Geology of the Eastern Arctic Islands and Continental Fridge of the Arctic Seas

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Abstract Expeditions carried out in the Arctic in recent years resulted in the accumulation of a significant amount of new information, which allowed better understanding the geology of the islands and coastal areas of the Arctic Ocean. Overviews on geology and evolution for the Severnaya Zemlya archipelago, the Taimyr Peninsula, the New Siberian Islands, the Wrangel Island and the areas of the Verkhoyansk Fold-thrust Belt adjacent to the Arctic Ocean, the Kolyma-Omolon Superterrane and the Chukchi-New Siberian Fold Belt include tectonic-stratigraphic maps showing petrographic composition, paleogeographic and lithogeodynamic conditions for the formation of sedimentary complexes, the phasing of tectonic and magmatic events.

The study of geology and tectonic evolution of the structures of the Arctic Basin bottom is complicated by severe polar conditions. The main sources of information here are remote geophysical data. The direct geological observations in this region are possible only on the islands and on the coastal areas of the Arctic Basin (Fig. 1). Therefore, these are the key territories to understanding the geological history and structure of the entire northeast of the Russian Arctic.

In recent years, a considerable quantity of empirical material has been assembled as a result of the various expeditions carried out in the region. These data substantially refined the knowledge of the geological structure of the islands and coastal of the Arctic Basin.

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Fig. 1 Map of the Eastern Arctic islands and continental fridge of the Arctic seas

In order to summarize the available new data, general settings of the geological structure and development have been compiled for a number of regions of insular and continental land of the eastern Arctic regions of Russia. Extensive retrospective material, including published scientific works, state geological maps and unpublished reports, was also used.

The description is based on a fomnational approach, considering the geodynamic settings, tectonics and magmatism characteristic of individual eras in the history of the development of each region. The result and illustration of this work are tectonic-stratigraphic schemes, compiled for the Severnaya Zemlya archipelago, Taimyr Peninsula, New Siberian archipelago, Wrangel Island, as well as the Verkhoyansk folded and thrust belt adjacent to the North Arctic Ocean areas, the Kolyma-Omolon superterrane and Chukotka-Novosibirsk folded system.

The schemes reflect the formational composition, paleogeographic and lithogeodynamic conditions for the formation of the tectonostrati-graphic complexes, as well as the phasing of tectonic and magmatic events.

1 Severnaya Zemlya Archipelago

The Severnaya Zemlya archipelago is an integral part of the Middle Mesozoic–Cenozoic North Kara Basin (Fig. 2). In the present-day structural plan, the archipelago forms an orogenic rise, which divides the sedimentary basins: the shelf South Kara and the oceanic Eurasian.

Tectonic conditions of formation of the pre-Jurassic–Cretaceous rocks were thought in various ways. During the early studies, these rocks were ascribed either to the geosyncline folded formations of the Kara platform with the Archaean–Palaeoproterozoic basement (Ravitch 1954; Vakar et al. 1958; Zabiyaka 1971), or to the Kara Hercynian—Early Cimmerian dome-plutonic epi-platformal rise with the Grenville

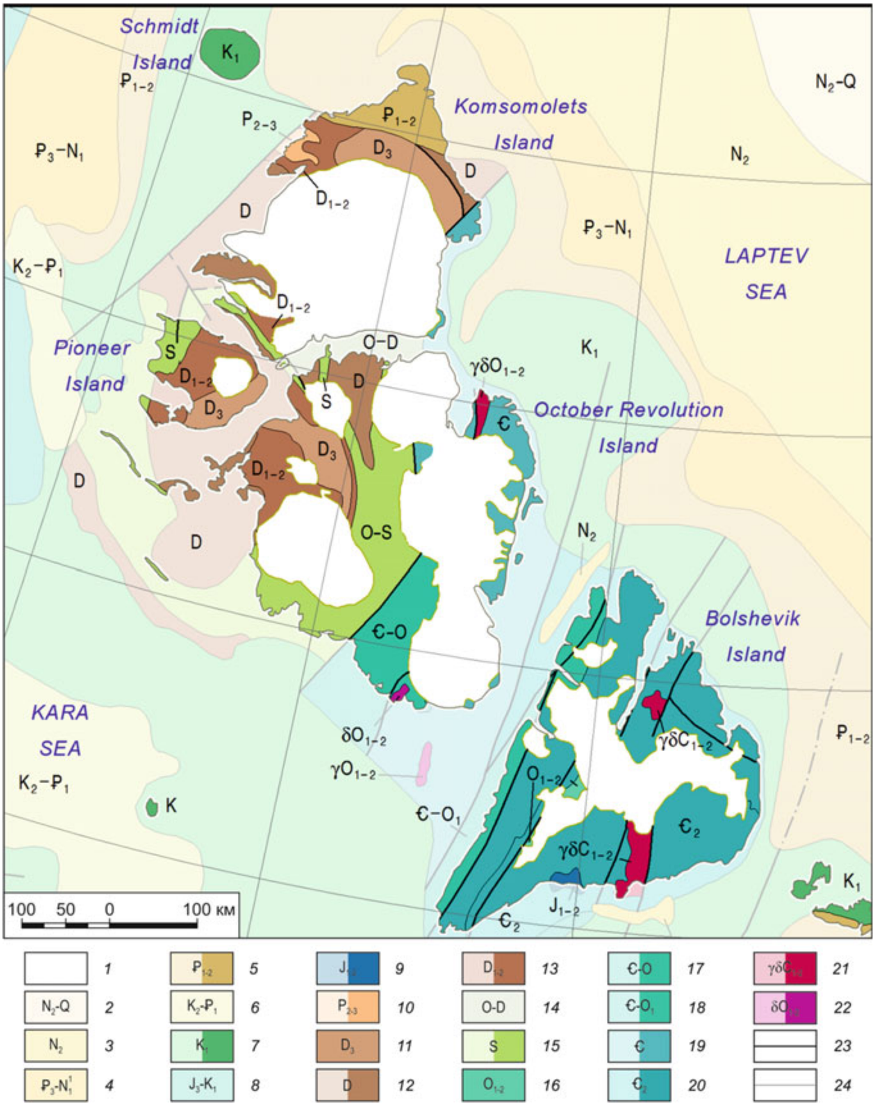

Fig. 2 Geological map of the Severnaya Zemlya Archipelago. *1* glacers; *2–10* epicontinental, mainly terrigenous deposits of the Cenozoic, Mesozoic, and Upper Paleozoic; *11–15* terrigenous-carbonate, carbonate, sulphate-bearing complexes of the Upper Ordovician Devonian gently folded in Variscan time; *16–20* terrigenous-carbonate, volcanogenic, and flysch complexes of the Cambrian—Middle Ordovician folded in Caledonian time; *21–22* Variscan and Caledonian granitoids; *23* tectonic boundaries; *24* geological boundaries

basement (Pogrebitsky 1976; Daragan-Sushcheva et al. 2009). At present, the pre-Jurassic rocks are tectonically attributed to the Kara Microcontinent, a part of the ancient Arctida (Zonenshain et al. 1990a, b; Uflyand et al. 1991; Vernikovsky 1996; Kuznetsov 2008) and/or North Kara Massif of Hercynian age with epi-platformal deposits on the Timanide (Late Baikalian) basement (Gee 2002; Proskurnin et al. 2002, 2014). Though debatable nowadays, the boundary between folded and platformal complexes separates the North Kara plate with the Paleozoic basement and the northern parts of the Taimyr-Severnaya Zemlya fold belt: this subdivision is assumed useful for purposes of seismic stratigraphy and studies of potential oil and gas resources.

Of the Kara Block rock complexes, the Severnaya Zemlya archipelago was proved to be the most representative area, although before 1925 it was absent not only in geological, but in geographical maps.

In the modern structure of the Kara Block, the North-Taimyr-Severnaya Zemlya fold belt is recognized: it underwent successive Baikalian, Caledonian and Hercynian orogenies. It encompasses the entire Northern Taimyr, the archipelagos of Severnaya Zemlya and Nordenskjöld and Izvestiy TCIK islands. Here, the Hutuda-Bolshevik and the Severnaya Zemlya folded zones are distinguished being separated by the Main Severnaya Zemlya deep fault. The core of the Kara Block comprises the North Kara syneclise of the Jurassic-Cenozoic age with underlying gently folded epi-platformal Late Ordovician-Devonian deposits.

The Khutuda–Bolshevik fold-and-thrust zone includes Bolshevik Island, the Izvestia TSIK Islands, as well as the easternmost part of October Revolution Island. The zone is composed of dislocated Late Riphean–Early Cambrian (?) sediments, metamorphosed under sericite-chlorite subfacies of the greenschist facies conditions. These rocks belong to the group of clastic marine flysch formations, whose age by acritarchs was defined as Riphean-Vendian. Recently, the presence in the flysch sandstone of the Cambrian age detrital zircons has been revealed.

On Bolshevik Island and in the east of October Revolution Island, the flysch deposits are intruded by granitoids of a granite-leucogranite formation of presumably Precambrian age and a 320 Ma old diorite-granodiorite. The granodiorite-porphyry and granite-porphyry are accompanied by gold-molybdenum-bearing mineralization. Dyke swarms on Bolshevik Island comprise Early–Middle Ordovician trachydolerite, Early Triassic gabbro–dolerite and Late Triassic lamprophyres.

The Late Riphean–Early Cambrian (?) sediments and the granodiorite are overlain with angular unconformity by continental coal-bearing Late Carboniferous-Permian sediments.

The Severnaya Zemlya fold zone is composed of the Lower–Middle Paleozoic folded epi-platformal rocks and fine Lower Permian platform deposits. The zone is located north of the Main Severnaya Zemlya fault and subdivided into two folded subzones: the East-October fold-and-thrust and the October-Pioneer gently folded subzones.

The East-October fold-and-thrust subzone is bounded in the west by the Kirov-Ozernaya strike-slip fault. The subzone comprises the Vendian–Middle Ordovician rocks. These deposits are folded into linear folds of the northeast and submeridional strike. The stratified rocks (Egiazarov 1959; Makariev et al. 1981; Markovsky et al. 1982a, b; Severnaya et al. 2000) are dominated by intensely dislocated deposits of the Upper Vendian, Cambrian, Lower and Middle Ordovician.

Bottom of the section is composed of marine black—gray limestone—sandstone—mudstone strata. Its lower part contains coarse siliciclastic sediments, the age of which is conditionally defined, according to their position in the section, as the Vendian-Early Cambrian (Proskurnin and Vereshchagin 1989) or Early Cambrian (Lazarenko 1982). The above lying Cambrian deposits are shallow-marine dark-colored clastic rocks containing remains of benthic fauna, mainly trilobites, less often brachiopods and crinoids.

The upper part of the *East-October fold-and-thrust subzone* section is composed of a volcanic-plutonic association with voluminous volcancs of mafic, intermediate and felsic composition of moderately alkalic Na-K and K affinity. The association encompasses stratified sedimentary-volcanic formations, as well as necks, subvolcanic and hypabyssal intrusions. The Severnaya Zemlya fault zone is traced by a chain of intense magnetic anomalies coinciding with the Early–Middle Ordovician rift (possibly back-arc) zone and centers of volcanic-plutonic structures with trachybasalt-trachyandesite-rhyolite and moderately alkalic gabbro-syenite-granite-porphyritic formations (Proskurnin 1995).

The October-Pioner gently folded subzone with a northwestern strike of structures is located westwards of the Kirov-Ozernaya strike-slip fault. Within the zone, the Ordovician, Silurian and Devonian deposits occur. They display results of two types of deformations: Lower and Middle Ordovician rock experienced compression, which formed linear asymmetric folds with reverse fault and thrust of the northwestern strike (Albanova-Ozernaya anticline), while Upper Ordovician to Devonian deposits folded to form concentric folds and reverse faults (Spokoynaya and Pioner-Vavilova brachysynclines).

In the Albanova-Ozernaya anticline, the variegated continental and coastal-marine volcanogenic-carbonate-siliciclastic deposits are exposed. They contain a volcanic admixture, felsic lavas, lenses and veins of gypsum, halite and gypsum grains. In the anticline's crest (river Knizhnaya), a dike swarm of the northwestern strike occurs: these are amphibolized gabbro-dolerites of the Early–Middle Ordovician age.

The gently sloping brachinsinclines (Spokoynaya and Pioner-Vavilova, etc.) are composed mainly of shelf carbonates of the late Ordovician-Silurian and siliciclastic Devonian rocks (Egiazarov 1959; Markovsky et al. 1982a, b; Khapilin 1982; Matukhin and Menner 1999; Severnaya et al. 2000).

The lower part of the Lower Ordovician—Silurian sequence comprises coastal-marine variegated sandstones, dolomites, calcareous dolomites, less often limestones and marls, whose age by coral and conodonts was defined as the Late Ordovician. With an angular and stratigraphic unconformity, it rests upon the Middle Ordovician gypsum along the eastern boundary of the Pioner-Vavilova brachysyncline. The sequence thickness increases from the west to east from 10–15 m to 100–200 m. The Silurian deposits are represented by a complex of shallow-marine mainly carbonate deposits, dominated by bioclastic, algal, stromatolite, and clayey limestones with scarce dolomite. In the upper part of the section, the rocks have a motley color. Interlayers of sandstones, siltstones, gypsum, argillites, marls occur along with sparse interlayers of ostracod clayey limestones.

The Devonian deposits are widespread in the central and western parts of October Revolution Island (Fig. 3) and almost entirely compose islands Pioner and Komsomolets The Lower Devonian sediments with disconformably rest upon various horizons of the Upper Silurian. The Lower Devonian deposits encompass the lower coastal-marine siliciclastic-carbonate and the upper lagoon-marine carbonate-clastic-sulfate formations. The overlaying deposits of the Middle and lower parts of the Upper Devonian are dominated by continental red-colored clastic complexes containing abundant fossil ichthyofaunas.

The plate complex consists of thin Carboniferous, Permian, Jurassic and Cretaceous sediments sporadically occurring on islands of the archipelago (Fig. 4). Continental sandstone and conglomerate with coal interlayers and traces of plant residues of the Middle Carboniferous–Lower Permian are known on Bolshevik Island; there are also individual outcrops of Jurassic terrigenous deposits. Coastal-marine calcareous sandstone with Permian brachiopods are have been found in the

Fig. 3 Outcrops of the Lower Paleozoic of October Revolution Island (photo by V. Ershova)

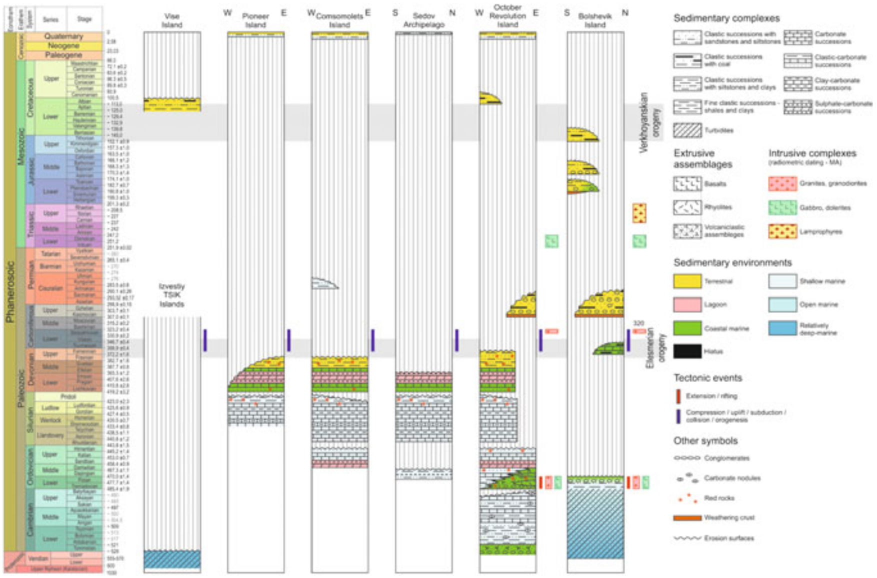

Fig. 4 Tectonostratigraphic charts of the Severnaya Zemlya archipelago

west part of Komsomolets Island. Lower Cretaceous terrigenous continental sediments are typical of some islands of the Kara Sea (Schmidt Island, Vise Island, etc.).

2 Taimyr Peninsula

The Taimyr-Severnaya Zemlya folded region is divided into three zones: North Taimyr–Severnaya Zemlya, Central Taimyr and East Taimyr-Olenek (part of the Verkhoyask belt) (Fig. 5). The first occurs on the Kara basement and is a part of the North Kara terrane. The Central Taimyr and the Eastern Taimyr-Olenek fold systems are parts of the Siberia's Craton. The boundary between the Kara terrane and Siberia Craton goes along the ophiolite suture of the Central Taimyr fold zone. The northern boundary of the Siberia Craton coincides with the Central Taimyr and the Pronchishcheva-Olenek sinistral strike-slip fault zone.

The North Taimyr–Severnaya Zemlya fold zone is composed of metamorphosed and strongly dislocated rocks of the Palaeo- and Neoproterozoic and partly Cambrian ages, as well as variously aged granitoids. It has a fold-and-thrust structure, which was formed during the Baikalian, Salairian and Early Cimmerian tectonic events. The lower parts of the section are composed of black phyllite, meta-siltstone and meta-sandstone of the Upper Palaeoproterozoic or, perhaps, Lower–Middle

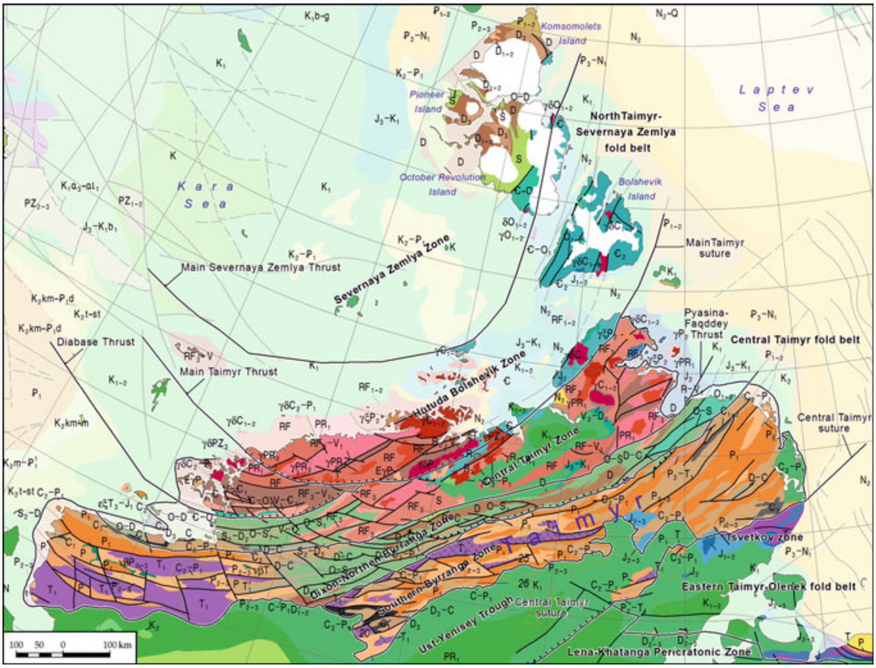

Fig. 5 Geological map of the Taimyr Peninsula

Riphean (Calymmian-Ectasian). Their metamorphic alteration reached amphibolite grade, as a result of which the siliciclastics transformed into gneisses and schists, underwent migmatization and various degree of melting produced gneissose granites of c.1.0 Ga age. The Upper Riphean weakly metamorphosed flysch rest unconformably over the basement. The Cambrian is composed of clastic-carbonate sediments similar to those of the Severnaya Zemlya Archipelago. They are unconformably overlapped by lesser deformed and non-metamorphosed Ordovician deposits with basal conglomerate discontinuous layer. The Precambrian complexes (gneisses and schists) are also found on islands neighboring the Taimyr Peninsula (archipelagos of the Plavnikovy Islands and Nordenskjöld). In the south, this zone is bounded by the Main Taimyr thrust.

The Central Taimyr fold zone is the most complex structure of the Taimyr Peninsula. It is composed of pre-Riphean (?) and Riphean sedimentary, volcanogenic and intrusive rocks that undergone metamorphic and hydrothermal-metasomatic alterations of various facies and types. These metamorphic formations are covered by the Vendian-Lower Carboniferous cover. The zone experienced a powerful compression, which resulted in massive thrusting. There are two allochthonous Precambrian metamorphic complexes: Mamont-Shrenk and Faddey. They are composed of high-metamorphosed clastic and carbonate rocks and metabasites. Two belts of ancient ophiolites, the Chelyuskin (southeastwards of the eponymous Cape) and Stanovskoy (coast of the Faddey Bay) occur in the zone. They form small bodies (from tens of meters up to 2 km in length and up to tens of meters in width) of metaperidotite and metamorphosed gabbroids. The ophiolites tectonically imbricated with narrow zones of serpentinite mélange, mylonitized green shales or metasomatites. Volcanics are tholeiitic metabasalts of the oceanic and metaryolite-andesite-basalts of the island-arc calc-alkaline series. The Upper Riphean comprises mainly dolomites. All the above-mentioned formations with angular unconformity are overlapped by molasse: clastic rocks, including coarse one, silt-mudstone and horizons of limestones.

The southerly located Early Mesozoic (Early Cimmerian) fold system is 150–200 km wide and more than 1000 km long. It unconformably overlaps the metamorphosed and strongly deformed Upper Proterozoic basement. The Vendian is composed of dolomites that are overlain by the Cambrian clay-carbonate. The Ordovician (Fig. 6), Silurian, Devonian and Lower Carboniferous are composed of either relatively deep-water clay-siliceous-carbonate deposits, or shallow-water limestones, marls and dolomites. The Upper Permian base typically comprises shallow-marine sediments, which are gradually replaced by continental siliciclastic coaliferous units when moving up the section. The Lower Triassic is represented by a trap complex. The Paleozoic and Triassic formations of the South Taimyr zone are intruded by small bodies of alkaline granites, syenites and nepheline syenites of the Late Triassic age. The South Taimyr zone underwent folding in the Pre-Jurassic time. The second, but weaker phase of deformations took place at the Jurassic-Cretaceous boundary.

Fig. 6 Field camp at the Kluevka River, Taimyr

The eastern Taimyr-Olenek fold zone in the Taimyr (the Tsvetkovky gently folded zone) is a fragment of the Verkhoyansk belt. The zone is bounded by the Central Taimyr in the northwest and by the northern coast of the Khatanga Bay in the south. Three complexes are distinguished.

1. Middle Carboniferous-Permian includes gray-colored clastic sediments.
2. Triassic volcaniclastic complex includes volcanic-plutonic associations of hot spots and taphrogenic deposits of the Late Triassic.
3. Jurassic-Neocomian is a clastic poorly coaliferous complex. The deposits form transgressive–regressive rhythms of high orders.

They accumulated under conditions of outer shelf. Pulses of folding occurred at the Permian–Triassic boundary, in the Middle-Late Triassic and Aptian-Albian (Late Cimmerian). During the final Late Triassic and in the Middle-Late Triassic, sub-alkaline basite-dacite cross-cutting bodies of fluidolith of the Carnian Age entraining minerals associated with diamonds (Tsvetkovsky Cape) formed. The youngest igneous rocks in the Eastern Taimyr, are sub-alkaline gabbro-dolerite-quartz-syenite (225–226 Ma), as well as intrusives and breccias of Sr-Ba carbonatite (219–238 Ma), some of which have fluid-explosive or volcanogenic genesis (Proskurnin et al. 2010; Petrov and Proskurin 2010) (Fig. 7).

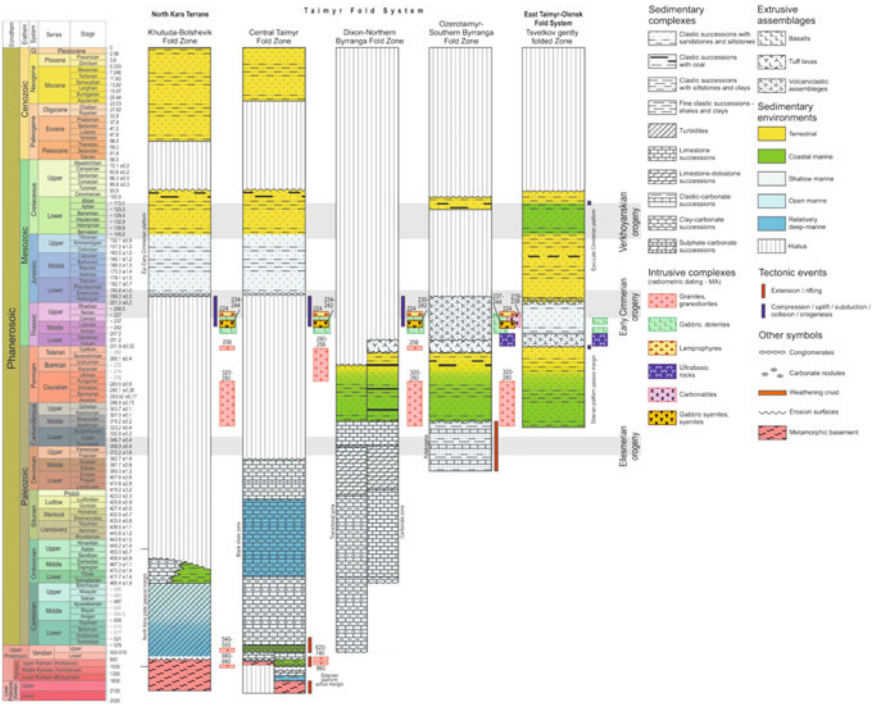

Fig. 7 Tectonostratigraphic charts of the Taimyr Peninsula

3 New Siberian Islands Archipelago

The New Siberian Islands are an archipelago located in the Eastern Arctic shelf between the Laptev and the East Siberian Seas (Fig. 8). The archipelago comprises three groups of the islands: the Lyakhovsky Islands (Bolshoi and Malyi Lyakhovsky, Stolbovoy); the New Siberian Islands, or the Anzhu Islands (Belkovsky, Kotelny, Bunge Land, Faddeevsky and New Siberia); as well as the De Long Islands (Bennett, Zhokhov, Vilkitsky, Henrietta and Jeannette) which are not big but significantly distant from each other.

In the modern structure, the archipelago of the New Siberian Islands is an orogenic uplift that separates the continent margin platforms and the sedimentary basins of the Laptev and East-Siberian Seas formed upon them.

In the structure of the folded basement of the Lyakhov Islands, several complexes are distinguished, differing in dislocation intensity, as well as the composition and degree of metamorphism of the rock comprising them. One of these is presented by flyschoid greywacke formations with different types of folding and varying degrees of metamorphism. According to the latest views, all flyschoid deposits on the Bolshoi and Malyi Lyakhovsky Islands are from the Late Jurassic-Early Cretaceous (Kuz'michev et al. 2006). In addition, in the southeastern part of the island, a complex of volcanic and metamorphic rocks of the South Anyuy suture is exposed

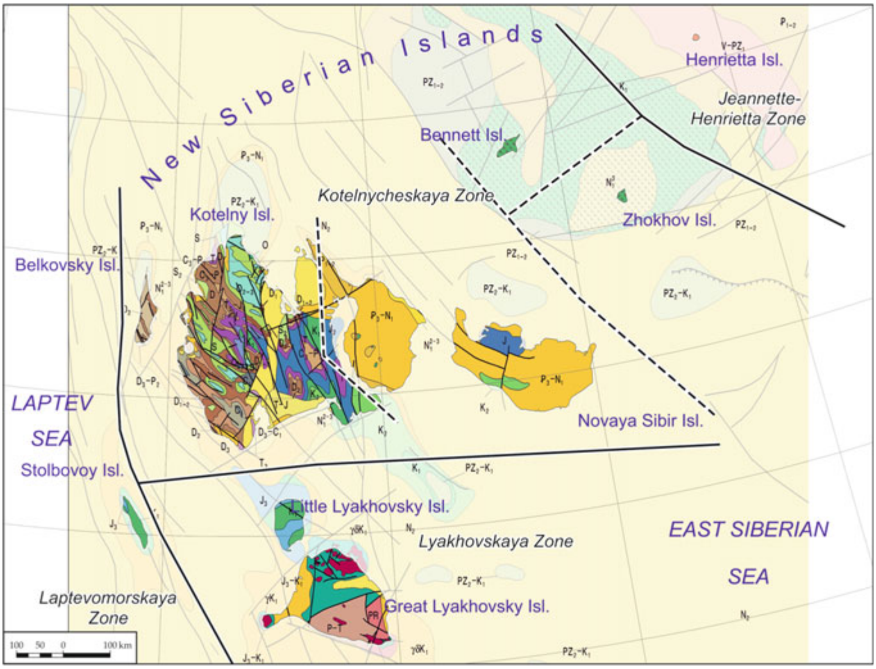

Fig. 8 Geological map of the New Siberian Islands Archipelago

Fig. 9 Pillow lavas on Bolshoi Lyakhovsky Island (by T. Tolmacheva)

(Fig. 9); this occured at the site of the ocean basin as a result of an early Cretaceous collision of the Eurasian and North American continental plates. All complexes on Bolshoi Lyakhovsky Island are broken through by intrusions of grano-diorites and granites of the Apt-Albian age of 122–108 Ma. (Dorofeev et al. 1999).

As paleomagnetic studies have shown, the Anjou and De Long islands belong to a single continental block (Metelkin et al. 2014) with a basement age defined as the Late Riphean (Akinin et al. 2015; Lorenz 2013).

On the Kotelny Island, deposits of the age range from the Ordovician to the lower Cretaceous are collected in folds of the north-west continuation. Here, three structural levels (complexes) can be distinguished: the Ordovician-Middle Devonian carbonates, treated as a deformed cover of the Epibaikalian platform; the Upper Devonian-Carboniferous terrigenous-carbonate intraplate and Upper Paleozoic-Jurassic terrigenous sediment, formed on the passive continental margin. Paleozoic-Jurassic sediments were dislocated and partially eroded in the early Cretaceous. Thermo-chronological studies of samples from Kotelny Island are avaragely aged to 125 ± 22, 106 ± 28 Ma (Prokopiev et al. 2018a, b). Lower Upper retaceous sediments were formed as a result of postfold rifting and are represented by a continental volcanogenic-terrigenous coal-bearing formation containing ignimbrites, rhyolite lavas and units of acidic tuffs (dates of 110–107 ± 2.5 Ma are obtained for ignimbrites). In terms of flora and spore-pollen complexes, the age of these sediments is defined as Apt-Albian and Cenomanian-Turonian, with the Upper Cretaceous deposits occurring on the weathering crust of the Lower Cretaceous rhyolites.

Cenozoic sediments are deposited with erosion on the underlying strata and are represented by thin intraplate terrigenous sediments with carbonaceous interiayers.

On the Faddeyevsky and New Siberia islands, the sediments of the Upper Cretaceous and overlying Cenozoic sediments overlapping it with structural discordance are exposed. These are represented by intraplate coal-bearing terrigenous sediments separated by large stratigraphic discordance on the Upper Cretaceous; Upper Paleocene-Middle Eocene (occurring on a widely developed weathering crust); Oligocene-Middle locene; Middle-Upper Miocene and Pliocene-Quaternary stratigraphic sequences.

The section of Bennett Island is composed of terrigenous deposits of the Cambrian and Ordovician and the Early Cretaceous sediments and basalt covers overlying them (Volnov and Sorokov 1961). The Cambrian is represented by sediments of the outer shelf: in the lower part (the Atdaban-May stages of the Cambrian), dark-coloured aleuro-argillites with sandstone interlayers, sandy limestones with trilobite detritus, which are replaced by black shales of the Upper Cambrian–Lower Ordovician. The Ordovician is composed of carbonate and silicyclastic turbidites containing residues of graptolites. This sequence is assumed to be formed under the conditions of a growing marginal continental rift trough (Danukalova 2016). The Ordovician deposits are covered by the weathering crust, formed as a result of Devonian orogeny with the age of tectonic exhumation is 378 ± 38 Ma (Prokopiev et al. 2018a, b). The Lower Cretaceous lies unconformably on the underlying sediments of the Lower Paleozoic. This structural tectonic complex reflects the stage of postorogenic rift genesis and is represented mainly by basalt covers, which, according to petrochemical characteristics, correspond to the traps of the Late Mesozoic high-latitude magmatic province (HALIP). The age of basalts is determined in the range of 106–125 Ma (Fedorov et al. 2005).

The islands of Henrietta and Jeannette are composed of Lower Paleozoic ensialic island-arc volcanogenic-sedimentary complexes: subcontinental gravelites, conglomerates and cross-laminated sandstones in association with the turbidite volcanogenic (tuff)-sedimentary sequences, basalt, andesites, rhyolite and rhyolite covers. These deposits are attributed to the Lower Paleozoic, based on the dating of zircons from igneous and sedimentary rocks. Thermochronological studies of samples from Jeannette Island provide a tectonic exhumation age of 400 ± 25 Ma, and from island Henrietta—385 + 30 Ma (Prokopiev et al. 2018a, b).

During the Cenozoic platform stage of development in the Neogene-Quatemary, within the boundaries of the De Long block, volcanic activity took place, as presented on the Zhokhova and Vilkitsky islands in the form of alkaline basalts and alkaline-ultrabasic volcanic rocks (foidites) (Akinin et al. 2015).

On the islands of the Laptev Sea (Belkovsky Island and Stolbovoy Island), Paleozoic and Neocom deposits are exposed (Fig. 10), with angularity blocked by Paleogene-Neogene (Eocene and Oligocene—Lower Miocene) coal-bearing sands and clays (Kuz'michev et al. 2013). On Belkovsky Island, Middle Devonian shallow-water marine limestones are in evidence, which are replaced by sloping clay, clay-siliceous deposits in association with turbidite sequences and units of olistostromes

Fig. 10 Coastal cliff on Stolbovoi Island (photo by M. Kos'ko)

in the upper Devonian-Permian. On Stolbovoy Island, a Volga-Neocom terrigenous turbidite structural tectonic complex is identified, represented by rhythmically bedded sandstones, aleurolites and argillites. The formation of this complex took place in the fore-trough of the closing basin of the South Anyui Ocean against the background of the Late Cimmerian orogenesis. Thermochronological studies of samples from Belkovsky Island give a tectonic exhumation age of 90 ± 11 Ma (Prokopiev et al. 2018a, b).

In 2011 and 2013, VSEGEI organized international geological expeditions to the New Siberian Islands. The goal was to study the best-exposed and most representative Paleozoic and Mesozoic geological sections, as well as varying in age and composition magmatic and metamorphic formations; and to collect rock samples for subsequent studies of mineral composition, as well as for isotope and paleomagnetic studies and paleogeographic reconstructions. During the expeditions, all the islands were visited, including Jeannette Island, where geologists had not been for over 70 years.

Large Russian and foreign geological surveys, mining companies, universities (Aarhus University, Denmark; BGR, Goethe University Frankfurt on the Main, Univ. Erlangen, Germany; Total, Sorbonne Universities, France; Univ. Siena, Italy; Univ. Uppsala, Stockholm University, Swedish Polar Research Secretariat, Sweden; University of Cambridge, UK). FGBU "VSEGEI", VNIIOkeangeologia, St. Petersburg State University, Moscow State University, DPMGI SB RAS, IPGG SB RAS, NEISRI FEB RAS from Russia) took part in organizing the expeditions. During the expeditions, some data on the Late Riphean age of the Koieinichesky Rise basement

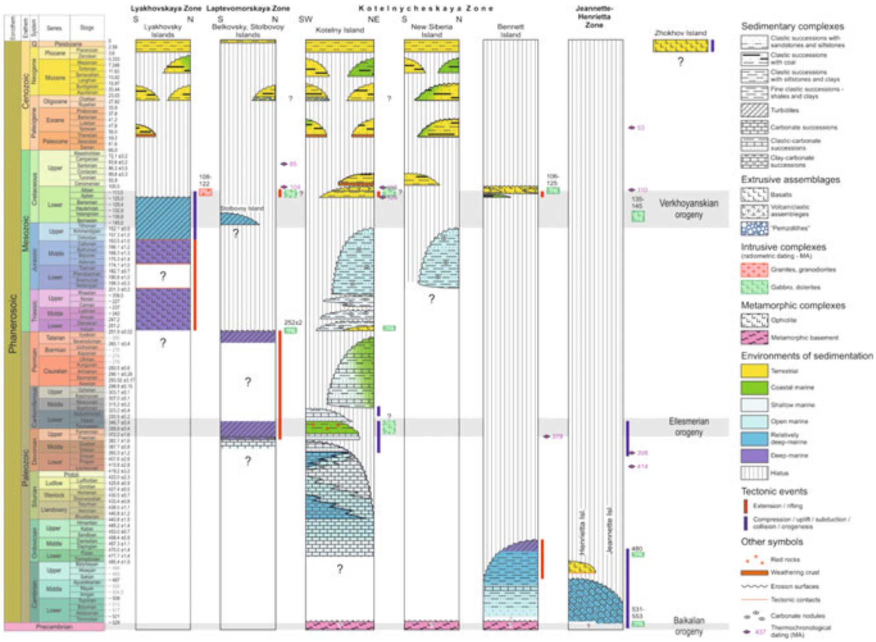

Fig. 11 Tectonostratigraphic charts of the New Siberian Islands Archipelago

were obtained based on the isotope dating of granite and metamorphic xenoliths from Cenozoic basalts of Zhokhov Island. The research findings on volcanogenic-sedimentary island-arc complexes of the Late Riphean–Early Paleozoic prove the presence of the Ellesmerian dislocations on the De Long Islands.

The continuation of the Verkhoyansk fold belt structures to the shelf of the Laptev Sea has been proved on the basis of a study of the geological structure of islands Belkovsky and Stolbovoy and their comparisons with similar coeval formations of continental land (Fig. 11).

4 Wrangel Island

Wrangel Island is located in the front of Mesozoic folded structures of the Arctic continental margin of Chukotka—the Wrangel-Gerald Ridge, to the north and south from South Chukchi and North Chukchi basins. The Wrangel Terrane belongs to the New Siberian-Wrangel fold system in the composition of the Chukchi Mesozoides and has a pronounced fold-thrust structure (Tilman et al. 1970; Kos'ko et al. 1993, 2003; Verzhbitsky et al. 2015) (Fig. 12).

Wrangel Island is built of metamorphic basement and complexly deformed sedimentary cover composed of terrigenous and carbonate Upper Silurian-Middle

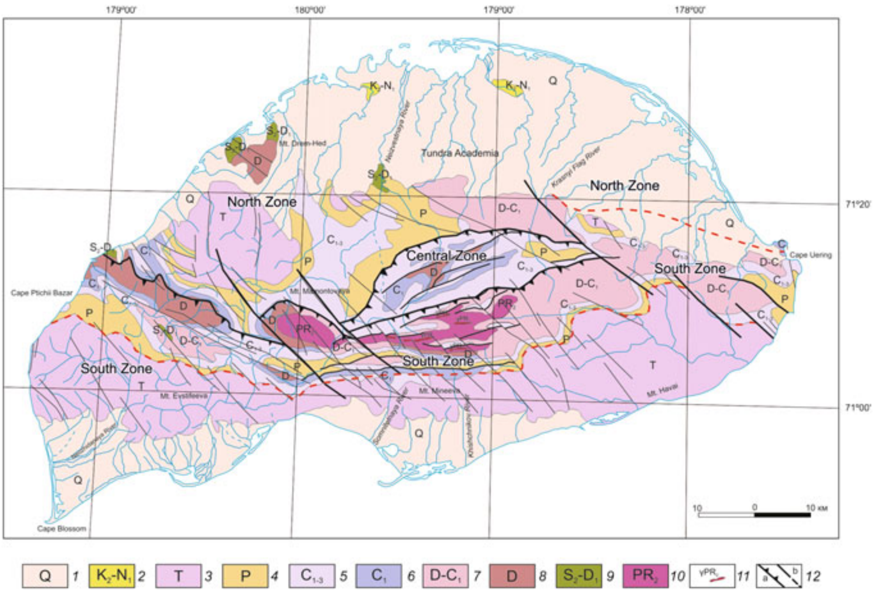

Fig. 12 Geological map and tectonic zones of Wrangel Island (Kos'ko et al. 2003; Sokolov et al. 2017). *1* Quaternary deposits; *2* Upper Cretaceous—Miocene deposits: clays, silts, sands and gravels; *3* Triassic deposits: mudstones, sandstones, siltstones; *4* Permian deposits: mudstones, limestones, sandstones, cherts and gravelits; *5* Lower and Middle Carboniferous deposits: limestones, siltstones, clay shists and phyllites; *6* Lower Carboniferous deposits: conglomerates, mudstones, limestones, dolostones, gypsum, acid and basic volcanic rocks; *7* Devonian and Lower Carboniferous deposits: sandstones, siltstones, conglomerates, carbonate and volcanic rocks; *8* Devonian deposits: sandstones, siltstones, mudstones, quarzites, conglomerates, limestones; *9* Upper Silurian and Lower Devonian deposits: limestones, dolostones, sandstones, siltstones, shales; *10* Upper Proterozoic, Wrangel Complex: meta-volcanics of acid, basic and intermediate compositions, meta-sandstones, schists; *11* Late Proterozoic granitoides; *12* structural boundaries: a—normal faults; b—other

Devonian, mainly terrigenous Lower-Middle Devonian, carbonate-terrigenous Upper Devonian-Lower Carboniferous, terrigenous-carbonate Upper Carboniferous, carbonate-terrigenous Permian and turbidite Upper Triassic complexes.

The metamorphic basement is composed of dislocated metavolcanic and metasedimentary rocks with single lenses and layers of marbled limestone. The granitoid and amphibolite bodies of the basements are metamorphosed in greenschist and epidote-amphibolite facies (Kos'ko et al. 2003). Current geochronological data (U-Pb zircon age of 594–598 and 700–630 Ma (Kos'ko et al. 1993, 2003; Luchitskaya et al. 2015) shows that it belongs to the Neoproterozoic age.

The Upper Silurian-Middle Devonian strata as thick as 1500 m are composed of quartzite sandstone, quartzite, silty and argillaceous shale with interbeds of limestone, gravelite and conglomerate are exposed to the north-west, in the Drum Head Mountains (Ganelin et al. 1989). Rare limestones contain corals, bryozoans and brachiopods (Ganelin et al. 1989; Kos'ko et al. 2003). The gravelite and conglomerate contain pebbles of quartz, quartzite, micaceous and quartz-mica schists. Marble and recrystallized limestone are exposed in the eastern part of the island (north of Cape Waring). The thickness of the carbonate section is about 400 m.

The Lower–Middle Devonian is represented by sandstone, siltstone, and shale with conglomerate and gravelite horizons (Kos'ko et al. 1993, 2003; Sokolov et al. 2015). In the Central Ridge, basal conglomerates overlap the Wrangel complex with unconformity and contain pebbles of granite, granite-gneiss and metamorphic schist, as well as mafic metaeffusive fragments. The thickness of the complex is 500–1000 m.

The Upper Devonian-Lower Carboniferous is represented by interbedded dolomite, dolomitized sandy-silty-clayey rocks, polymictic sandstone, siltstone, calcareous rocks with interlayers of gypsum conglomerate and gravelite. The thickness of the Upper Devonian-Lower Carboniferous sediments varies from 500 to 800 m.

The Upper Carboniferous is mainly composed of various organogenic and organogenic-clastic limestones with subordinate shale and mudstone interbeds. The limestone is characterized by flint interlayers and lenses. In the lower part, there are conglomerates with fragments of quartzite, multi-coloured shale and granite, and carbonate rocks have graded bedding: calcirudites, calcarenites and calcilutites are distinguished. The upper part of the section is composed of alternating limestone and shale. The total thickness of the Upper Carboniferous reaches 1200 m.

The Permian in the lower part is composed of alternating bituminous limestone and silty-clayey rocks with rare interlayers of finegrained sandstone. Above, there is a black shale sequence with interbeds of siltstone and aleuropelite. In the upper part, there are horizons of rhythmic alternation of sandstone, siltstone and mudstone, which makes them similar to Triassic turbidite. The thickness of the complex is 1000–1200 m.

The Triassic consists of a sequence of terrigenous turbidite, which is characterized by rhythmic intercalation of dark sandstone, siltstone and shale. The Carian-Norian age has been determined based on rare fauna finds (Kos'ko et al. 2003; Sokolov et al. 2017). The thickness of the complex is 1200–2000 m.

Three tectonic zones have been identified within the island: Northern, Central and Southern, each of which has structural, stratigraphic and lithologic features (Sokolov et al. 2017).

Northern zone. Characteristic features of the zone are: (1) the lack of metamorphic basement outcrops; (2) occurrence of Upper Silurian-Lower Devonian sediments in the base of the section; (3) the Upper Silurian-Lower Devonian complex is crushed into the folds of submeridional strike that distinguishes it from the structural parageneses of the younger Wrangel Island complexes of sublatitudinal strike. The structural plan of the Upper Silurian-Lower Devonian complex was formed under conditions of sublatitudinal compression and is considered to be a result of Ellesmerian deformations (Verzhbitsky et al. 2015; Sokolov et al. 2017).

Fig. 13 Lower Carboniferous gypsum-bearing strata, Central zone, Krasny Flag River

Central zone. The zone consists of two structural stages. The lower one is composed of metamorphosed basalts and acid volcanic rocks and intensely deformed carbonate-terrigenous Devonian-Lower Carboniferous complex (Fig. 13). The age of zircons from acid volcanic rocks is 598.6 ± 7.5 and 594.4 ± 7.1 Ma (U-Pb, SHRIMP-II), from basalts 500–600 Ma (U-Pb, LA-ICP-MS) (Luchitskaya et al. 2015; Sokolov et al. 2017). The upper structural stage is composed of slightly deformed Lower and Upper Carboniferous-Permian limestone, which lie with sharp unconformity and erosion on volcanogenic strata. Coeval complexes of the Northern and Southern zones are characterized by intensive fold-thrust deformations of the northern vergence.

Southern zone. The most complete sections are widespread there, including the metamorphic basement and the overlying sedimentary cover in the stratigraphic range from the Devonian (Fig. 14) to the Triassic.

There are two large thrusts within the Southern zone. Along the Main Thrust in the Central Mountains, the rocks of the Wrangel complex are overthrust onto Devonian and Carboniferous sediments (Ganelin et al. 1989). The Mineev Thrust is located to the south and in most places is distinctly expressed in relief. Along the thrust, the Triassic sediments gently overlap and cut the structural plan of the Paleozoic complexes.

Fold-thrust deformations are of sublatitudinal strike and northern vergence. They formed in the Chukchi (Late Cimmerian) phase of deformations at the end of the Early Cretaceous. The structures are deformed by dextral and sinistral shift faults

Fig. 14 Lower-Middle Devonian basal conglomerate, Southern zone, Central Mountains

of northwestern strike (Kos'ko et al. 1993, 2003; Verzhbitsky et al. 2015), some of which intersect and displace structures of the Northern, Central and Southern zones. They formed during the Chukchi (Late Cimmerian) phase of deformations in the late Early Cretaceous (Fig. 15).

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5 Continental Eastern Arctic

The onshore part of the eastern Russian Arctic comprises the Siberian platform and surrounding—the Verkhoyansk-Kolyma orogenic region (VKOR) and the Novosibirsk-Chukotka fold system in the east. The northern VKOR includes the Verkhoyansk-Chersky orogenic belt consisting of the Verkhoyansk fold-and-thrust belt in the west and the Kolyma-Omolon superterrane in the east (Parfenov et al.

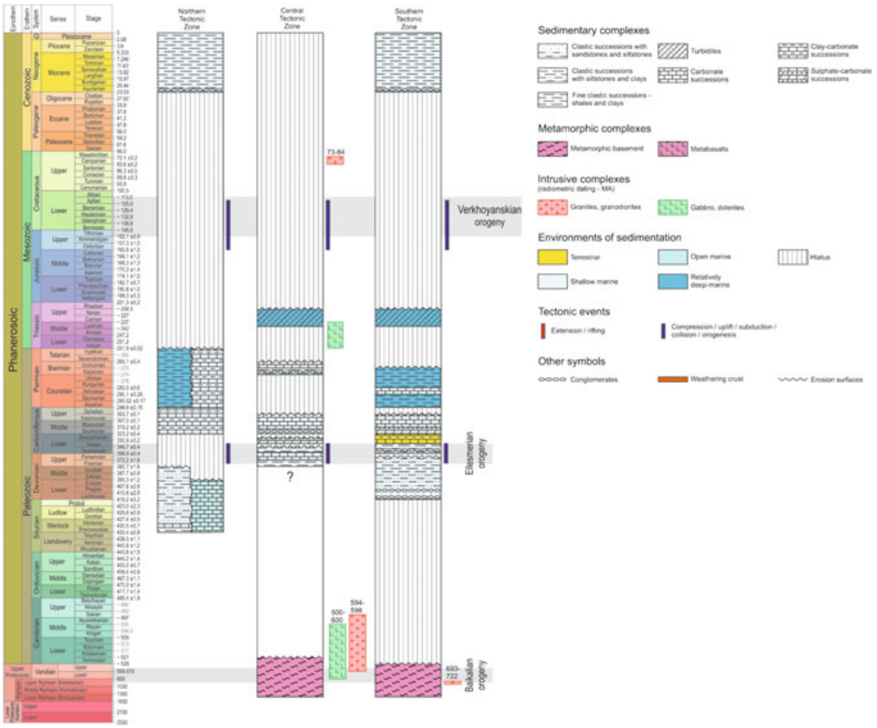

Fig. 15 Tectonostratigraphic charts of Wrangel Island

2003; Prokopiev, 2000; Khudoley and Prokopiev 2007). In plan, the VKOR forms an orocline known in literature as the Kolyma loop (Zonenshain et al. 1990a, b). Further to the east, the VKOR borders along the South Anyui suture zone (accretionary wedge terrane) on the continental part of the Novosibirsk-Chukotka fold system including Chukotka terrane. The eastern and south-eastern parts of the Kolyma-Omolon superterrane and the Chukotka cratonal terrane are overlapped by the Okhotsk-Chukotka volcano-plutonic belt (Parfenov et al. 1993a, b, 2003).

The sedimentary cover of the northeastern Siberian platform is made of clastic-carbonate, volcanogenic, and volcaniclastic rocks of Proterozoic, Paleozoic, and Mesozoic age. Magmatic formations include the Early Cambrian rift-related bimodal complex, Middle Paleozoic, Permo-Triassic and Mesozoic kimberlites, fields of intrusive and effusive Permo-Triassic traps, and plutons composed of Middle Paleozoic ultra-mafic-alkali rocks. The Archean and Early Proterozoic rocks of the crystalline basement of the Siberian platform are exposed in the Aldan shield, in the western part of the same name anteclise, and in the Olenek uplift ahead of the front of the Verkhoyansk-Kolyma orogenic region. Rift-related basins of Late Precambrian and Middle Paleozoic age (Khastakh, Sukhano-Motorchuna, and Kyutyungde) are located within the Anabar anteclise (Prokopiev et al. 2001).

The Lena-Anabar basin made of Upper Paleozoic and Mesozoic rocks and the more northerly Olenek fold belt extend sublatitudinally along the Laptev Sea coast. Limbs of anticlines and cores of synclines within the belt limits are composed of Jurassic and Lower Cretaceous rocks, while Triassic and Upper Permian sandstones and siltstones are exposed in the cores of anticlines.

Outer and inner zones can be identified within the Verkhoyansk fold-and-thrust belt extending along the eastern margin of the Siberian platform. The outer zone includes the Priverkhoyansk foreland basin made of Late Jurassic-Cretaceous clastic rocks and the frontal part of the Verkhoyansk fold-and-thrust belt. The Kular-Nera slate belt (terrane) and the Polousnyi-Debin terrane are located in the inner zone (Prokopiev 2000).

The Verkhoyansk fold-and-thrust belt sedimentary strata initially formed along the passive continental margin of the Siberian (North-Asian) craton. These strata comprise close to Siberian platform margin mainly Carboniferous and Permian deposits which change to Triassic and Jurassic rocks further to the east. This is thick sedimentary wedge (up to 15 km) traditionally called the Verkhoyansk clastic complex which lies on top of the Late Precambrian-Lower Paleozoic clastic-carbonate shelf sediments and Middle Paleozoic rift deposits, exposed in the north along the platform boundary, and comprises clastic shallow-marine, deltaic and open shelf sediments prograding eastwards (Tectonics, geo-dynamics, and metallogeny…, 2001; Prokopiev et al. 2008). Late Mesozoic transverse granitic belts [140–100 Ma (Prokopiev et al. 2018a, b)] penetrate the Verkhoyansk fold-and-thrust belt.

The Kular-Nera and the Polousnyi-Debin terranes are composed of repeatedly deformed Upper Permian-Jurassic elastics predominated by shale, siltstone, sandstone, and tuffs (Fig. 16). Olistostrome horizons are also present. The Upper Jurassic deposits of the northern Polousnyi synclinorium are mainly characterized by a clayey composition of sediments with sporadic andesite, basaltic andesite, and basalt belonging to the Svyatoi Nos-Oloy magmatic arc. The Late Cenozoic deposits of the Primorsky lowland overlap the deposits of these terranes in the north.

The Kolyma-Omolon superterrane is located to the east of the Kular-Nerra terrane and consists of terranes of various geodynamic affinity that were amalgamated into a single block in the late Middle Jurassic. The northern part of the superterrane comprises the Omulevka terrane and the Nagondzha turbidite terrane while the central part includes the Alazeya island-arc and Kenkel'da accretionary wedge terranes. To the north, the rocks of the Berezovka turbidite and the Oloy and Khetachan island-arc terranes are exposed.

The Omulevka terrane stretches for 1000 km along the southwestern and northwestern margins of the Kolyma-Omolon superterrane, and has a width of 100–150 km. The terrane is composed mainly of Ordovician-Early Carboniferous and, to a lesser extent, Upper Paleozoic-Early Mesozoic deposits. Pre-Ordovician formations are composed of metamorphic rocks. Along with the primary sedimentary rocks, they include felsic and intermediate volcanic rocks. Several types of rock associations are identified in the Ordovician-Lower Carboniferous deposits: bioherm of the carbonate platform, red-colored sulfate-bearing lagoonal and shallow marine

Fig. 16 Deformed Permian deposits of the frontal part of the Verkhoyansk fold-thrust belt in the estuary of the Lena River (photo by A. Prokopiev)

dolomites and marls, turbidites with slump folds, as well as deep-water shales with Ordovician graptolites and basalts. Late Paleozoic strata are composed of deep-water deposits. The Triassic, Lower and lower Middle Jurassic deposits mainly comprise fine-grained clastic rocks.

The Nagondzha turbidite terrain stretches for 450 km as a narrow strip to the north and west of the Omulevka terrane. The terrane is composed of repeatedly deformed Late Paleozoic and Early Mesozoic strata. The oldest Carboniferous-Permian deposits consist of hemipelagic volcaniclastic and carbonate-clastic rocks. The Middle Triassic (Ladinian) and lower units of the Upper Triassic sediments are composed of distal turbidites. The overlying Upper Triassic-Lower Jurassic deposits are composed of rhythmically intercalated siltstone, shale and sandstone. The upper part of the section is composed of Bathonian-Callovian clastic deposits with olistostromes. The Berezovka turbidite terrane is composed of Upper Devonian–Triassic volcaniclastic and carbonate sediments. The Oloy island arc terrane adjacent to the northern part of Berezovka terrane is represented by metamorphic Middle–Upper Devonian rhyolites, tuffs, siltstones, limestones and sandstones, and Carboniferous clastic strata. They are overlain with unconformity by volcaniclastic rocks. The Khetachan island-arc terrane is formed by the folded Upper Triassic and Lower Jurassic volcaniclastic strata which are unconformably overlain by Kimmeridgian-Volgian volcanic rocks of the Svyatoi Nos-Oloy island arc.

The Alazeya island-arc and Kenkel'da accretionary wedge terranes comprise the central part of the Kolyma loop. The Alazeya terrane extends to the south-west of the Khetachan terrane and is composed of Carboniferous-Early Jurassic predominantly volcaniclastic rocks, which are deformed into gentle open folds. The Kenkel'da terrane is adjacent to the north-western part of the Alazeya terrane. The terrane consists of unknown age rocks: metabasalts (oceanic tholeiites and olivine basalts), which are associated with quartzites, amphibole-mica-quartz, actinolite-epidote-chlorite, chlorite and glaucophane schists; greywackes, tuffs, interlayers and lenses of gravelites, silicites, jasper, pelitomorphic limestone and rare basalt layers. The intrusive rocks of the terrane are represented by tonalites, plagiogranites and gabbro-diorites. The Kenkel'da and Alazeya terranes are overlapped with unconformity by slightly deformed Middle and Upper Jurassic shallow-water marine sediments with conglomerates at the base (Parfenov et al. 2003).

In the west of the Kolyma-Omolon superterrane ophiolites with associated metamorphic rocks obducted in Late Mesozoic time crop out in tectonic sheets (Oxman et al. 1995; Oxman 2003; Parfenov et al. 2003).

The axial part of the Verkhoyansk-Chersky orogenic belt is cut by granitoid plutons of the Late-Jurassic-Early Cretaceous [156–144 Ma (Akinin et al. 2009)] Main (Kolyma) and the Early Cretaceous [137–100 Ma (Layer et al. 2001)] Northern batholith belts. Along the Omulevka terrane and adjacent areas of the Polousnyi-Debin terrane there extends the Uyandina-Yasachnaya magmatic arc composed of Oxfordian-Volgian volcanogenic-sedimentary rocks.

The South Anyui accretionary wedge terrane (suture) extends along the northern margin of the VKOR and the Novosibirsk-Chukotka fold system. It can be traced by linear magnetic and gravity anomalies to the north-west for 400 km under a cover of Cenozoic sediments from the lower reaches of the Kolyma R. to the coast of the East Siberian Sea. The terrane is composed of Callovian and Oxfordian pillow basalt, greywacke, shale, and subordinate chert as well as Lower Cretaceous turbidite. Glaucophane shale and fragments of ophiolites are reported. All deposits are very complexly and repeatedly deformed. Flat-lying Al-bian-Late Cretaceous volcanic rocks of the Okhotsk-Chukotka belt overlap the terrane (Katkov et al. 2010; Sokolov et al. 2014, 2015; Ganelin 2015).

The Chukotka terrane (a fragment of the Late Paleozoic-Early Mesozoic passive margin) is represented by intensely deformed and metamorphosed Precambrian rocks in the greenschist and amphibolite fades, clastic-carbonate Paleozoic deposits, and is dominated by thick terrigenous Triassic turbidites (Tuchkova 2011; Tuchkova et al. 2014). The earlier Phanerozoic tectonic events in Chukotka are associated with the Ellesmerian orogeny, as indicated by early Carboniferous granitoids (Luchitskaya et al. 2015). Permo-Triassic basalts and dolerite sills are known in the east of the terrane (Ledneva et al. 2011). Upper Jurassic-Lower Cretaceous volcaniclastic deposits are widespread in several small depressions. The rocks of the terrane are intensely and repeatedly deformed, and in the east are penetrated by Late Jurassic granite plutons. Metamorphic core complexes of Late Mesozoic age are reported. In the southwest of the terrane, the Triassic folded deposits are unconformably overlain by the shallow-water marine sedimentary and volcanic Upper Jurassic deposits and penetrated by the Late Mesozoic granites of the Nutesyn magmatic arc (Katkov et al. 2010). The uppermost sue cession comprises the Hauterivian-Barremian continental clastic deposits (Sokolov et al. 2014; Ganelin 2015). The northern part of the terrane

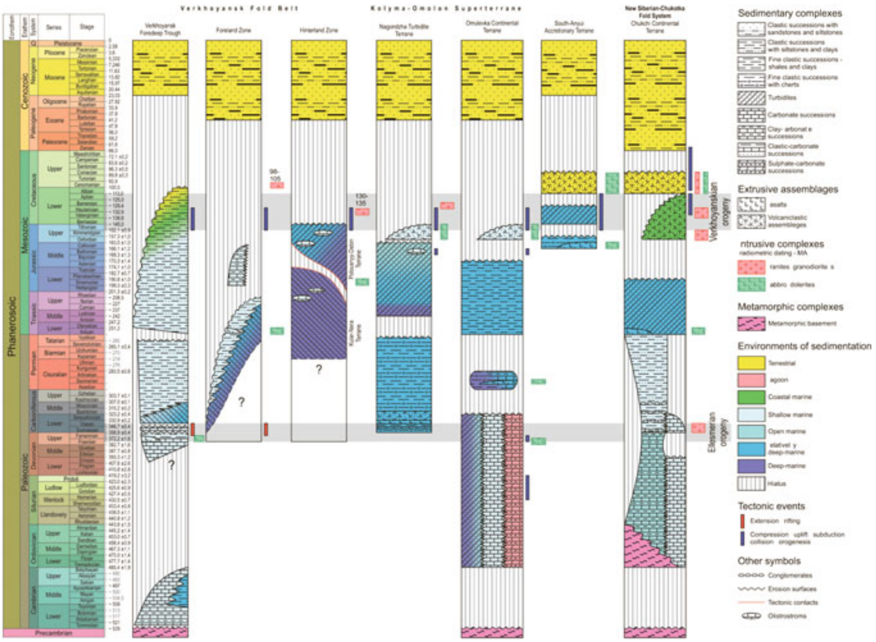

Fig. 17 Tectonostratigraphic charts of the continental eastern Arctic

is hidden under the East Siberian and Chukchi seas, in the southwest it borders on the South Anyui terrane: and in the south and southeast it is covered by Upper Cretaceous volcanic rocks of the Okhotsk-Chukotka volcanic belt (Fig. 17).

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