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The Tectonics and Stages of the Geological History of the Yenisei–Khatanga Basin and the Conjugate Taimyr Orogen

A. P. Afanasenkov[a, b], A. M. Nikishin[b], A. V. Unger[a], S. I. Bordunov[b], O. V. Lugovaya[a], A. A. Chikishev[a], and E. V. Yakovishina[b]

[a] *Russian Research Geological Oil Institute, sh. Entuziastov 36, Moscow, 105118 Russia*
[b] *Geological Faculty, Moscow State University, Moscow, 119991 Russia*
e-mail: afanasenkov@vnigni.ru

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Abstract—A new interpretation of the seismic profile series for the Taimyr Orogen and the Yenisei–Khatanga Basin is given in terms of their tectonics and geological history. The tectonics and tectonostratigraphy of the Yenisei–Khatanga and the Khatanga–Lena basins are considered. In the Late Vendian and Early Paleozoic, a passive continental margin and postrift shelf basin existed in Taimyr and the Yenisei–Khatanga Basin. From the Early Carboniferous to the Mid-Permian, the North and Central Taimyr zones were involved in orogeny. The Late Paleozoic foredeep was formed in the contemporary South Taimyr Zone. In the Middle to Late Triassic, a new orogeny took place in the large territory of Taimyr and the Noril'sk district of the Siberian Platform. A synorogenic foredeep has been recognized for the first time close to the Yenisei–Khatanga Basin. In the Jurassic and Early Cretaceous, this basin was subsided under transpressional conditions. Thereby, anticlinal swells were formed from the Callovian to the Aptian. Their growth continued in the Cenozoic. The Taimyr Orogen underwent tectonic reactivation and apparently right-lateral transpression from Carboniferous to Cenozoic.

Keywords: Taimyr, Yenisei–Khatanga Basin, Siberian Platform, tectonostratigraphy, tectonics, formation conditions, seismic profile

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INTRODUCTION

The Yenisei–Khatanga Basin remains one of the few large sedimentary basins in Russia, the geological history of which is treated in contradictory terms [2, 9–13, 20, 23, 30]. This is primarily caused by the fact that the pre-Jurassic sediments more than 5 km in thickness have been studied only with seismic methods. This allows various versions of the pre-Jurassic stratigraphy to be assumed. The currently available information and seismic profiles for the Yenisei–Khatanga Basin may be found in [1, 9–13, 25, 26, 30]. In this paper, our attention is focused on all available geological and geophysical data. The coverage of the region under study by seismic exploration and drilling is shown in Figs. 1 and 2.

In recent years, the geological history of the Taimyr Orogen has been substantially revised on the basis of the new datings of many sedimentary, metamorphic, and igneous complexes [3, 7, 22, 27, 28, 41, 45]. This compels us to reappraise the formation conditions of the Yenisei–Khatanga Basin.

We report and consider new data on the history of the Yenisei–Khatanga Basin, the folded structure of the Taimyr Orogen, and the northern Siberian Platform (Fig. 3).

In doing so, we attempt to define tectonostratigraphic units (rock complexes) formed in specific tectonic settings and to use them for recognition of related stages in geological evolution.

TECTONICS AND FORMATION STAGES OF THE TAIMYR OROGEN

The geology of the Taimyr Orogen is treated in various ways. We follow here the geological data represented by [2, 7, 23, 27, 28], with allowance for the latest results of seismic exploration and the timing of sedimentary and igneous rocks.

As concerns the Taimyr Orogen, we consider the conventional North Taimyr, Central Taimyr, and South Taimyr zones [2] (Fig. 3).

The North Taimyr Zone is mainly composed of metamorphic complexes and commonly regarded as a basement of the Early Precambrian North Kara Massif. Recent works, however, show that the rocks from this zone contain Vendian–Middle Cambrian detrital zircons [7, 17, 22]. In the North Kara Basin, this basement is overlain by sedimentary cover beginning from

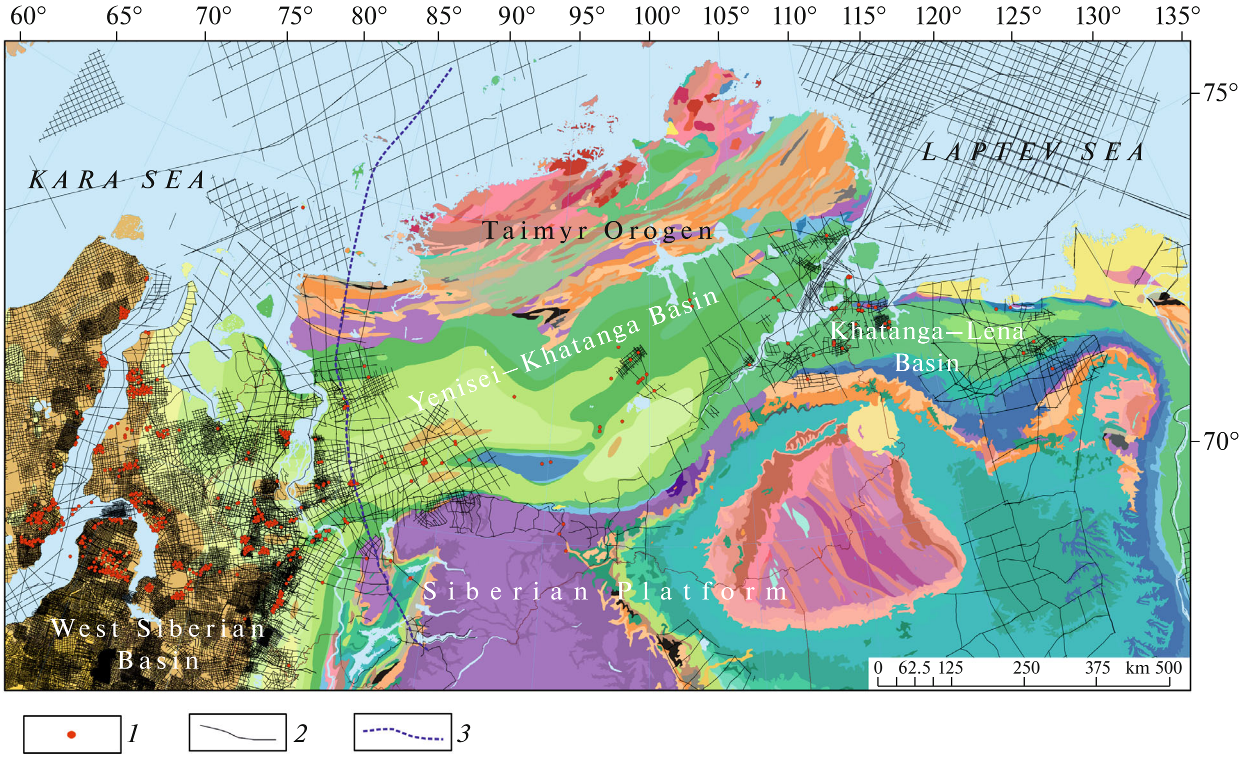


Fig. 1. Coverage of Yenisei–Khatanga Basin by seismic exploration and deep drilling on the basis of regional geological map. Colors correspond to the accepted colors of age in geological map. (*1*) deep boreholes; (*2*) reflection CMP seismic exploration; (*3*) Dikson–Lake Khantai seismic line on land and its offshore continuation (geological section along this line is shown in Fig. 12).

Ordovician rocks [18], providing evidence that Cambrian complexes participate in the structure of the basement [7, 22, 45].

The Central Taimyr Zone is represented by a Neoproterozoic accretionary complex [2]. The folded Neoproterozoic units are overlain with angular unconformity by the Upper Vendian–Lower Cambrian Sequence, including conglomerates of the Prodol'ninsky Formation [7]. It is thought that the main Baikalian folding developed approximately at the Riphean–Vendian boundary [2, 3, 7]. The Cambrian–Upper Vendian rocks in the northeastern Siberian Platform contain Neoproterozoic detrital zircons. This implies that the Central Taimyr Terrane was a part of the Siberian paleocontinent as early as the Late Vendian–Cambrian and underwent erosion [16, 35].

The North Taimyr and Central Taimyr zones are cut through by Late Paleozoic granitic plutons. Three groups of intrusions are distinguished by their ages: (i) Carboniferouis granitoids with predominance of Viséan rocks, (ii) Carboniferous–Permian, and (iii) Permian intrusive bodies [7]. As follows from geochemistry, these granitoids are suprasubduction, syn-, and postcollisional [7, 41]. These zones were involved in compression and mountain building in Carboniferous and Permian [2, 3, 22, 41].

The South Taimyr Zone consists of a folded sedimentary cover varying from Late Vendian to Early Triassic in age [7, 27, 28]. The basal conglomerates of the Nizhneostantsovsky and Prodol'ninsky formations rest upon underlying rocks with angular unconformity [7]. The main folding took place before the Early Jurassic [2, 7]. According to our interpretation of seismic data, the main angular unconformity and erosion, a few kilometers deep is traced in the deformed cover approximately at the boundary between the Lower and Middle Carboniferous (Fig. 4). The rocks, from the Upper Vendian to Lower Carboniferous in age, are largely represented by shelf carbonate sediments. The Viséan–Middle Carboniferous–Permian sequence is made up of shallow-water marine and continental molasse (sandstone, clay, coal-bearing units) [7]. The carbonate sedimentation gave way to terrigenous sediments apparently in the Mid-Viséan. Beginning from the Makarov Unit (upper Viséan–Middle Carboniferous), sandstones are predominant [32], however, transition to the prevalent sandstones can vary from Mid-Viséan to the Bashkirian or Moscovian stages. The sedimentary rocks of the Early Paleozoic carbonate platform in the north (primarily in the Central Taimyr Zone) pass to deepwater sediments of the continental slope, including typical black shales [7].

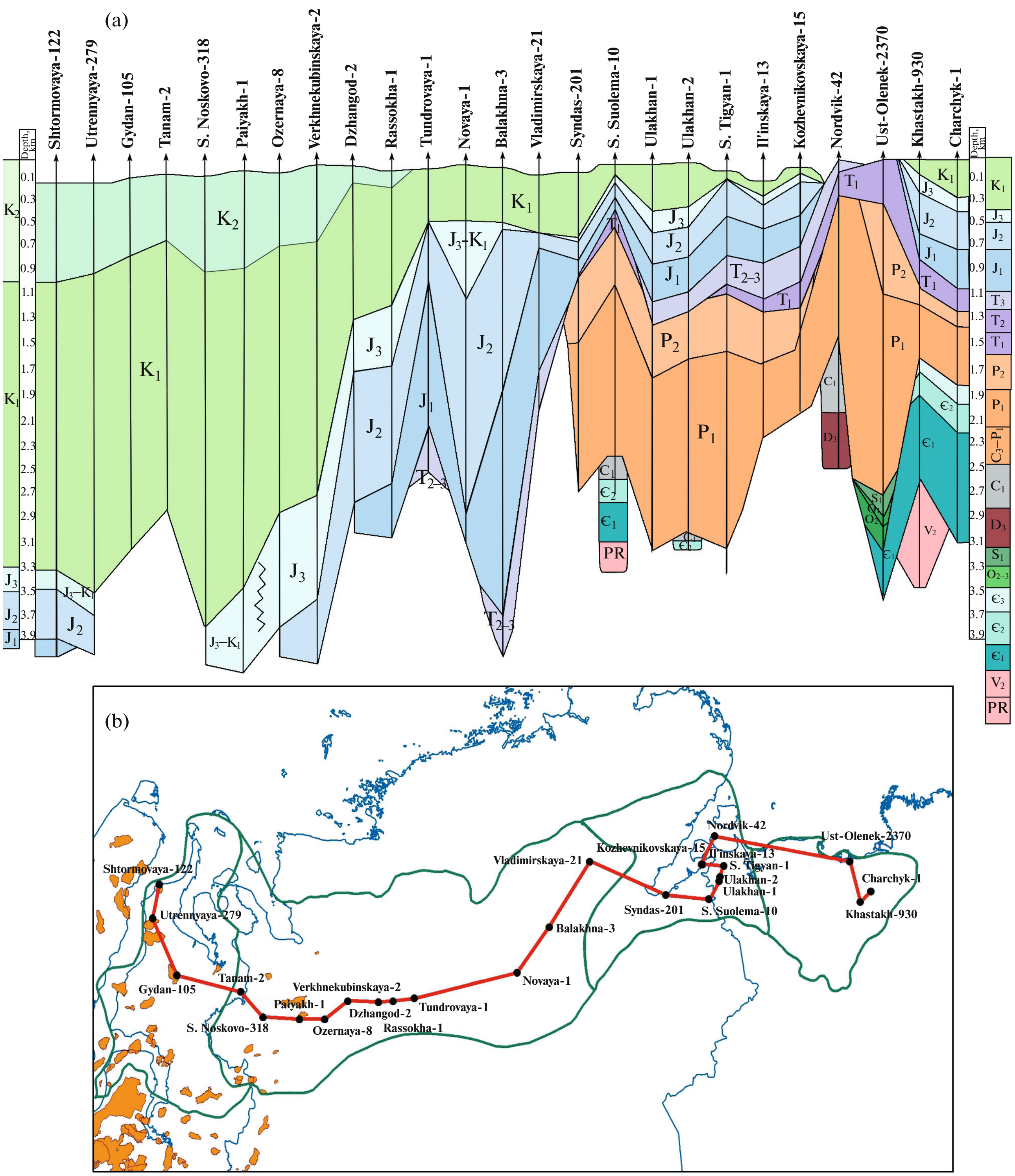


Fig. 2. Correlation of main deep borehole sections in Yenisei–Khatanga and Khatanga–Lena basins (a) and location of boreholes (b).

The Lower Triassic is represented by basaltic traps similar to those of the Siberian Platform [27, 28]. The basement of the South Taimyr Zone plunges deeply. It may be a continuation of either Baikalides from the Central Taimyr Zone or the basement of the Siberian Platform. We adhere to the first hypothesis, but unequivocal data are not available. Many authors, based on the interpretation of seismic data, suppose that the continuous Riphean–Lower Triassic cover in the South Taimyr Zone extends from the

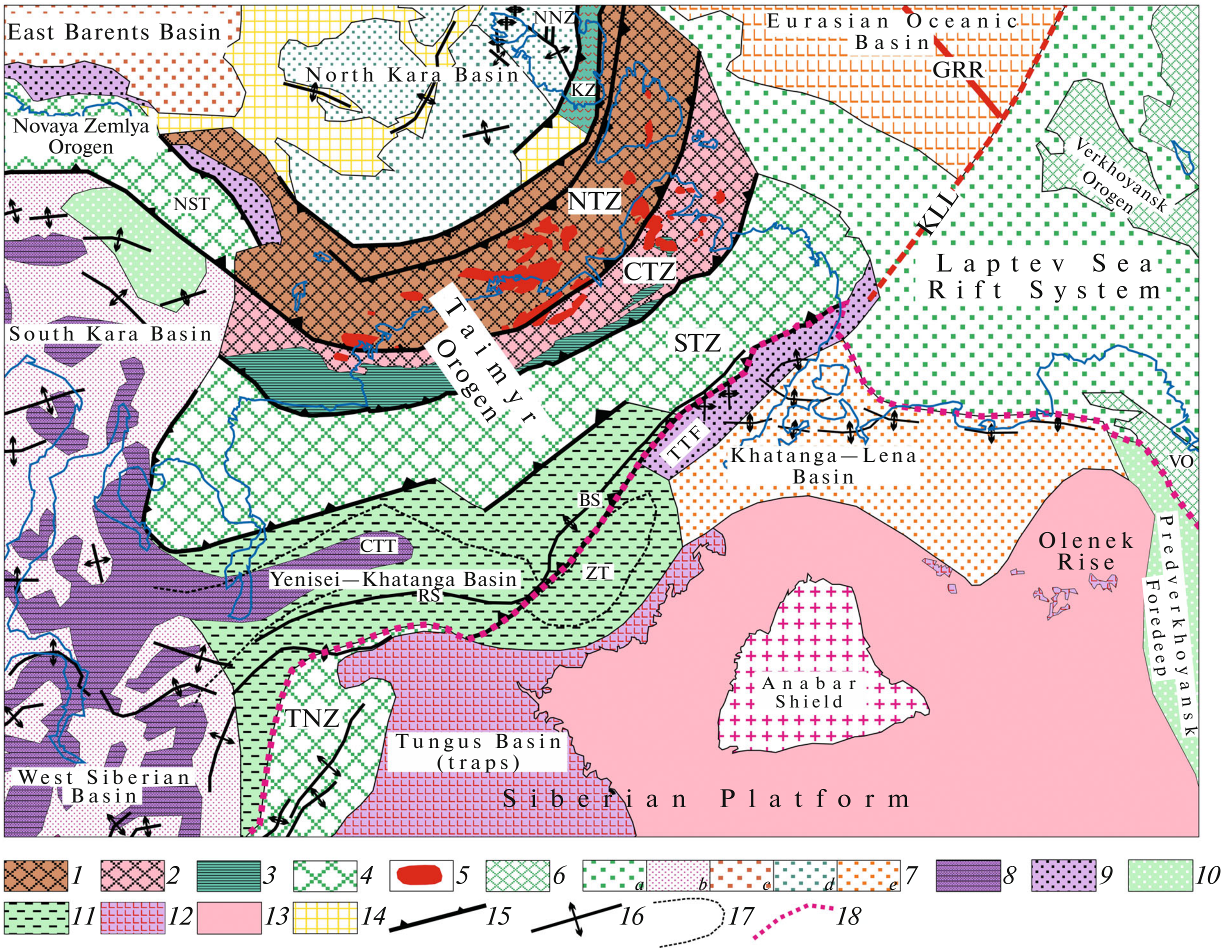


Fig. 3. Schematic tectonic map of Taimyr Peninsula and Yenisei–Khatanga Basin. Compiled by authors after [2, 7, 13, 39, 40]. (*1*) North Taimyr Zone; (*2*) Central Taimyr Zone; (*3*) Central Taimyr Zone with Vendian–Paleozoic sedimentary cover; (*4*) South Taimyr Zone and Novaya Zemlya Orogen; (*5*) Carbonaceous and Permian granitoids; (*6*) Verkhoyansk Orogen; (*7*) rift–postrift basins with (*a*) Cretaceous, (*b*) Triassic, (*c*) Late Devonian, (*d*) Ordovician, and (*e*) Vendian–Cambrian rifting; (*8*) Permian–Triassic rifts beneath sedimentary cover; (*9*) Middle–Late Triassic foredeeps; (*10*) Early Cretaceous foredeeps; (*11*) rift–postrift basins transformed into Mesosoic marginal (intermontane) trough; (*12*) Late Permian–Early Triassic traps in Siberian Platform; (*13*) cover of Siberian Platform; (*14*) uplifts in sedimentary basins; (*15*) thrust fault; (*16*) anticlinal swell; (*17*) depocenter in basin; (*18*) boundary of Siberian Platform. Symbols in map: NTZ, North Taimyr Zone; CTZ, Central Taimyr Zone; STZ, South Taimyr Zone; NNZ, Northern North Zemlya Zone (deformed part of North Kara Basin); NST, North Siberian threshold; TNZ, Turukhansk–Noril'sk Zone; KZ, Kruzhilikha Zone (Early–Middle Ordovician volcanic belt); CTT, Central Taimyr Trough; ZT, Zhdanikhinsky Trough; TTF, Triassic Taimyr Foredeep; RS, Rassokha Swell; BS, Balakhna Swell; GRR, Gakkel Ridge Rift; KLL, Khatanga–Lomonosov Lineament; VO, Verkhoyansk Orogen.

northern Siberian Platform [25, 30]. New data on the age of detrital zircons in the rocks previously assumed to be Riphean in the northeastern Siberian Platform show that they are actually Cambrian [14, 35]. Current information on the age of the rocks formerly dated back to the Riphean shows that there are no grounds to assume that thick and continuous Riphean and Neoproterozoic sequences occur near the Anabar Massif and the Olenek Uplift. They have been broken down into separate fragments differing in age [16, 35].

The Lower Jurassic rocks unconformably overlap the fold complex of the South Taimyr Zone. Therefore, it is thought that folding took place between the Early Triassic and Jurassic. Pre-Cretaceous angular unconformity is identified locally as well. Therefore compressive deformation in Jurassic also cannot be ruled out. A sequence of conglomerates, sandstones, and siltstones with Middle and Late Triassic plant remains (Mamonov Formation) has been established in the middle reaches of the Zhdanov River. This molasse overlies the Upper Ordovician rocks with angular unconformity [7]. Thus, the main phase of folding, uplifting, and erosion in the South Taimyr Zone is dated approximately back to the Middle Triassic.

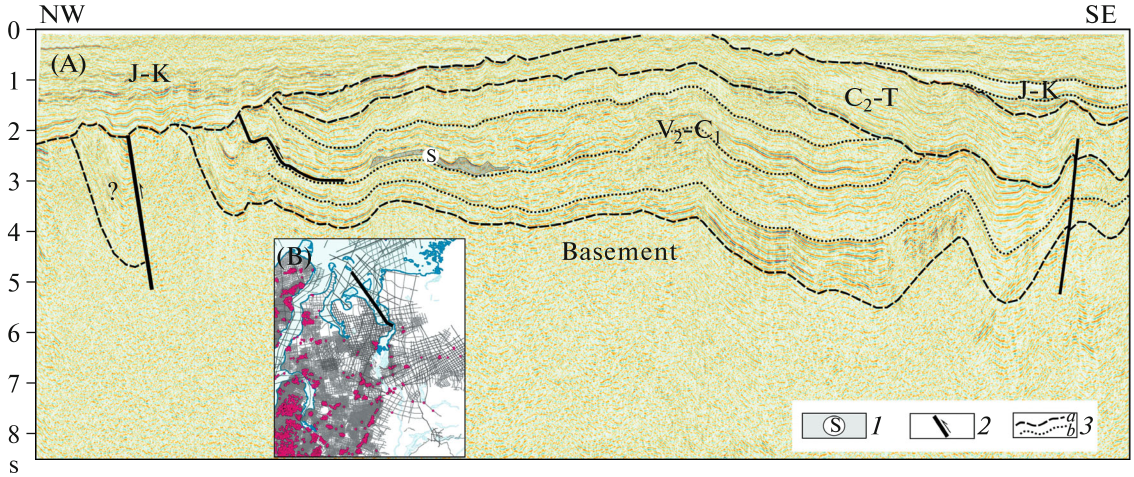


Fig. 4. Interpretation of time section along seismic line 240706 (A). Compiled by authors after [25, 30]; see inset (B) for seismic line location. Seismic line crosses western continuation of South Taimyr Zone in Kara Sea. Angular and erosion unconformity presumably at bottom of Middle Carboniferous (Tungus unconformity) is shown, as well as regional pre-Jurassic unconformity. It should be emphasized that pre-Jurassic (apparently Carboniferous) thrusting is directed to the north (observed in northern part of this section. (*1*) level of supposed Early–Middle Devonian salt (evaporites); (*2*) thrust fault zone; (*3*) seismic reflectors: (*a*) boundary of major seismic complex, (*b*) subordinate boundary.

Minor syenite stocks and dikes that cut through the fold structure are known in the South Taimyr Zone. Their age is suggested to be Middle–Late Triassic [27].

THE TECTONOSTRATIGRAPHY OF BASINS IN THE REGION UNDER STUDY

The northern Siberian Platform and the Khatanga–Lena and Yenisei–Khatanga sedimentary basins occur in the region discussed in this paper; the boundaries of these tectonic units remain ambiguous. They are considered separately hereafter, however, it should be kept in mind that the Siberian Platform does not possess a generally accepted northern boundary.

The Northern Siberian Platform

The following tectonostratigraphy units separated by unconformities and breaks in sedimentation are distinguished in the northwestern Siberian Platform near the city of Noril'sk: Riphean, Vendian–Lower Carboniferous, Middle Carboniferous–Permian, uppermost Permian–Lower Triassic, Jurassic, and Cretaceous.

The Riphean sedimentary rocks, ~3.5 km in thickness, form a gentle fold complex. The Vendian sequence overlies the Riphean complex with angular unconformity and basal conglomerate. The Vendian sequence near the Dudinka Rise apparently fills a rift (Fig. 5). The Vendian–Lower Carboniferous complex, 3–4 km thick, makes up an inferred carbonate platform with clay, sandstone, and evaporite interlayers.

We define as a Tungus unconformity the regional unconformity between the Viséan Stage of the Lower Carboniferous (Tundrinsky Formation) and the Middle Carboniferous, which corresponds to the growth of anticlinal swells and nonuniform erosion up to a kilometer deep. The Middle Carboniferous–Permian sedimentary rocks make up the Tungus Group. Rocks from the Middle Carboniferous to Permian occur at its bottom. Permian rocks overlie Lower Paleozoic rocks down to the Ordovician. The Tungus Group, 40–600 m in thickness, is composed of sandstone, siltstone, claystone, and coal-bearing rocks. The Upper Permian and Lower Triassic are primarily characterized by the formation of a basaltic trap complex. The sequence lies on underlying rocks with erosion (200–300 m deep) unconformity. The thickness of trap complex reaches 3.5 km. Jurassic rocks overlie with angular unconformity a complex of rocks varying in age from Vendian (?) and Lower Paleozoic to Triassic along the northern and western margins of the Siberian Platform. Thus, folding in the Noril'sk district occurred between the Early Triassic and Jurassic [20] (Fig. 5). The Lower Cretaceous rocks cut off the Jurassic sequence at the northern and western margins of the Siberian Platform. This implies that deformation in the northwestern corner of the Siberian Platform may continue at the Jurassic–Cretaceous boundary.

At the northeastern margin of the Siberian Platform, a Tungus unconformity is also evident. Carboniferous sedimentary rocks commonly lie directly on Cambrian or Ordovician rocks. Permian rocks overlap the Cambrian sequence on the northwestern slope of the Olenek Rise.

In the Lena–Anabar Basin, Permian sedimentary rocks overlie Cambrian, Ordovician, Silurian, and Devonian rocks with scouring and angular unconformity at the base, as follows from sections of Ust-

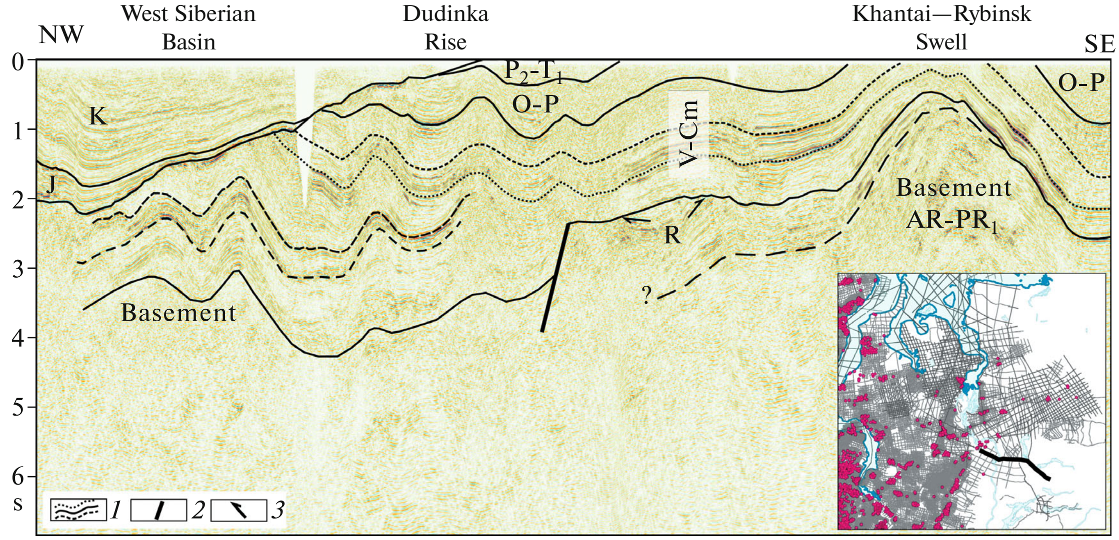


Fig. 5. Interpretation of composite time section along seismic lines 0206010–6205010; see inset for seismic line location. Angular unconformity between Jurassic and Vendian–Triassic rocks is shown. Cover of Siberian Platform margin has been deformed in folds between Jurassic and Early Triassic. (*1*) seismic reflectors; (*2*) normal faults, (*3*) angular unconformity.

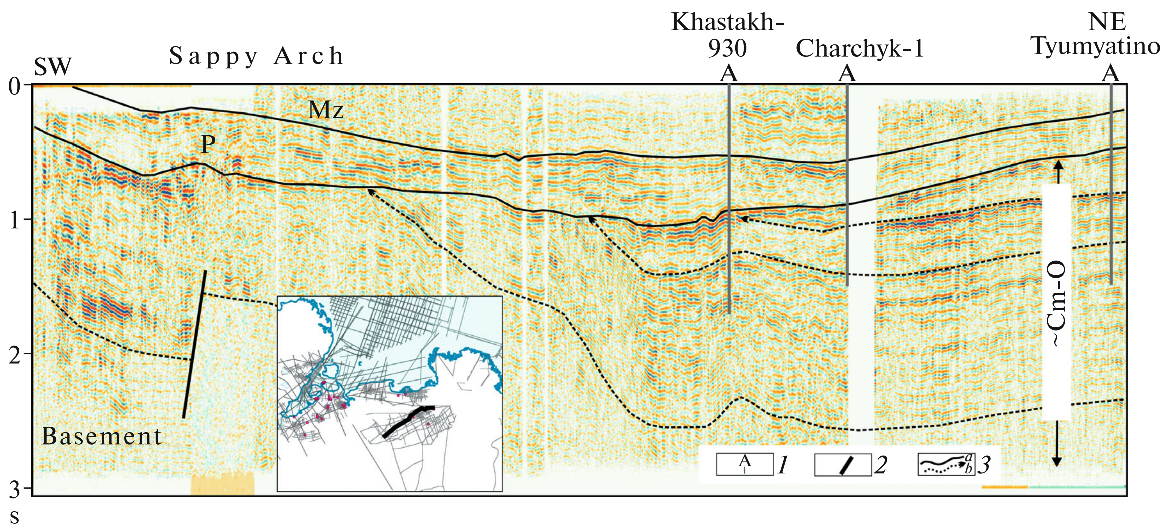


Fig. 6. Interpretation of time section along seismic line Reg–3. Compiled by authors, after [12]. See inset for seismic line location. Pre-Permian (presumably Tungus) unconformity is clearly seen. Normal faults at base of this section are supposed after [12]. (*1*) borehole; (*2*) normal faults; (*3*) seismic reflectors: (*a*) in Permian and Mesozoic and (*b*) in Lower Paleozoic. Arrows indicate angular unconformity.

Olenek-2370, Charchyk-1, Khastakh-930, and Bursk-3410 boreholes [12] (Fig. 6). On a regional scale, these contacts are regarded as the Tungus unconformity, because locally Permian rocks are underlain by a Middle–Upper Carboniferous terrigenous sequence (results of drilling).

Khatanga–Lena Basin

The region between the Siberian Platform and the Taimyr Orogen are conventionally called the Yenisei–Khatanga Basin. With the provided insight into the geology of this region, the Yenisei–Khatanga Basin has been divided into two main basins: (1) Yenisei–Khatanga proper in the west and center, where it is characterized by an anomalously great thickness of the Jurassic to Cretaceous sediments, and (2) the Khatanga–Lena (Anabar–Lena, or Anabar–Khatanga in other authors) in the east, where Paleozoic and Triassic rocks are predominant. A boundary between these basins is conditional.

The following tectonostratigraphic units are distinguished in the Khatanga–Lena Basin on the basis of the results of geological mapping [27, 28] and the interpretation of seismic profiles [13] (Fig. 7): Riphean–Lower Vendian, Upper Vendian–Lower Cambrian, Middle Cambrian–Lower Carboniferous, Middle Carboniferous–Permian, Triassic, and Jurassic–Cretaceous.

The occurrence of the Riphean–Lower Vendian complex at the base of sedimentary cover remains a matter of debate. New data on the age of detrital zircons from the rocks penetrated by the Khastakh-930 and Ust-Olenek-2370 boreholes [14, 35] show that these rocks are Lower Cambrian; earlier they were regarded as Riphean. Therefore we suppose that there are no widespread Riphean rocks at the base of the Khatanga–Lena sedimentary basin. It cannot be ruled out, however, that they actually occur but have been deformed due to Baikalian folding and are now incorporated into acoustic basement in seismic sections.

The Upper Vendian–Lower Cambrian sedimentary rocks are exposed on northern slope of the Siberian Platform and penetrated by boreholes in the lower reaches of the Anabar and Olenek rivers. These rocks remain poorly dated and studied. In general, they are composed of diverse sandstones and carbonates. The Lower Cambrian sandstone from the Khastakh-930 Borehole contains Neoproterozoic detrital zircons with peaks of age at 715, 645–640, and 600–595 Ma [35]. The Baikalides of the Taimyr Peninsula are the provenance of these sandstones [35]. We suggest that the Late Vendian–Early Cambrian rifting with the formation of a graben system developed in the Yenisei–Khatanga Trough (Fig. 6). The uplift of the graben's shoulders makes them provenances of clastic material. At that time, rifting also developed at the northeastern margin of the Siberian Platform [34].

The Middle Cambrian–Lower Carboniferous rocks do not crop out, and the results of drilling remain insufficient. In general, these are deposits of shelf carbonate platform with diverse limestones, dolomites, and other rocks [27, 28]. The evaporite units with rock salt, gypsum, and anhydrite occur at several stratigraphic levels from Emsian to Frasnian or Famennian in the Nordvik area [27, 28] (Figs. 8 and 9). A maximum of evaporite thickness falls on the upper Emsian–lower Eifelian [28].

The Middle Carboniferous–Permian (probably upper Viséan–Permian) sedimentary rocks (sandstone, siltstone, claystone, coal seams) make up molasse that fills the Taimyr Foredeep [20, 23]

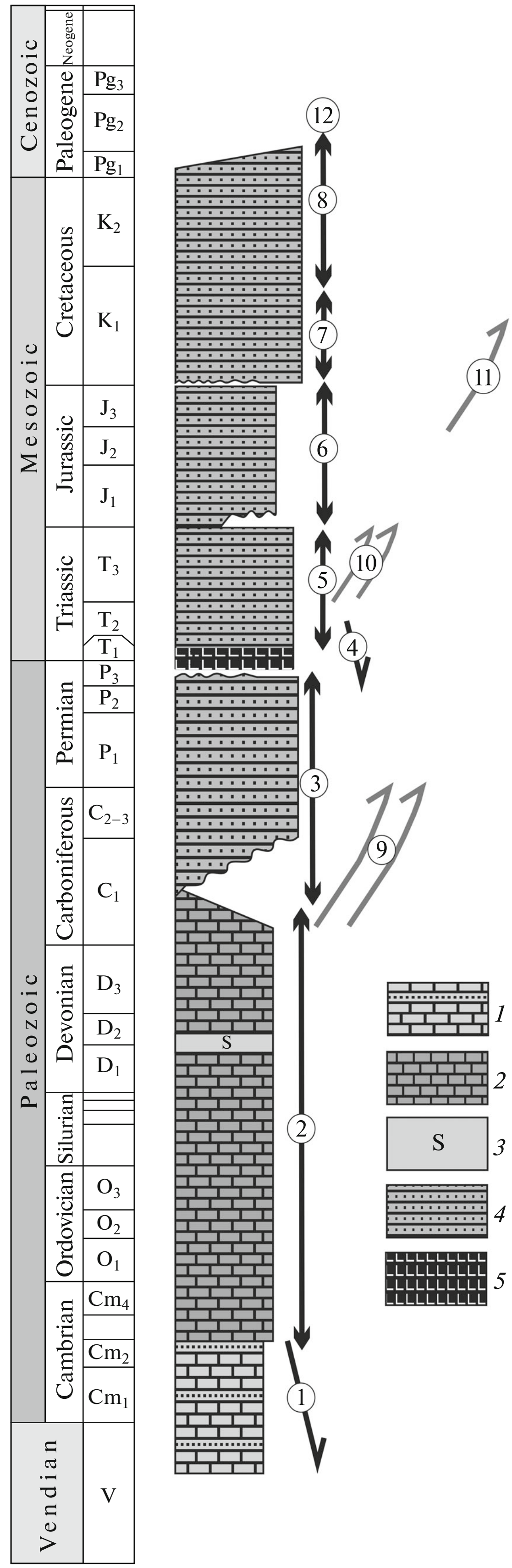


Fig. 7. Tectonostraigraphy of Yenisei–Khatanga Basin. Numerals in circles: (1–8) main tectonostratigraphic units: (1) synrift, (2) shelf postrift carbonate platform, (3) piedmont foredeep, (4) synrift in western part, basaltic magmatism; (5) foredeep, (6) piedmont foredeep, (7) sediments coeval to Verkhoyansk Orogeny, (8) platform evolution; (9–12) tectonic events: (9) orogeny in North Taimyr and Central Taimyr zones, (10) orogeny in South Taimyr Zone, onset of swell growth; (11) Verkhoyansk Orogeny, swell growth, transpression; (12) subordinate swell growth, transpression. Lithology: (*1*) carbonate and terrigenous rocks; (*2*) carbonate rocks; (*3*) salt, (*4*) sandstone and clay; (*5*) basalt.

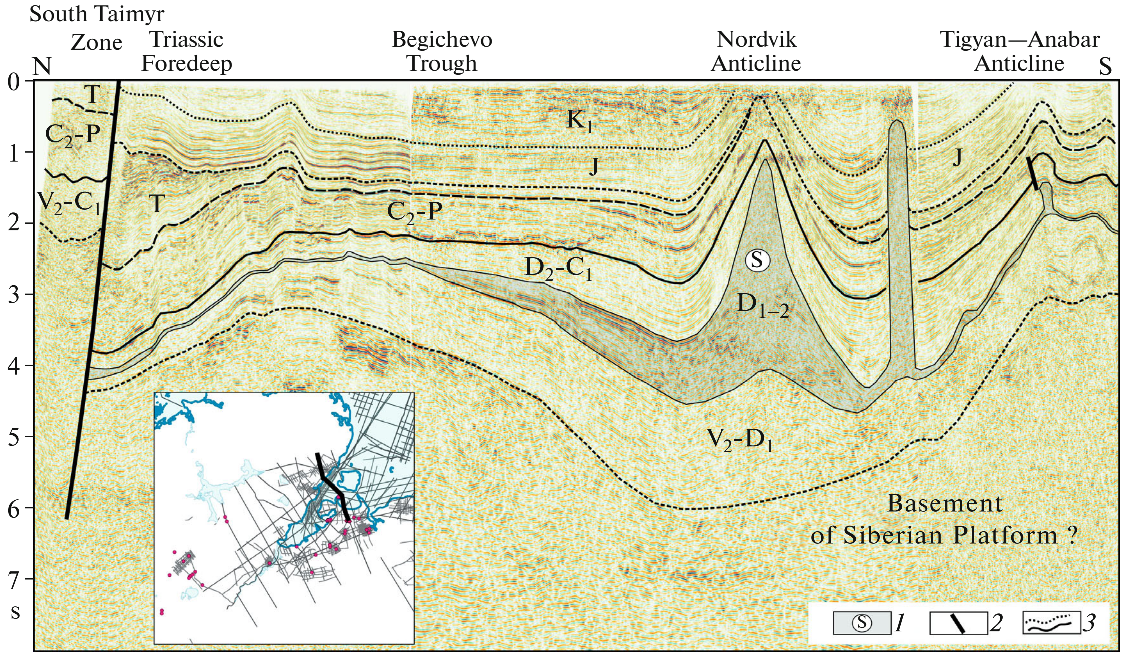


Fig. 8. Interpretation of composite time section along seismic lines 5109307–240804–5109310. Compiled by authors after [25, 30]. See inset for seismic line location. Middle–Upper Triassic rocks form sedimentary wedge, which corresponds to complex of foredeep. (*1*) salt; (*2*) fault; (*3*) seismic reflectors.

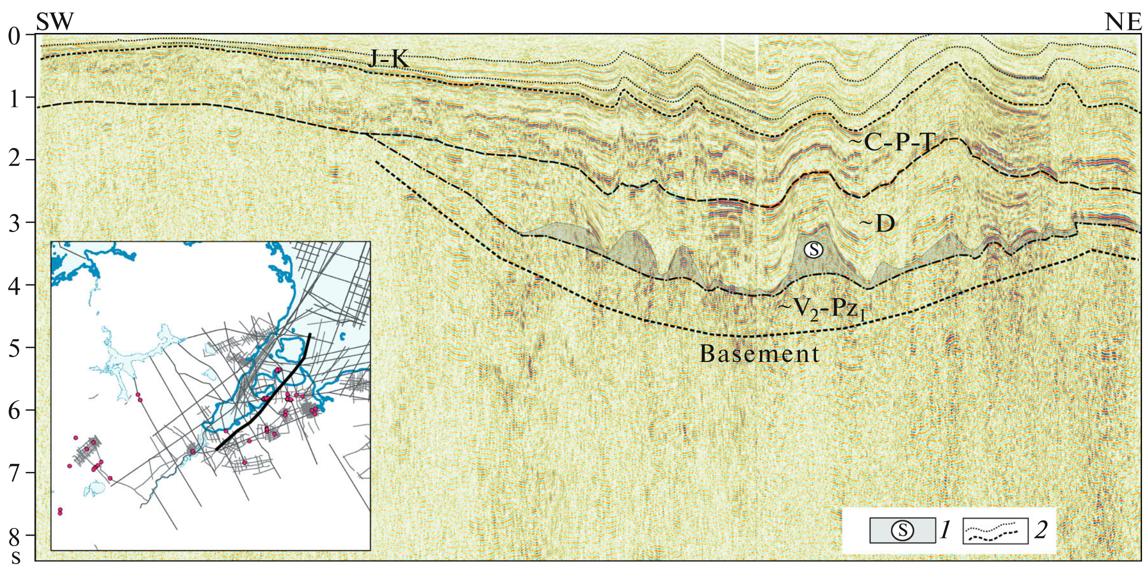


Fig. 9. Interpretation of composite time section along seismic lines 5109303A–5109303–4012508. See inset for seismic line location. Level with presumably Early–Middle Devonian salt structures and salts is pointed out. Entire suprasalt sequence has been deformed into folds before Early Cretaceous (age of the youngest rocks in section) apparently in Cenozoic. It is suggested that level with salts was served as a detachment surface in process of folding. (*1*) supposed salt; (*2*) seismic reflectors.

(Figs. 6 and 10). The unconformity at the base of the Carboniferous–Permian complex has been established at the southern wall of the Yenisei–Khatanga Basin, where various levels of this complex overlie Lower Paleozoic sequences.

The age of detrital zircons from the Middle–Upper Carboniferous and Permian sedimentary rocks has been estimated in the South Taimyr Zone [45]. For the Middle Carboniferous–Lower Permian Turuzovo Formation, the peaks of zircon age are 369, 337, 567, 426, 868, 733, 606, and 1771 Ma; for the Lower Permian Byrranga Formation these are 290, 358, 304, 420, 541, 507, 693, 660, 589, and 573 Ma; for the Lower Permian Sokoliny Formation, 358, 325, 304, 278, 487, 503, 2614, 1834, and 783 Ma; and for the Upper Perm-

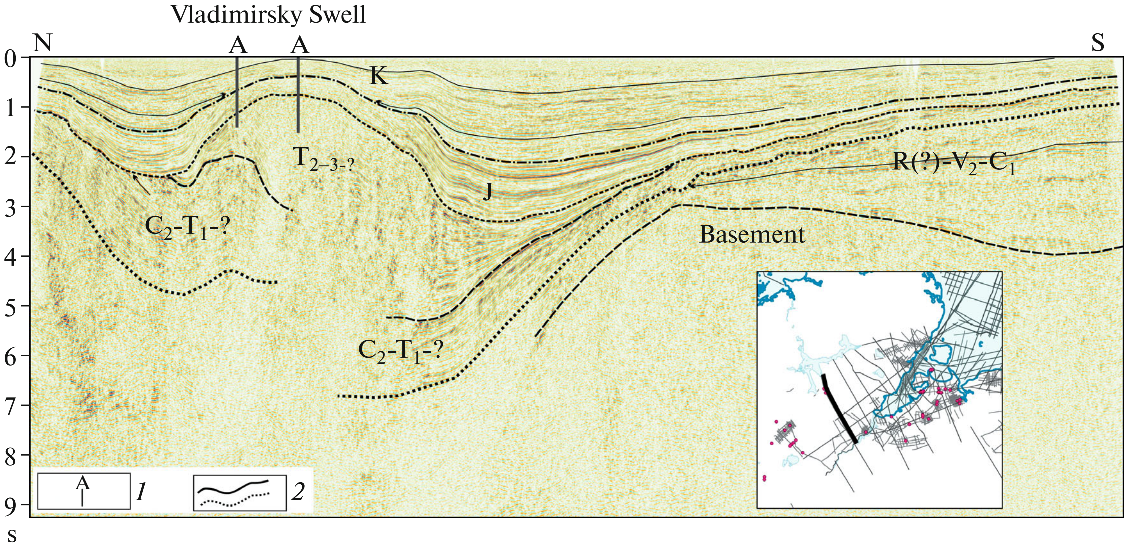


Fig. 10. Interpretation of time section along seismic line 3212205, which crosses Vladimirsky Swell. See inset for seismic line location. To south of this swell, sedimentary rocks make up a continuous sequence from Carboniferous to Cretaceous. To the north of swell, pre-Jurassic angular unconformity is recorded. Presumably Middle–Upper Triassic rocks form a sedimentary lens, which is interpreted as a rock complex of foredeep in front of Triassic Taimyr Orogen. (*1*) borehole, (*2*) seismic reflectors. Arrows at lines mark angular unconformities.

ian Baikur Formation, 263, 348, 325, 387, 502, 882, 714, 602, 1936, and 1875 Ma. The abundant Carboniferous and Permian zircons in coeval sediments apparently show that the North Taimyr and Central Taimyr zones, where numerous Carboniferous and Permian granitoid intrusions [45] and volcanics of the same age are known, have been eroded during formation of the Taimyr Foredeep. The peak of detrital zircon age for the Upper Permian molasse falls in the Late Permian (263 Ma).

The age of detrital zircons from the Viséan and Serpukhovian sedimentary rocks of the Verkhoyansk Complex has been studied in the Tiksi district [24]. Peaks of age at 500, 386, and 346 Ma have been established for Serpukhovian rocks (Tiksi Formation). It is supposed that beginning from early Viséan, the sediments were transported from the Taimyr Orogen [24].

The Triassic rocks make up a continuous sedimentary megasequence [6, 8, 28]. The Northern (Cape Tsvetkov), Central (Nordvik), and Southern (Maimecha–Kotui) zones are traced in the Khatanga–Lena Basin. A break in sedimentation is established at the base of the Triassic in all zones. The Lower Triassic basalts are apparently coeval with volcanic rocks of the Tungus traps in the Siberian Platform.

The most complete Triassic section is inherent to the Northern Zone. The sequence with volcanics is overlain by siltstone, claystone, and sandstone beds. The thickness of Triassic rocks decreases toward the Central Zone. More breaks of sedimentation and erosion boundaries appear in this direction. Triassic and Jurassic sequences are separated by stratigraphic unconformity, so that the Upper Triassic locally disappears.

The interpretation of seismic profiles shows that Triassic rocks near Cape Tsvetkov form a sedimentary wedge with increasing thickness northward (Fig. 8). It is suggested that the Lower Triassic sedimentary rocks and basaltic traps form a continuous cover of the Siberian Platform and the Taimyr, while the Middle and Upper Triassic sedimentary rocks fill the foredeep in front of the younger Taimyr Orogen [40]. To the south of Lake Taimyr near the Vladimirsky Swell, a thick lens of presumably Middle–Upper Triassic sediments is outlined from the interpretation of seismic data (Fig. 10). This tectonostratigraphic unit corresponds to the foredeep complex. Inasmuch as we are not able to trace this complex toward the Zhdanikhinsky Trough in front of the Balakhna Swell (Fig. 11), we propose to call this Middle–Upper Triassic trough the Triassic Taimyr Foredeep.

Jurassic and Cretaceous sedimentary rocks make up a common megasequence. Their description is based on the data reported by [19, 28, 44]. In the northern part of basin, Jurassic rocks overlie with angular unconformity Paleozoic–Triassic rocks.

The Hettangian–Bathonian, Callovian–Valanginian, Hauterivian–Barremian, and Aptian–Cenomanian stages are distinguished in Jurassic–Cretaceous history [19, 28]. The Hettangian–Bathonian stage is characterized by a stable setting with a uniform pelitic sedimentation. In the north of the basin near Cape Tsvetkova, pelitic rocks are intercalated by sandstone and conglomerate interbeds [28], indicating that hilly land existed at the spot of the Taimyr Orogen.

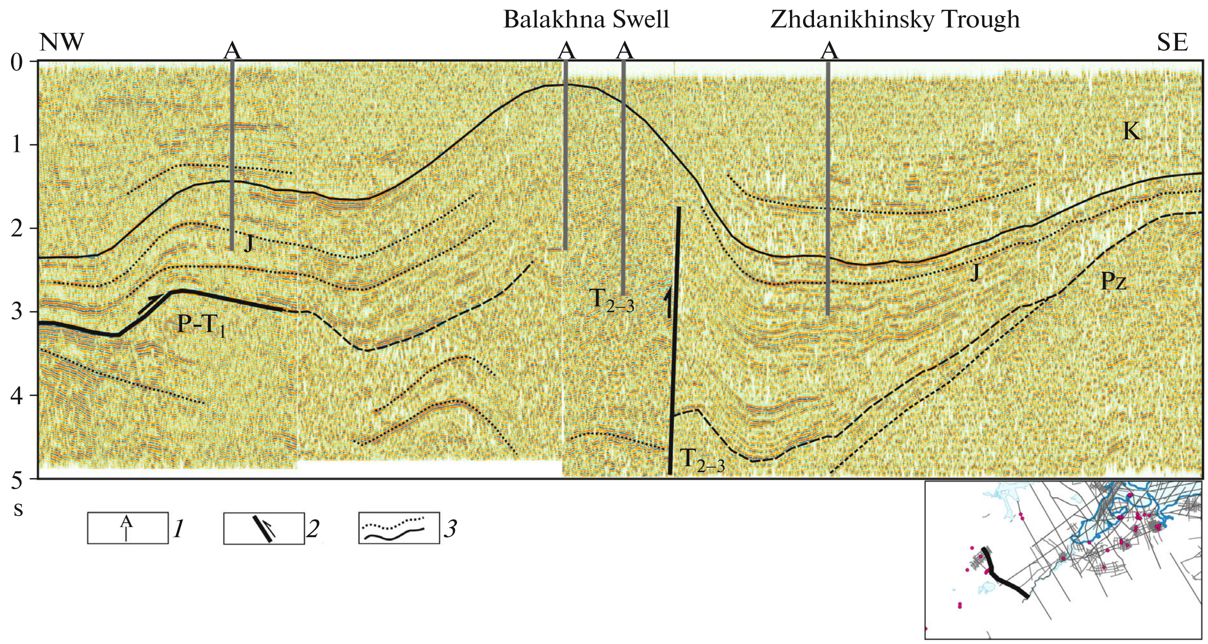


Fig. 11. Interpretation of composite time section along seismic line 023886–03a3886–033886–043886. See inset for seismic line location. Seismic line crosses Balakhna Megaswell. Boreholes reached Jurassic–Upper Triassic. (*1*) borehole; (*2*) fault and offset direction; (*3*) seismic reflectors.

The marine, mainly pelitic sedimentation is also typical of the Callovian–Valanginian; however, the sedimentation setting is diverse. The shallow-water marine and continental sediments are typical of the Hauterivian–Barremian. Similar settings with the prevalence of continental sedimentation are noted for the Aptian–Cenomanian.

The Yenisei–Khatanga Basin

The Yenisei–Khatanga Basin differs from the Khatanga–Lena Basin primarily in its thick (no less than 7–11 km) cover of Jurassic–Cretaceous rocks. All pre-Jurassic sedimentary rocks were studied using seismic exploration, and only a few boreholes have penetrated the Upper Triassic rocks.

Such tectonostratigraphic units as the Riphean–Lower Vendian, upper Vendian–Lower Cambrian, Middle Cambrian–Lower Carboniferous, Middle Carboniferous–Permian, Triassic, Jurassic, and Cretaceous–Eocene (Figs. 7 and 12) are distinguished in the Yenisei–Khatanga Basin on the basis of drilling, our interpretation of seismic profiles, and taking [9–13] into account.

In general, the Yenisei–Khatanga Basin resembles the Yenisei–Khatanga Basin. The main differences are considered below. The axis of the Triassic trough extends approximately along the axis of the Yenisei–Khatanga Basin, and it cannot be ruled out that rifts were formed here at the end of the Permian and in the Early Triassic, as took place in the West Siberian Basin. The Rassokha, Balakhna, and other giant swells (anticlinal uplifts) are typical of the Yenisei–Khatanga Basin (Figs. 11, 13, 14). The swells underwent synsedimentation growth in the Callovian–Late Jurassic to Late Jurassic–Neocomian [9, 10]. Some uplifts, e.g., the Rassokha Swell, started to form synchronously with Middle–Late Triassic sedimentation (Fig. 14). Most swells underwent postsedimentation growth in Cenozoic, likely after early Eocene. The Yenisei–Khatanga Basin separated as a self-dependent depocenter of thick sediments in Jurassic and Cretaceous. The Jurassic–Cretaceous history of this basin is generally similar to history of the West Siberian Basin [9–11, 42], and there is no distinct boundary between them.

At the northern and southern walls of the trough, the main angular unconformity is localized at the base of the Jurassic (Figs. 15 and 16). The Cretaceous rocks are more extensive than the Jurassic rocks and overlap with angular unconformity the northern and southern walls of the basin, where the Jurassic disappears. The pre-Jurassic angular unconformity is locally established within the Yenisei–Khatanga Basin, e.g., near the Rassokha Swell (Fig. 14). The Tungus unconformity is recorded approximately between the Lower and Middle Carboniferous and is suggested to be within the Yenisei–Khatanga Basin, but so far has not been recorded in seismic profiles. At the bottom of this basin, Late Vendian–Early Cambrian grabens are assumed, but are also not recorded in the available seismic sections.

The Triassic rocks of the Yenisei–Khatanga Basin are commonly recorded in seismic sections as a lens in cross-section. The Permian–Triassic normal faults apparently control this basin; however, their occurrences are not yet proven distinctly. The bottom of the Triassic sedimentary rocks have also not been detected precisely. The preliminary interpretation of Triassic history assumes rifting apparently accompanied by trap magmatism at the Permian–Triassic boundary. In the Middle–Late Triassic, the basin became marginal or intermontane between the growing orogen of the South Taimyr Zone and the zone of uplifts in the northwestern and northern Siberian Platform (Turukhansk–Noril'sk Zone).

The Jurassic sequence is 2–4 km thick. Angular unconformities at its base are recorded at the basin walls, while in its center, Jurassic rocks conformably rest upon Triassic ones. As follows from the interpretation of seismic profiles, the Jurassic basin is locally bounded by normal faults. The Jurassic sedimentation proceeded against the background of the uplift of the Taimyr Orogen and the northern Siberian Platform [9]. The slow synsedimentation growth of the Rassokha, Balakhna, and other swells developed approximately from the Callovian to the end of the Late Jurassic [9]. Issuing from these data, we suppose that the Jurassic sedimentation proceeded against the background of compression and regional right-lateral strike-slip faulting in transpressional and local transtensional regimes. Compression may have led to the sagging of the basinal lithosphere and the synchronous uplift of the Taimyr domain and the northern Siberian Platform. Shearing combined with compression gave rise to the formation of a chain of antilinal uplifts and positive flower structures in the central part of the basin.

Cretaceous rocks are up to 2–4 km thick and are more extensive than Jurassic rocks; they record angular unconformity at the margins of the basin. The Cretaceous section is distinctly subdivided into Neocomian (Berriasian–Barremian) and Aptian–Upper Cretaceous stratigraphic units. As in western Siberia, the Neocomian is characterized by a clinoform structure. In the western Yenisei–Khatanga Basin, the clinoforms commonly strike along the axis of the basin and record transport of sediments from the Siberian Platform [1]. In the northernmost Yenisei–Khatanga Basin, the clinoforms are characterized by the transport of material from Taimyr. The growth of anticlinal swells continued in the Neocomian and ceased in the Aptian. The continental sediments were mainly deposited in the Aptian and the Late Cretaceous; clinoforms of this age are unknown.

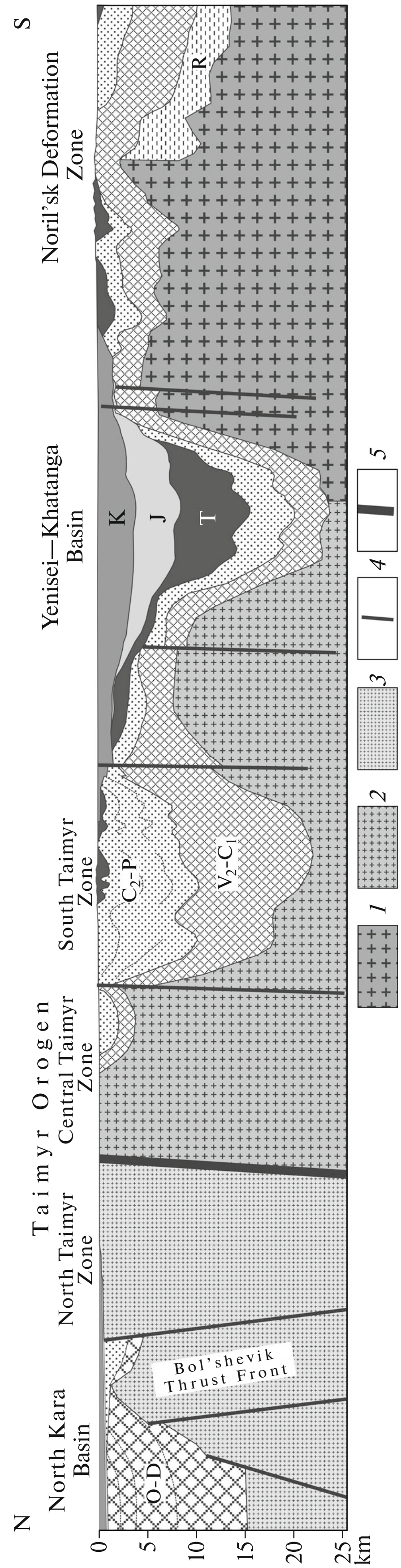


Fig. 12. Regional geological section from Siberian Platform to North Kara Sedimentary Basin. Interpretation of Dikson–Lake Khantaiskoe seismic section was used for land and data from [12, 21] for offshore zone. See Fig. 1 for location of regional section. (*1*) basement of Siberian Craton; (*2*) Neoproterozoic (Baikalian) basement; (*3*) Cambrian basement; (*4*) fault; (*5*) Main Taimyr Suture.

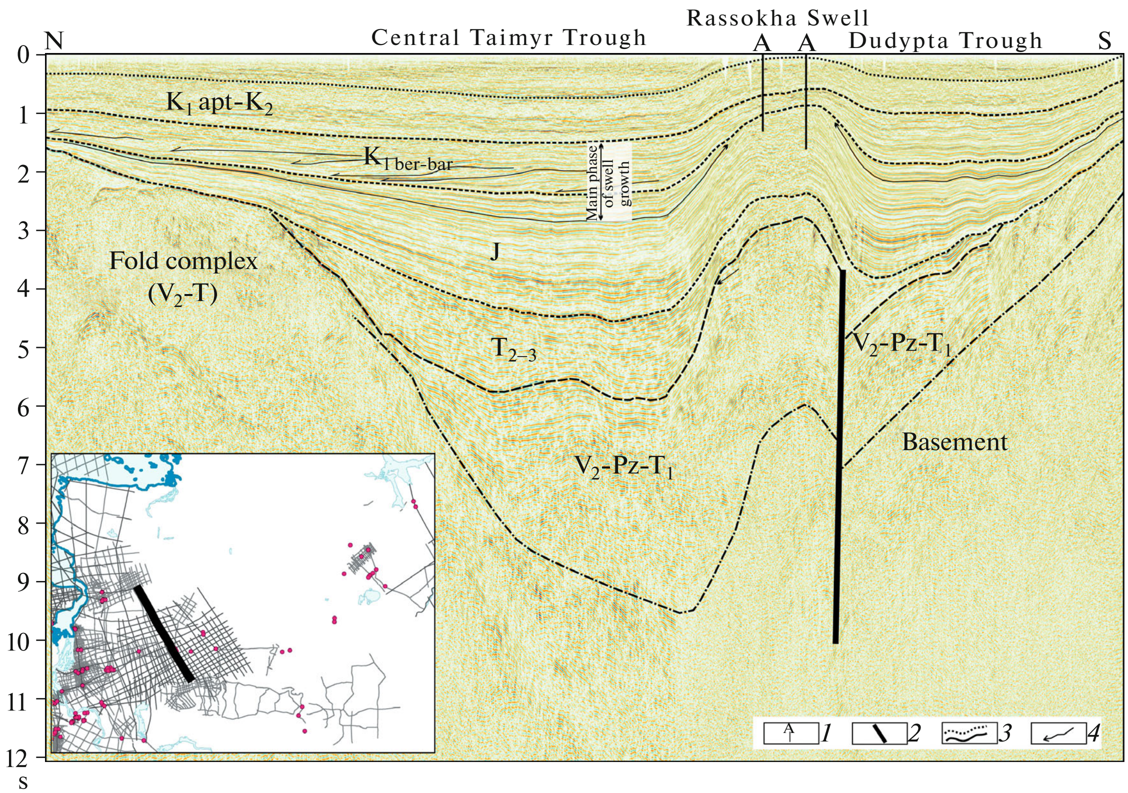


Fig. 13. Interpretation of time section along seismic line 6210113. See inset for seismic line location. (*1*) borehole, (*2*) fault, (*3*) seismic reflectors; (*4*) direction of layer abutment.

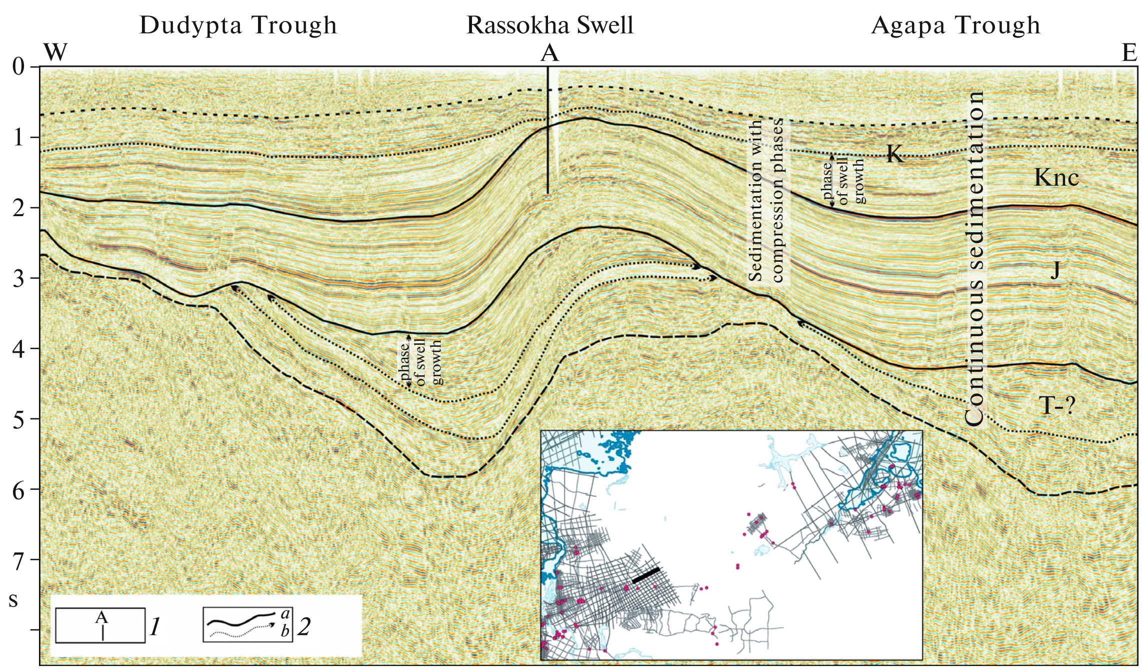


Fig. 14. Interpretation of time section along seismic line 6214418, area of Rassokha Megaswell. See inset for seismic line location. Three main phases of swell growth are shown: presumably in Middle–Upper Triassic, at Jurassic–Cretaceous boundary and in Neocome, and in post-Cretaceous time. (*1*) borehole, (*2*) seismic reflectors (*a*) and direction of layer abutment (*b*).

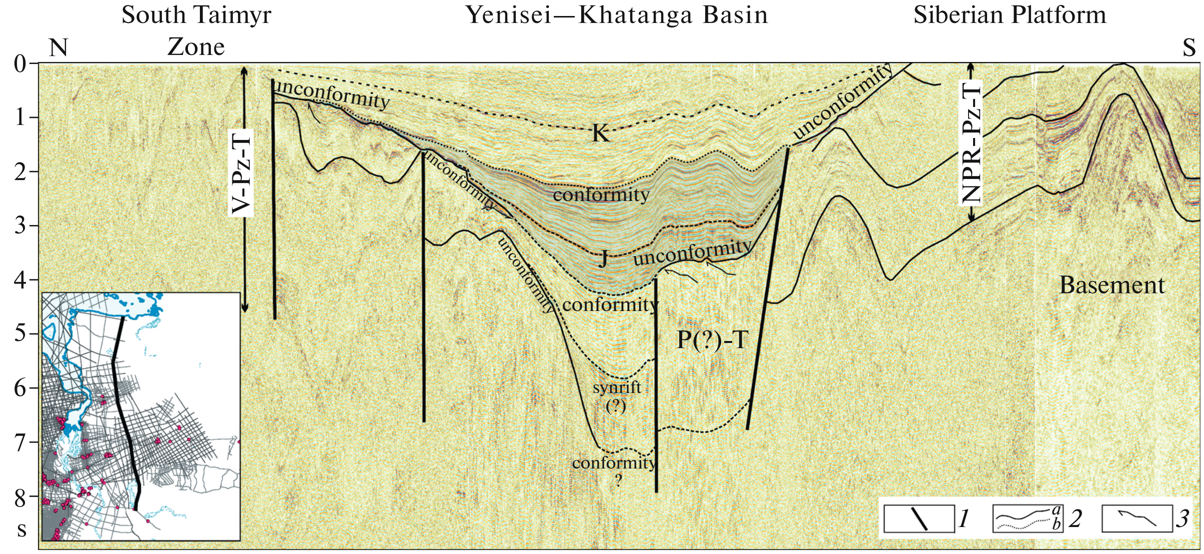


Fig. 15. Interpretation of composite time section along seismic lines 0409209–0411109 across western Yenisei–Khatanga Trough. See inset for seismic line location. Angular unconformities are shown at bottom of the Jurassic–Cretaceous complex close to basin walls. Basin is characterized by continuous section from Paleozoic to Cretaceous; pre-Jurassic angular unconformity is noted close to southern wall. (*1*) borehole, (*2*) seismic reflectors, (*3*) direction of layer abutment.

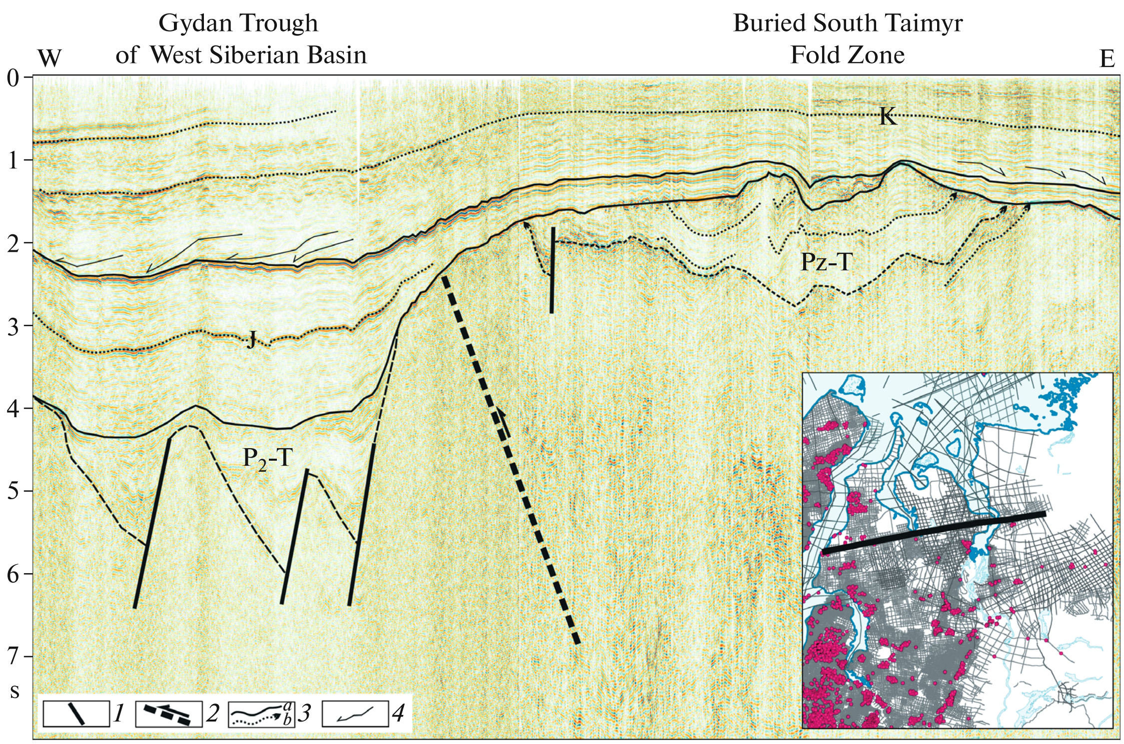


Fig. 16. Interpretation of composite time section along seismic lines 4485042–0208008–6209214. See inset for seismic line location. Continuous section from Permian–Triassic to Cretaceous is recorded in Gydan area. Angular unconformity at base of Jurassic appears close to South Taimyr Zone. It is suggested that pre-Jurassic thrust fault occurs between Taimyr Orogen and West Siberian Basin. (*1*) fault, (*2*) pre-Jurassic thrust fault, (*3*) seismic reflectors, (*4*) direction of layer abutment.

Paleocene–Eocene sediments have been retained locally in the basin. These are primarily continental sediments, conformably overlying Upper Cretaceous sedimentary rocks.

The Neocomian sediments of the Yenisei–Khatanga Basin were formed synchronously with the Verkhoyansk Orogeny, the culmination of which falls in the Tithonian–Barremian [31]. The Verkhoyansk Orogeny also developed in the South Anyui Orogen. The syncollisional flysch–molasse basins in the Lyakhovsky Islands were formed in the Tithonian–Neocomian [15, 36]. The swells grew in the Yenisei–Khatanga Basin in the Late Jurassic–Neocomian synchronously with the orogeny in the Verkhoyansk–Chukchi Peninsula zone. The onset of orogeny and the growth of swells are not dated accurately; it may be that this was the Callovian. It is suggested that in general, the Jurassic–Cretaceous subsidence of the Yenisei–Khatanga Basin was intensified by shear combined with compression deformations (transpression).

Most swells in the Yenisei–Khatanga Basin are characterized by syncompression (transpressional?) growth in the Cenozoic, apparently, after the deposition of the Early Eocene sediments. The anticlinal swells located close to the Khatanga and Anabar bays were formed after the Early Cretaceous, presumably in the mid-Eocene to the Oligocene. The section of this fold zone (Fig. 9) shows that all sedimentary rocks from the Paleozoic to the Cretaceous are deformed as a common fold system under the effect of compression. Salt domes are outlined beneath many anticlines. The level of Devonian salts apparently was the level of main detachment. The activation of swelling in Cenozoic was caused in some way by the reorganization of the lithospheric plate boundaries in the Arctic Region, as is described, for example, in [33, 40].

DISCUSSION

The data reported in this paper allow us to recognize the main stages of the formation of the Yenisei–Khatanga Basin and its conjugate Taimyr Orogen (Fig. 17).

The composite terrane of the Central Taimyr Zone accreted to the margin of the Siberian continent approximately at the Riphean–Vendian transition [2, 3, 7]. In Late Vendian–Early Cambrian, the clastic material was transported to the north of the Siberian Platform from the Baikalides, including the Central Taimyr Zone [16, 35].

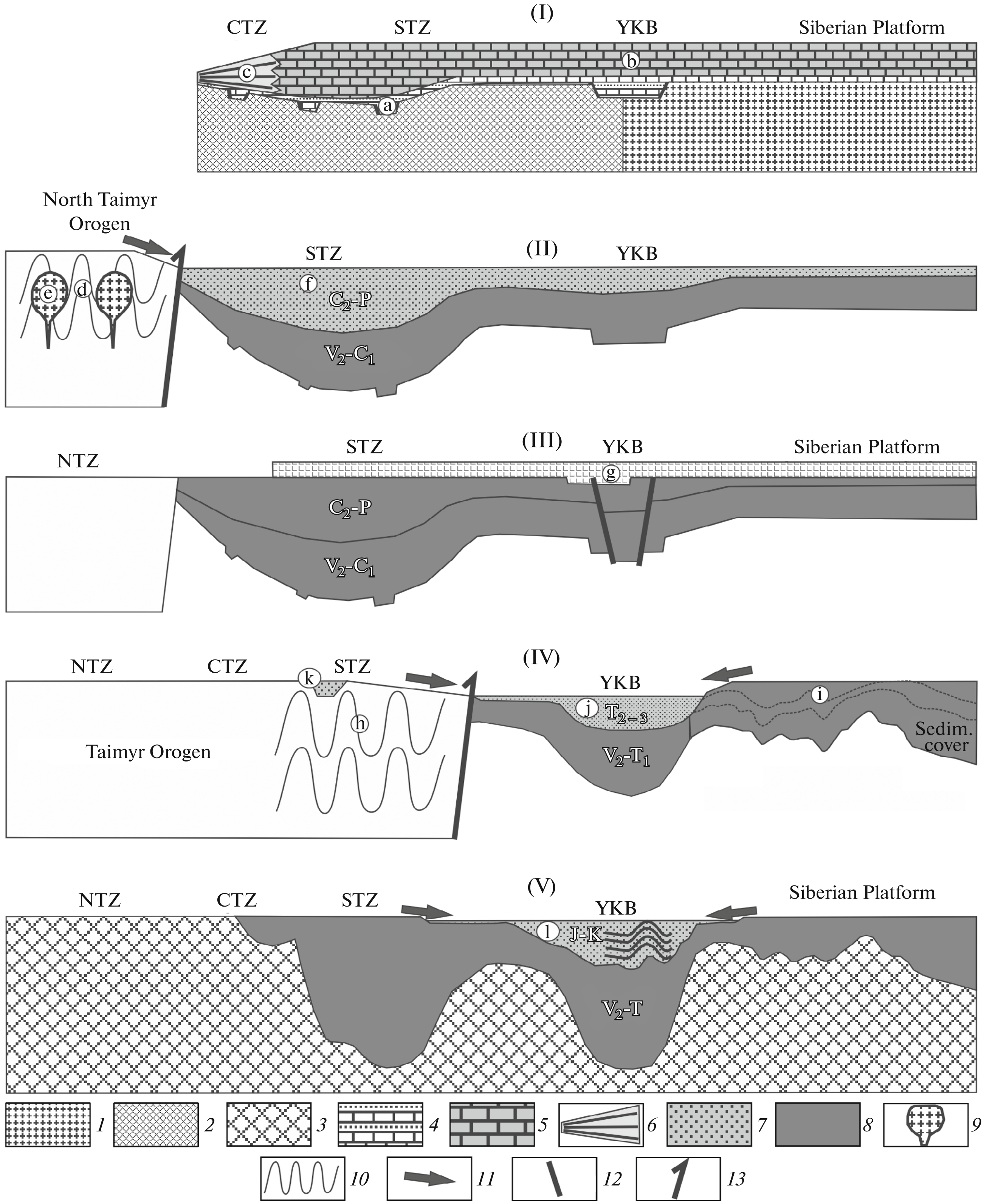
Continental rifting in the Yenisei–Khatanga Basin and the zones of the South and Central Taimyr apparently resulted in the formation of a hypothetical Middle Cambrian oceanic basin to the north of the contemporary Central Taimyr Zone. Approximately since the Middle Cambrian, the South Taimyr Zone and the Yenisei–Khatanga Basin have become a shelf basin. In the Central Taimyr Zone, this basin passed into continental slope [7, 20].

The North Kara Block and the North Taimyr Zone, as part of it, collided with the Central and South Taimyr zones, approximately from the end of the Devonian or at the onset of the Carboniferous (presumably from the Viséan) to the Late Permian [2, 3, 18, 20, 24, 40] (Fig. 4). This major collision followed the closure of the oceanic basin and was accompanied by the subduction of oceanic lithosphere in the Carboniferous. Subduction was apparently directed to the north. The collision was terminated by the emplacement of the Permian granitoids [7].

The Carboniferous–Permian mountain building in Taimyr lasted for an anomalously long time (~90 Ma). At that time, the Uralian and Central Asian paleooceans between the Siberian and East European paleocontinents were being closed. When the paleooceans closed in the Carboniferous and Permian, the North Kara Block, as a part of the East European continent [38, 43], apparently did not move relative to Baltica. During the convergence of the Siberian paleocontinent and Baltica in the Carboniferous and Permian, large-amplitude strike-slip faults may have extended along the Taimyr Orogen. Following V.A. Vernikovsky [2], we suggest that the Taimyr Orogen, which underwent collision and right-lateral strike-slip faulting, may be regarded as a transpressional tectonic unit. This explains the long time interval of mountain building, granitoid magmatism, and volcanic activity. The Taimyr orogen is characterized by bilateral southern and northern vergence (Figs. 4 and 12). In the course of this deformation, the Paleozoic ophiolitic suture may have been disintegrated [2].

Approximately from the Viséan or at the transition from the Early to the Middle Carboniferous, the Taimyr Fordeep, filled with molasse, began to form at

Fig. 17. Geological history of Yenisei–Khatanga Basin along Dikson–Lake Khantai seismic line. NTZ, North Taimyr Zone; CTZ, Central Taimyr Zone; STZ, South Taimyr Zone; YKB, Yenisei–Khatanga Basin. (I) Late Vendian–Devonian: Formation of marginal continental shelf postrift carbonate platform. Letters in circles: (a) Upper Vendian–Lower Cambrian synrift sediments, (b) postrift carbonate platform, (c) deepwater shale (sediments on continental slope). (II) Middle Carboniferoius–Permian: (d) main folding and (e) granitoid magmatism in northern Taimyr; (f) formation of piedmont foredeep. (III) Late Permian–Early Triassic: (g) regional trap magmatism, possible rifting in Yenisei–Khatanga Basin. (IV) Middle–Upper Triassic: (h) folding in STZ and (i) Noril'sk region of Siberian Platform, (j) formation of molasse foredeep in JKB and (k) intermontane molasse troughs of STZ. (V) Late Jurassic–Early Cretaceous, regional transpression: (l) YKB is intermontane molasse basin. (*1*) basement of Siberian Platform; (*2*) Neoproterozoic (Baikalian) basement; (*3*) basement varying in age; (*4*) carbonate and terrigenous rocks; (*5*) carbonate platform; (*6*) deepwater shale; (*7*) terrigenous sediments; (*8*) sediments formed before given stage; (*9*) granitoid intrusions; (*10*) folding; (*11*) direction of clastic sediment transport; (*12*) normal fault; (*13*) thrust fault.


(I)
CTZ
STZ
YKB
Siberian Platform
a
b
c
North Taimyr
Orogen
(II)
STZ
YKB
d
e
f
C2-P
V2-C1
(III)
NTZ
STZ
YKB
Siberian Platform
g
C2-P
V2-C1
(IV)
NTZ
CTZ
STZ
YKB
k
h
i
j
T2-3
V2-T1
Taimyr Orogen
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the spot of the contemporary South Taimyr Zone and the Yenisei–Khatanga Basin (Figs. 4, 6, 10). The foredeep formation was preceded by irregular low-angle compression and vertical movements accompanied by erosion. The Carboniferous–Permian Tunguska Basin of the Siberian Platform was a distal zone of the foreland basin filled with molasse. During the development of the foredeep, the North and Central Taimyr zones underwent erosion.

At the Permian and Triassic boundary and in the Early Triassic, trap magmatism was widespread in the studied region as a part of the vast territory affected by the mantle superplume [4, 5, 39]. Permian–Triassic rifting possibly developed in the western Yenisei–Khatanga Basin, as in western Siberia [39].

Folding and rising took place during the Middle–Late Triassic (before the Jurassic) in the South Taimyr Zone and the Turukhansk–Noril'sk Zone of the Siberian Platform. The entire territory of the Taimyr Orogen was affected by pre-Jurassic uplifting [7]. The Triassic Taimyr Foredeep arose synchronously with folding in the northern Khatanga–Lena Basin (Figs. 8 and 10). Folding also developed at the walls of the Yenisei–Khatanga Basin, where separate anticlinal swells, e.g., the Rassokha Swell, started to grow (Fig. 14).

Important conclusions ensue from the timing of detrital zircons from the Triassic rocks of Franz Josef Land (FJL) and the Chukchi Peninsula. Many Carboniferous to Triassic zircons are contained in the Middle–Upper Triassic rocks [29]. The peak at 231–233 Ma is characteristic of Triassic zircons. It is thought that the Taimyr Orogen was a source of clastic material for FJL in the Middle–Late Triassic [29]. The Triassic peak of zircon ages is also typical of rocks on the Chukchi Peninsula and on Wrangel Island. This implies that the Taimyr Orogen had a Middle–Late Triassic provenance [37]. Thus, many data show that the Taimyr Orogen was a mountainous region in the Middle–Late Triassic.

In the Early–Middle Jurassic (pre-Callovian), the Yenisei–Khatanga Basin subsided as an intermontane trough between the uplifting Taimyr Orogen and the northern Siberian Platform. The subsidence was governed by compression and right-lateral strike-slip faulting.

The main anticlinal swells of the Yenisei–Khatanga Basin were formed from the Callovian to the Aptian. A maximum of growth has been achieved close to the Jurassic–Cretaceous boundary. The epoch of swell growth coincides with Verkhoyansk Orogeny related to collision. In general, the Yenisei–Khatanga Basin subsided in the Callovian–Barremian in the regime of compression and the overall sagging of the basin as a lithospheric syncline. The transpressional growth of anticlinal swells developed against the background of these processes.

In the Neocomian, the Taimyr Orogen was leveled and the Siberian Platform began to rise, probably due to the progress of the Verkhoyansk collision and regional compression. Under these conditions, clastic material was supplied from the Siberian Platform. The Yenisei–Khatanga Basin was characterized by clinoform sedimentation such as the West Siberian Basin. A great deal of Triassic, Permian, and Carboniferous detrital zircons were revealed in Neocomian continental sediments close to Cape Chelyuskin in the north of Taimyr. This implies that the uplifted Taimyr Orogen was a provenance of clastic material [45].

In the Aptian–Late Cretaceous, shallow-water marine and continental sediments accumulated in the Yenisei–Khatanga Basin in a relatively quiet tectonic setting, which apparently continued up to the middle Eocene.

Some anticlinal swells continued to grow in the Late Cenozoic, probably beginning from the middle–late Eocene in the setting of right-lateral transpression (Figs. 8–14).

CONCLUSIONS

Based on available data, we propose a new scenario of the Phanerozoic geological history inherent to the Taimyr and Yenisei–Khatanga Basin.

Since the Late Vendian–Cambrian and up to the Devonian–Carboniferous boundary, a shelf basin and passive continental margin have been being formed in the South Taimyr and Central Taimyr zones, as well as in the Yenisei–Khatanga Basin.

The collision of the Taimyr continental margin and the North Kara Block (North Taimyr Zone) started approximately at the Devonian–Carboniferous boundary. This gave rise to folding in the North Taimyr Zone, whereas vertical movements and erosion down to hundreds of meters and a few kilometers were characterized for the South Taimyr Zone and the Yenisei–Khatanga Basin.

The Taimyr Foredeep, with a depocenter in the South Taimyr Zone, was formed from the Middle Carboniferous to the end of the Permian.

Extensive trap magmatism caused by a mantle plume developed at the Permian–Triassic boundary. Rifting in the western Yenisei–Khatanga Basin cannot be ruled out.

In the Middle–Late Triassic, the Yenisei–Khatanga Basin was transformed into the piedmont foredeep, with molasse accumulating against the background of the resumed rising of the Taimyr Orogen. The axis of the Middle–Late Triassic foredeep was located to the south of the Carboniferous–Permian foredeep. Taimyr and the northwestern margin of the Siberian Platform underwent folding.

In the Jurassic and Cretaceous, the Yenisei–Khatanga Basin was affected by right-lateral transpressional deformation and underwent compressive sagging of its lithosphere.

Beginning from the middle–late Eocene, the growth of anticlinal swells resumed in the Yenisei–Khatanga Basin under transpressional conditions.

It is important that two epochs of large-scale orogeny are recorded in Taimyr in the Late Paleozoic and the Middle–Late Triassic. The axis of the Middle–Late Triassic foredeep was situated to the south of the Late Paleozoic foredeep. The Yenisei–Khatanga Basin consists of sedimentary complexes (megasequences) formed in different tectonic settings.

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Reviewers: Yu.A. Volozh and S.D. Sokolov

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