Verkhoyansk region. *Aphanaia popowi* (Muromzeva and Kusnezov), *A. pogorevitschi* (Muromzeva and Guskov) and *Praekolymia* ? *alitis* (Astafieva) are endemics of the South Verkhoyansk subregion and the northeastern margin of the Okhotsk Massif; the former is also found in the West Verkhoyansk subregion. The species *Polidevcia lunulata* (Dembskaya), *Solemya solikamica* Muromzeva, *Aviculopecten*? *uralicus* Fredericks, *Permophorus angustus* Muromzeva and *Prothyris cilindricus* Muromzeva and Guskov are typical for the Kungurian-Ufimian fauna of the Urals, Novaya Zemlya, West Verkhoyansk and South Verkhoyansk regions.

The floral assemblage of the Upper Tumarian Subhorizon is typical of the Kemerovo Horizon of the Kuznetsk Basin and the

Upper Burguklin Subhorizon of the Siberian Platform (Tolstikh, 1974; Danilov and Budnikov, 1989; Durante, 1996; Durante and Pukhonto, 1999).

No ammonoids are known from the upper Tumarian Horizon of the Verkhoyansk region ('Lower Moguchan' or 'Kadachan' beds). This level is characterized by a brachiopod assemblage dominated by *Kolymaella ogonerensis*. This upper part of the horizon is conventionally attributed to the Ufimian Stage on the basis of its stratigraphical position between beds with Kungurian and Roadian ammonoids.

3.3.4. The Delendzhian Horizon

The type locality of this horizon is the section of the Delendzha Formation located in the Delendzha Basin along Takamkyt Brook (Andrianov, 1966). The thickness of the horizon ranges from 575 to 950 m, reaching a maximum of 2500 m in the East Kharaulakh subzone of the Central Verkhoyansk zone. Two subhorizons and three zones (beds with faunas) are recognized within the horizon. The Lower Delendzhian Subhorizon covers the brachiopod *Mongolosia russiensis* Zone and beds with *Terrakea*, and also the ammonoid zones of *Sverdrupites harkeri* and *Sverdrupites baraiensis*. In general, brachiopods are typical of the base of the Upper Permian in many regions of northeastern Russia. Ammonoids indicate a Roadian age (Andrianov, 1985; Kutygin, 1996, 1997). The subhorizon also matches the lower part of the Kazanian Stage of the Russian Platform, because the genus *Sverdrupites* has been found there (Leonova et al., 2002). Within the Upper Delendzhian Subhorizon, beds with *Tumarinia zavodowskyi* are recognized.

The Delendzhian Horizon of the Verkhoyansk–Okhotsk region contains four bivalve zones originally established in sections in the Kolyma–Omolon region (Ganelin et al., 2003) (Table 2). The genus *Kolymia* s.s. appears at the base of the horizon. The lower *Aphanaia dilatata* Zone can only be distinguished on the northeastern margin of the Okhotsk Massif, where the index species coexists with *Polidevcia omolonica* Biakov, *Aphanaia stepanovi* (Muromzeva), *Kolymia simkini* Popow and *K.* ex gr. *yurii* Popow. The *Kolymia inoceramiformis* Zone is distinguished virtually throughout the Verkhoyansk–Okhotsk region. Along with the characteristic species of the fauna such as *Polidevcia omolonica* Biakov, *Kolymia aurita* Astafieva, *K. simkini* Popow, *K.* ex gr. *yurii* Popow and *K.* cf. *nikolaevi* (Voronez), some other taxa are observed only locally within the Verkhoyansk–Okhotsk region. For example, within the northeastern margin of the Okhotsk Massif, only kolymiid and some ctenodontid bivalves are present, and *Aviculopecten kolymaensis* Maslennikov, *Wilkingia?* sp. and *Myonia* ex gr. *komiensis* (Maslennikov) appear in the Okhotsk Massif and in the South Verkhoyansk subregion. In the North Verkhoyansk subregion, the endemic species *Aphanaia licharewi* Muromzeva seems to occur at this level. In the West Verkhoyansk subregion, the Delendzhian Horizon is enriched with *Pyramus* ex gr. *bonus* (Lutkevich and Lobanova), *Myonia* sp. (*M.* ex gr. *elata* (Popow)), *Liebeia*? sp., *Pseudomonotis*? sp., *Permophorus*? sp., *Astartella* sp. and *Dulunomya*? sp. The *Kolymia plicata* Zone is distinguished in some sections of the northeastern margin of the Okhotsk Massif. The index species coexists there with *Kolymia* cf. *pergamenti* Muromzeva, *K.* cf. *nikolaevi* (Voronez) and *K. simkini* Popow. In the West Verkhoyansk region this zone is recognized by the presence of *K.* cf. *plicata* Biakov, *K.*? cf. *irregularis* Licharew, *Kolymia*? sp., *Kolymia kasanenkoi* Astafieva and Kusnezov, *Kolymia* ex gr. *angusta* Astafieva and *Wilkingia* sp.; the last three species being endemics. Large *Aphanaia* ex gr. *stepanovi* (Muromzeva) disappears. In the North Verkhoyansk region, the endemics, *Kolymia miranda* Astafieva, *K. anaticula* Astafieva and *K. nebulae* Kulikov, as well as *K. aurita* Astafieva, are present at this level. The *Kolymia multiformis* Zone is rather ubiquitous. In addition to the index species, there are *Polidevcia* cf. *cumboides* (Lutkevich and Lobanova) *Kolymia pergamenti* Muromzeva, *Kolymia nikolaewi* (Voronez), *Maitaia lenaensis* (Voronez), *Oriocrassatella elongata* Newell and *Myonia* ex gr. *komiensis* (Maslennikov). The endemic species, *Kolymia verchojanika* Popow, *Maitaia absoluta* Astafieva, *Maitaia solominae* Astafieva and *Myonia bulkurensis* Astafieva–Urbajtis, typically occur in the North Verkhoyansk subregion, and *Aviculopecten orientalis* Fredericks is also found there. The genus *Kolymia* becomes completely extinct at the Delendzhian-Dulgalakhian boundary.

The floral assemblage of the Upper Delendzhian Subhorizon is comparable with that of the upper Kuznetsk-lower Il'yin subseries of the Kuznetsk Basin and the top of the Pelyatkin Horizon of the Siberian Platform (Tolstikh, 1974; Danilov and Budnikov, 1989). According to M.V. Durante and Kuznetsk geologists, the Upper Delendzhian floral complex should be restricted to the Mitino Horizon of the Kuznetsk Basin (Betekhtina et al., 1988; Durante, 1996; Durante and Pukhonto, 1999, and others).

3.3.5. The Dulgalakhian Horizon

This horizon is recognized at the type locality in the Dulgalakh River Basin (Andrianov, 1975). The horizon matches the range of the brachiopod *Cancrinelloides obrutshevi–C. curvatus* Zone. The thickness of the horizon varies in the region from 380 to 900 m, reaching a maximum, 2250 m, in the East Kharaulakh subzone of the Central Verkhoyansk structural facies zone (Grinenko et al., 1997) (Fig. 2). The upper Dulgalakhian Horizon coincides with the range of the *Maitaia bella* Zone. Beds with *Polidevcia* ex gr. *ovata* are distinguished in the lower part of this horizon in the West Verkhoyansk subregion. Along with the *Polidevcia* ex gr. *ovata* Laseron, *Cunavella etheridgeiformis* Astafieva–Urbajtis, '*Modiolus extensus* (Lutkevich and Lobanova)', *Myonia elata* Popow and *M.* aff. *gibbosa* (Maslennikov) occur at the bottom, whereas at the top there are *Streblopteria* cf. *levis* (Lutkevich and Lobanova), *Modiolus* sp. and *Cunavella etheridgeiformis* Astafieva–Urbajtis. In the North Verkhoyansk subregion, *Wilkingia bulkurensis* (Muromzeva) and the endemic *Myonia lutkevichi* Astafieva–Urbajtis, *Australomya sulcatiformis* Astafieva–Urbajtis typically occur at the bottom of the horizon. In the South Verkhoyansk subregion,

Megadesmus borealis Muromzeva is found. Most of the species of the Dulgalakhian Horizon are not known in the Kolyma–Omolon sections, with the exception of species of *Myonia* and *Maitaia bella* Biakov.

The upper part of the horizon is characterized by a flora typical of the Kazankovo, Markovo, and Leninsk Horizons of the Kuznetsk Basin and the Degalinsk Horizon of the Siberian Platform (Tolstikh, 1974; Danilov and Budnikov, 1989; Durante, 1996).

3.3.6. The Khalpirki Horizon

This horizon forms the top of the Upper Paleozoic succession in the Verkhoyansk–Okhotsk region. Its type section lies in the Khalpirki River (Solomina, 1997; Kutygin et al., 2003). The deposits of this horizon are 125–250 m thick, reaching 750 m in the East Kharaulakh subzone of the Central Verkhoyansk Zone. Brachiopods species typical of the Khalpirki Horizon are *Marginalosia*? *magna* Abramov and Grigorieva, *Biplatyconcha lungersgauzeni* (Solomina), *Grantonia grandis* Solomina, *Baitugania*? sp. and *Crassispirifer monumentalis* Abramov and Grigorieva. These brachiopod species have not been found elsewhere in eastern Russia.

Two bivalve zones are recognized in the Khalpirki Horizon. The lower *Maitaia tenkensis* Zone is distinguished at the bottom in the West Verkhoyansk subregion only. In addition to the index species it contains *Polidevcia* ex gr. *zabaikalica* Biakov, *Polidevcia* sp., *Maitaia belliformis* Biakov, *Maitaia* sp. and *Streblopteria levis* (Lutkevich and Lobanova), as well as bipolar *Atomodesma variabile* Wanner and *A. exaratum* Beyrich. The *M. tenkensis* Zone is also present on the northeastern margin of the Okhotsk Massif and in the Ayan–Yuryakh anticlinorium (Biakov and Vedernikov, 1990). The *Intomodesma costatum* Zone is distinguished throughout the Verkhoyansk–Okhotsk region in the upper half of the Khalpirki Horizon. The fauna includes numerous representatives of *Intomodesma*: *I. costatum* Popow, *I. evenicum* Kusnezov, *I. turgidum* Popow and *I. bicarinatum* (Muromzeva), as well as *Myonia bicarinata* Astafieva–Urbajtis, *Myonia gibbosa* (Maslennikov), *Streblopteria levis* (Lutkevich and Lobanova) and *Streblochondria*? *corrugata* Lutkevich and Lobanova. Also, *Polidevcia magna* (Popow), *Polidevcia* ex gr. *zabaikalica* Biakov, *Polidevcia* sp., *Vnigripecten volucer* (Lutkevich and Lobanova) are typical components of the zone in the South and West Verkhoyansk subregions. Most of the above species are typical of the upper part of the Khivach Horizon of the Kolyma–Omolon region (Biakov, 2000). The endemics are: *Myonia bytantajensis* Astafieva–Urbajtis in the North Verkhoyansk subregion, *Streblopteria kusnezovi* Muromzeva and *Fasciculiconcha*? *tompe* (Muromzeva) in the West Verkhoyansk subregion, and *Cunavella*? *dibika* Muromzeva in the South Verkhoyansk subregion. The Australian species *Vacunella*? *oblonga* Waterhouse is also found in the North Verkhoyansk subregion.

In addition to marine invertebrates, the upper part of the Khalpirki Formation at its type locality contains floral remains: *Rufloria* cf. *brevifolia* (Gorelova), *Cordaites gracilentus* (Gorelova), *C. gorelovae* Meyen, *C.* sp. typ. *C. kuznetskianus* (Gorelova), *Crassinervia* cf. *pentagonata* Gorelova, *Lepeophyllum rotundatum* Radczenko, *Nephropsis* sp. (similar to *N. schmalhausenii* Radczenko), *Samaropsis* ex gr. *borisovaensis* Suchov and *Tungussocarpus tychtensis* (Zalesskiy). In V.E. Sivchikov's opinion, the age of these plants is safely determined as equivalent to the Il'yin series of the Kuznetsk Basin, which he believes to be Kazanian (Budnikov et al., 2003). According to M.V. Durante (Durante and Izrailev, 1977), ruflorias-free *Erunakov* assemblages are present at the top of the section in the Verkhoyansk region. However, our recent studies of the sections of the Kol'chugino series in the Kuznetsk basin suggest that the *Rufloria* extinction was not drastic and was connected with a sea-level drop in the paleobasin and the complete disappearance of the basin facies in the second half of Erunakovo time (Budnikov et al., 2003). As to the Verkhoyansk region, littoral-marine conditions of sedimentation with *Rufloria* continued until the end of the Permian.

Triassic deposits with a distinct lithology overlap the deposits of the Khalpirki Horizon In the Verkhoyansk–Okhotsk region (Setorym River) the Permian-Triassic contact is considered to be concordant where beds with early Induan goniatites *Otoceras* overlie Permian beds with *Mexicoceras*.

4. Conclusions

The best marine Permian sections of Siberia occur in the Verkhoyansk–Okhotsk region. The entire succession of the Permian terrigenous rocks (sandstones, siltstones and argillites) is about 4–6 km thick. The biostratigraphy and the stratigraphic correlation of these Permian rocks are based mainly on brachiopod and bivalve faunas, but the location of stage boundaries in particular sections are defined mainly by ammonoids. Six regional horizons and 19 biozones have been established for the Permian of this region. The Khorokytian Horizon is of Asselian-Early Sakmarian age and includes the brachiopod *Jakutoproductus verchoyanicus–Spirelytha kislakovi* Zone and the ammonoid *Bulunites mezhvilki* Zone. The Echian Horizon is of Late Sakmarian-Artinskian age and includes two brachiopod zones: *Jakutoproductus rugosus–Alispiriferella gydanensis* and *Jakutoproductus burgaliensis–Spirelytha kislakovi* and three ammonoid zones: *Uraloceras simense, Eotumaroceras endybalense* and *Eotumaroceras subyakutorum,* all in ascending order. The Tumarian Horizon is of Kungurian-Ufimian age and includes three brachiopod zones: *Anidanthus aagardi, Megousia kuliki* and *Kolymaella ogonerensis* and two ammonoid zones: *Tumaroceras yakutorum* and *Epijuresanites musalitini*. The Delendzhian Horizon is of Kazanian-Early Tatarian age and incorporates three brachiopod zones: *Mongolosia russiensis, Terrakea* and *Tumarinia zavodowskyi* and two ammonoid zones: *Sverdrupites harkeri* and *Sverdrupites baraiensis.* The Dulgalakhian Horizon is of Middle Tatarian age and includes brachiopod zone *Cancrinelloides obrutschevi.* Ammonoidea are not known. The Khalpirki Horizon is of Late Tatarian age and includes the brachiopod *Crassispirifer monumentalis* Zone, with no ammonoids.

On the whole the Permian faunas and floras of the Verkhoyansk–Okhotsk region are similar to those of the

Taimyr, Transbaikalia and Kolyma–Omolon regions. Differences from latter are related to the wide distribution of carbonate facies in the Kolyma–Omolon region. The Primorye fauna has mixed Boreal–Tethyal features. Certain similarities between the Verkhoyansk–Okhotsk region and Gondwanaland (Australia) can be explained by the equidistance of both these regions from the equator.

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