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Influence of syn-sedimentary faults on orogenic structure: examples from the Neoproterozoic–Mesozoic east Siberian passive margin

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Abstract

The east margin of the Siberian craton is a typical passive margin with a thick succession of sedimentary rocks ranging in age from Mesoproterozoic to Tertiary. Several zones with distinct structural styles are recognized and reflect an eastward-migrating depocenter. Mesozoic orogeny was preceded by several Mesoproterozoic to Paleozoic tectonic events. In the South Verkhoyansk, the most intense pre-Mesozoic event, 1000–950 Ma rifting, affected the margin of the Siberian craton and formed half-graben basins, bounded by listric normal faults. Neoproterozoic compressional structures occurred locally, whereas extensional structures, related to latest Neoproterozoic–early Paleozoic rifting events, have yet to be identified. Devonian rifting is recognized throughout the eastern margin of the Siberian craton and is represented by numerous normal faults and local half-graben basins.

Estimated shortening associated with Mesozoic compression shows that the inner parts of ancient rifts are now hidden beneath late Paleozoic–Mesozoic siliciclastics of the Verkhoyansk Complex and that only the outer parts are exposed in frontal ranges of the Verkhoyansk thrust-and-fold belt. Mesoproterozoic to Paleozoic structures had various impacts on the Mesozoic compressional structures. Rifting at 1000–950 Ma formed extensional detachment and normal faults that were reactivated as thrusts characteristic of the Verkhoyansk foreland. Younger Neoproterozoic compressional structures do not display any evidence for Mesozoic reactivation. Several initially east-dipping Late Devonian normal faults were passively rotated during Mesozoic orogenesis and are now recognized as west-dipping thrusts, but without significant reactivation displacement along fault surfaces.

Keywords: Reactivation; Neoproterozoic to Paleozoic rifting events; Mesozoic orogeny; East Siberia

1. Introduction

The east margin of the Siberian craton is a typical passive margin with a thick succession of sedimentary rocks ranging in age from Mesoproterozoic to Tertiary (Nokleberg, 1994; Parfenov, 1995; Parfenov and Kuzmin, 2001). Carbonate and terrigenous rocks predominate, but mafic volcanics and sills are found throughout the succession. During the Mesozoic, the succession was deformed and thrust onto the Siberian craton, forming the frontal ranges of the Verkhoyansk

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thrust-and-fold belt, which separates the ancient Siberian craton from Paleozoic and Mesozoic accretionary complexes of northeast Russia (Fig. 1).

The stratigraphy and composition of synchronous units do not significantly vary along the east margin of Siberian craton, suggesting that sedimentation occurred in a single basin (Kovalskiy, 1985; Parfenov, 1995; Parfenov and Kuzmin, 2001). The most complete section encompassing the Mesoproterozoic to Mesozoic is located in the South Verkhoyansk (southern part of the Verkhoyansk thrust-and-fold belt). This section will be discussed in this paper in the most detail. Some Proterozoic successions are also exposed in the northernmost part of the Verkhoyansk thrust-and-fold belt (Kharaulakh range), but most of the lower Paleozoic rocks in the Kharaulakh range were eroded prior to Devonian. Devonian rocks are also locally exposed above the main basal detachment that separates the thrust-and-fold belt from the Siberian craton. The rest of the frontal ranges of the Verkhoyansk thrust-and-fold belt are covered with Carboniferous to Triassic siliciclastics (Verkhoyansk Complex).

The Mesozoic tectonic and magmatic events have been described by Parfenov et al. (1995), Prokopiev (1998), Layer et al. (2001), Parfenov and Kuzmin (2001) and others. In addition, during the Neoproterozoic and Paleozoic time, the east margin of the

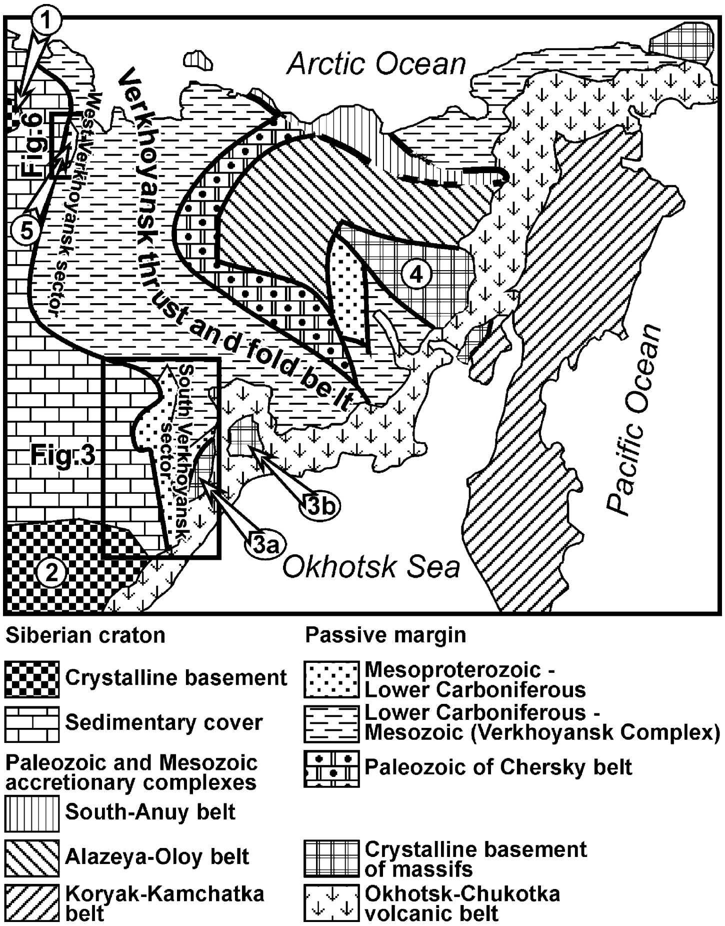


Fig. 1. Simplified tectonic map of the northeastern Russia. Numbers in circles are the main areas referred to in the text: 1—Olenek uplift, 2—Aldan shield, 3—Okhotsk massif (3a—Upper Maya uplift, 3b—Kukhtuy uplift), 4—Omolon massif, 5—Kharaulakh segment of the West Verkhoyansk.

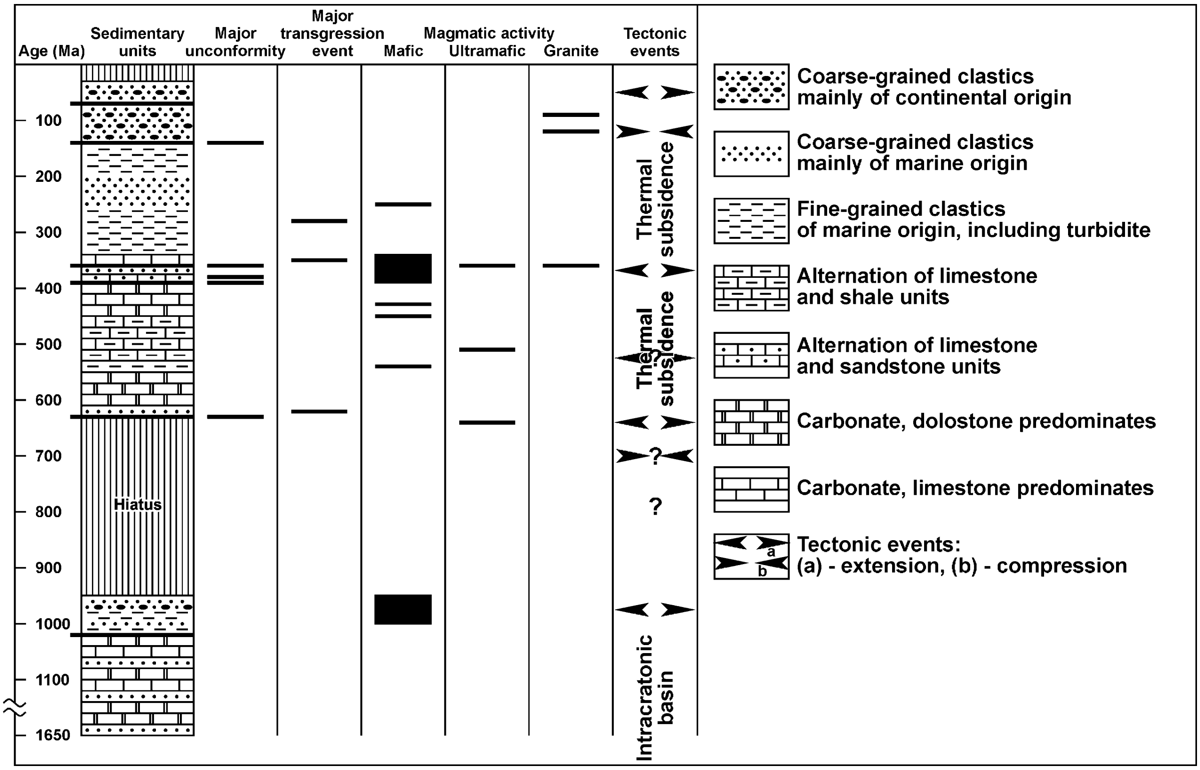


Fig. 2. Tectonic evolution of the east margin of the Siberian craton, summarizing data from the South Verkhoyansk sector and Kharaulakh segment of the West Verkhoyansk sector. Sedimentary units are separated by heavy lines into major cycles, corresponding to evolution of tectonic environments. Data sources: Yan-Zhin-Shin (1983), Kovalskiy (1985), Bowring et al. (1993), Rainbird et al. (1998), Khudoley et al. (2001a,b), Khudoley and Serkina (2002), Layer et al. (2001), Parfenov and Kuzmin (2001), Prokopiev et al. (2001).

Siberian craton was affected by several rifting and compressional events (Fig. 2). Related structures are clearly recognized in outcrop and on large-scale geologic maps, or are inferred from the compositions of related sedimentary and magmatic rocks. Our main objective in this paper is to illustrate the relationships between modern and ancient structures and to demonstrate which pre-Mesozoic event had the largest impacts on the geometry of Mesozoic faults in the frontal ranges of the Verkhoyansk thrust-and-fold belt.

2. Geologic framework and structural style of the Mesozoic orogen

The Verkhoyansk foreland thrust-and-fold belt consists of the West Verkhoyansk and South Verkhoyansk sectors, with several segments characterized by specific frontal thrust structures (Parfenov et al., 1995). The West Verkhoyansk sector is overthrust onto the Mesozoic foredeep basin. However, in the South Verkhoyansk sector the Mesozoic foredeep pinches out, and foreland thrust sheets are in direct contact with the Siberian craton. In the South Verkhoyansk, a major thrust separating the Siberian craton from foreland structures is usually described as the Nelkan–Kyllakh thrust. Three major, strike-parallel zones, the Maya–Kyllakh, Sette–Daban and South Verkhoyansk synclinorium are recognized in the South Verkhoyansk sector, along with a number of subzones (Fig. 3) (Yan-Zhin-Shin, 1983; Prokopiev, 1989; Khudoley and Guriev, 1994; Parfenov and Kuzmin, 2001). These zones reflect eastward migration of the sedimentary basin depocenter from Mesoproterozoic to late Paleozoic time. Structural style is

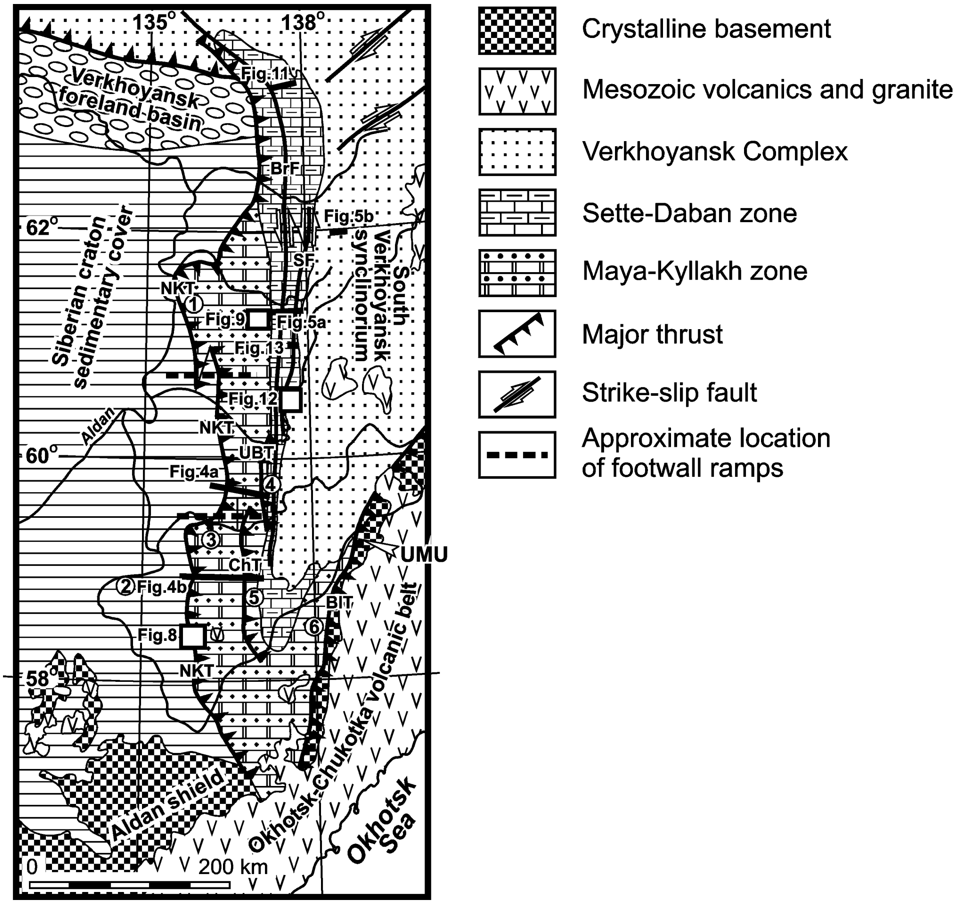


Fig. 3. Simplified tectonic map of the South Verkhoyansk sector of the Verkhoyansk thrust-and-fold belt. See location in Fig. 1. Numbers in circles indicate locations of the main sections of the Uy Group discussed in the text. Abbreviations: BrF—Burkhala fault, BlT—Bilyakchan thrust, ChT—Chelat thrust, NKT—Nelkan–Kyllakh thrust, SF—Setaniya fault, UBT—Ulakhan–Bam thrust, UMU—Upper Maya uplift of the Okhotsk massif.

controlled by proximity to the Siberian craton and by the distribution of more resistant units within the succession.

The westernmost zone, the Maya–Kyllakh, is dominated by Precambrian and Cambrian rock units that are locally overlain with low-angle unconformity by Lower Carboniferous, Lower Permian, or Lower Jurassic rocks. The Precambrian succession contains both resistant carbonate and sandstone and recessive shale units, which from oldest to youngest comprise the Uchur, Aimchan, Kerpyl, Lakhanda, Uy and Yudoma groups. Most of these groups are bounded, above and below, by regional unconformities. The main structural style of the Maya–Kyllakh zone is manifested by a west-vergent imbricate thrust fan with fault-bend and fault-propagation tight anticlines separated by wide, flat synclines (Fig. 4). According to available potential field (gravity and aeromagnetic) data, the crystalline basement surface does not show significant offsets, but gradually dips eastward, implying predominance of thin-skinned tectonics (Prokopiev, 1998; Parfenov and Kuzmin, 2001). Thick, resistant carbonate and sandstone units favored the development of thick thrust sheets with relatively simple internal structure. We interpret the stratigraphic setting of rocks exposed at the base of thrust sheets to indicate that, in the northern part of the Maya–Kyllakh zone, the basal detachment is

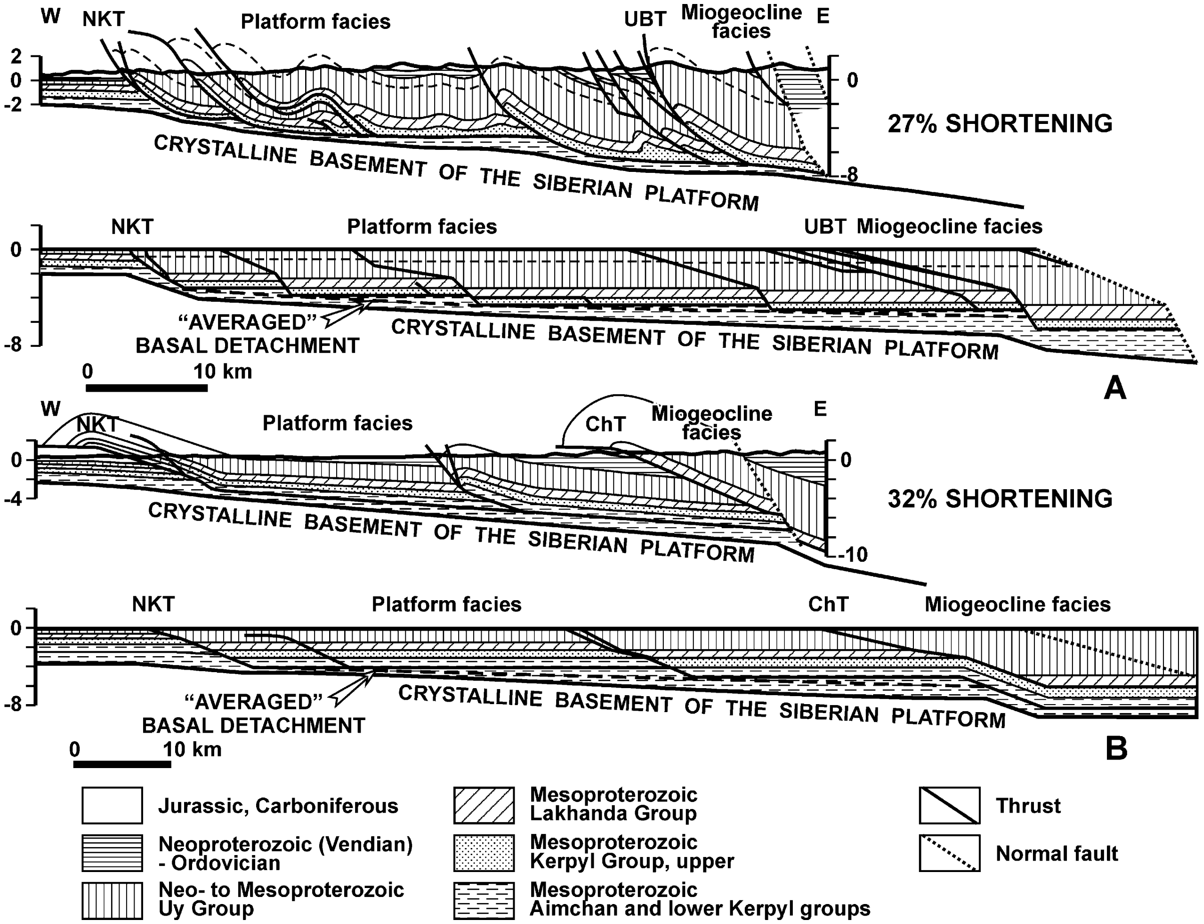


Fig. 4. Balanced and restored cross-sections, Maya–Kyllakh zone. See location in Fig. 3. Abbreviations: ChT—Chelat thrust, NKT—Nelkan–Kyllakh thrust, UBT—Ulakhan–Bam thrust.

located in the lower part of the Uchur Group, and probably separates the sedimentary succession from the crystalline basement. In the central part of the zone, basal detachment is located within the sedimentary succession within the upper Kerpyl Group or at the base of the Lakhanda Group. In the southern part of the zone, the basal detachment is at the base of the Kerpyl Group or within the Aimchan Group and is fairly close to crystalline basement. These kilometer-scale changes in the stratigraphic location of the basal detachment point to the occurrence of transverse footwall ramps (Fig. 3), which most likely represent pre-Mesozoic transverse structures. Average estimated shortening varies from approximately 20 to 40 km, and is typically about 25–35% of initial width of the Maya–Kyllakh zone. This range of horizontal shortening is close to reported values from other parts of the frontal ranges of the Verkhoyansk thrust-and-fold belt (Parfenov et al., 1995). In the eastern part of the Maya–Kyllakh zone, the Ulakhan–Bam and Chelat thrusts separate slope facies of the Uy Group from an area dominated by synchronous platform facies. The thickness of individual thrust sheets increases eastward, mainly due to significant thickening of the late Mesoproterozoic Uy Group and presence of a more complete stratigraphic section. Total composite thickness of the Maya–Kyllakh zone succession is inferred to be about 16 km (Yan-Zhin-Shin, 1983; Khudoley et al., 2001b; Parfenov and Kuzmin, 2001).

The Sette–Daban zone is located to the east of the Maya–Kyllakh zone and consists of Vendian to Lower Carboniferous strata. However, northwards, the Maya–Kyllakh zone pinches out and the Sette–Daban zone is in direct contact with the Siberian craton (Fig. 3). Although carbonate rock units predominate, Cambrian and Lower Ordovician successions contain thick shale units and shale interbeds. Shale content increases eastward. Sedimentation was nearly continuous until the Early Devonian, but Middle Devonian to Lower Carboniferous rocks contain many local and regional unconformities (Fig. 2). Wide distribution of recessive shaly limestone and shale units favored the development of folds with a very complex geometry above a regional detachment. The most characteristic structural features of the Sette–Daban zone are fan-like fold-and-thrust structures near the Burkhala fault, and a set of en echelon faults, collectively known as the Setaniya fault. These structures are dominated by normal bedding west of the fault zones and by west-dipping, overturned bedding to the east (Fig. 5A). Both the Burkhala and Setaniya faults have a significant sinistral strike-slip component of displacement and are often interpreted as transpression zones with related flower-like structures (Prokopiev, 1989). However, their origin may be the result of oblique wedging of the sedimentary succession during Mesozoic thrusting. Several stages of the Mesozoic deformation are recognized in the easternmost part of the Sette–Daban zone.

In the less deformed northern part of the Sette–Daban zone, sinistral strike-slip faults are not accompanied by fan-like structures. In the western part of this area, several east-dipping thrust sheets with very complex internal folding are thrust onto the Siberian

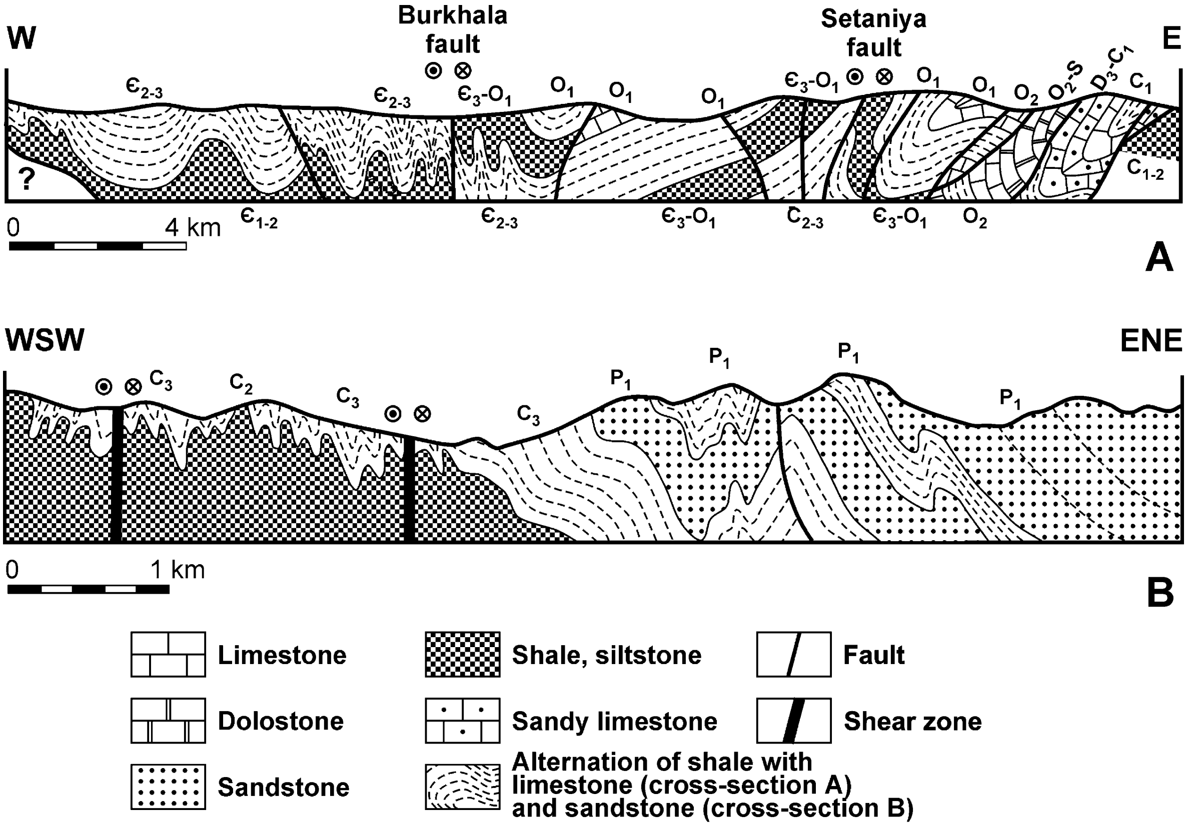


Fig. 5. Cross-sections, showing modern structure of the South Verkhoyansk sector of the Verkhoyansk thrust-and-fold belt. (A) Sette–Daban zone, (B) South Verkhoyansk synclinorium. See location in Fig. 3.

craton. However, in the eastern part, east-dipping thrusts alternate with approximately parallel, normal faults. Shaly units are cleaved and affected by low-grade greenschist metamorphism. Fold-related shortening is estimated as 30–40% (Prokopiev, 1989). The total composite thickness of the Vendian to Lower Carboniferous succession is inferred to be about 14 km (Yan-Zhin-Shin, 1983; Parfenov and Kuzmin, 2001).

The easternmost zone of the South Verkhoyansk sector is the South Verkhoyansk synclinorium, which consists of Lower Carboniferous to Jurassic siliciclastics of the Verkhoyansk Complex. These rocks cover most of the Verkhoyansk thrust-and-fold belt and form a coarsening and shoaling upward succession typical of delta-submarine fan systems (Egorov, 1993; Khudoley and Guriev, 1994). Sedimentation within this complex was nearly continuous, although some unconformities are recognized in Triassic rocks. Folds of different geometry are the most characteristic structures of the South Verkhoyansk synclinorium. The west part of the synclinorium, with a predominance of recessive fine-grained siliciclastics, contains highly deformed sinistral shear zones (Fig. 5B). Outside of the shear zones, the enveloping surfaces of minor folds have relatively simple geometries. Farther east are widespread occurrences of resistant, massive sandstone units; structures are dominated by close to open folds with simple geometries, as well as transverse dextral strike-slip faults. Rocks of the South Verkhoyansk synclinorium are intruded by Early Cretaceous granites (Prokopiev, 1998; Layer et al., 2001). Total composite thickness of the Verkhoyansk Complex is inferred to be about 18 km (Khudoley and Guriev, 1994; Parfenov and Kuzmin, 2001).

The Okhotsk massif lies to the east and southeast of the South Verkhoyansk synclinorium. The southwest part of the Okhotsk massif, the Upper Maya uplift, is thrust onto the Maya–Kyllakh zone and South Verkhoyansk synclinorium along the Bilyakchan thrust (Fig. 3). Probably, the Bilyakchan thrust also contains a sinistral strike-slip component of displacement (Parfenov and Kuzmin, 2001). The age and composition of its basement is close to that of the Aldan shield of the Siberian platform (Kuzmin et al., 1995). Paleomagnetic data indicate that, in late Mesoproterozoic time, the Okhotsk massif was rela-

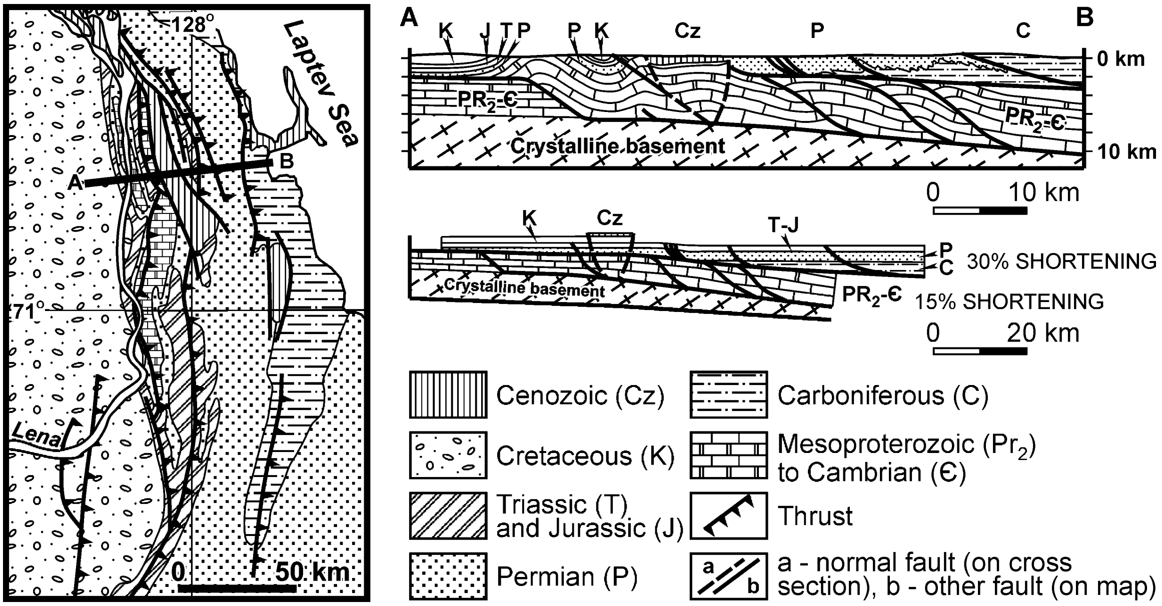


Fig. 6. Geologic map and cross-section of the Kharaulakh segment of the West Verkhoyansk sector, after Mezhvilk et al. (1978), Parfenov et al. (1995), and Parfenov and Kuzmin (2001). See location in Fig. 1.

tively close to the Siberian craton (Pavlov et al., 1991). However, the relationship between the Siberian craton and Okhotsk massif is still in dispute (Parfenov, 1995). The southern part of the Okhotsk massif and southernmost Verkhoyansk thrust-and-fold belt are overlapped by Cretaceous volcanics of the Okhotsk–Chukotka volcanic belt.

In the Kharaulakh segment of the West Verkhoyansk thrust-and-fold belt, Precambrian and lower Paleozoic rocks cover significantly less area than in the South Verkhoyansk (Fig. 6). Structural style and stratigraphic sections show that in the Kharaulakh segment there are correlatives of the Maya–Kyllakh zone and South Verkhoyansk synclinorium, whereas correlatives of the Sette–Daban zone are represented by very local occurrences of Upper Devonian basalts and carbonates. Most latest Neoproterozoic to Mesozoic tectonic events are recognized in both Kharaulakh and South Verkhoyansk. The Kharaulakh segment does not contain rocks synchronous to the Uy Group of the South Verkhoyansk, representing 1000–950 Ma rifting, but was affected by Tertiary rifting that is not recognized in the South Verkhoyansk.

3. Meso- to Neoproterozoic (~1000–950 Ma) rifting

A rifting event that occurred at ca. 1000–950 Ma is well documented by voluminous mafic sills and flows (up to 900 m total thickness) and significant changes in depositional environments (Rainbird et al., 1998; Khudoley et al., 2001b; Parfenov and Kuzmin,

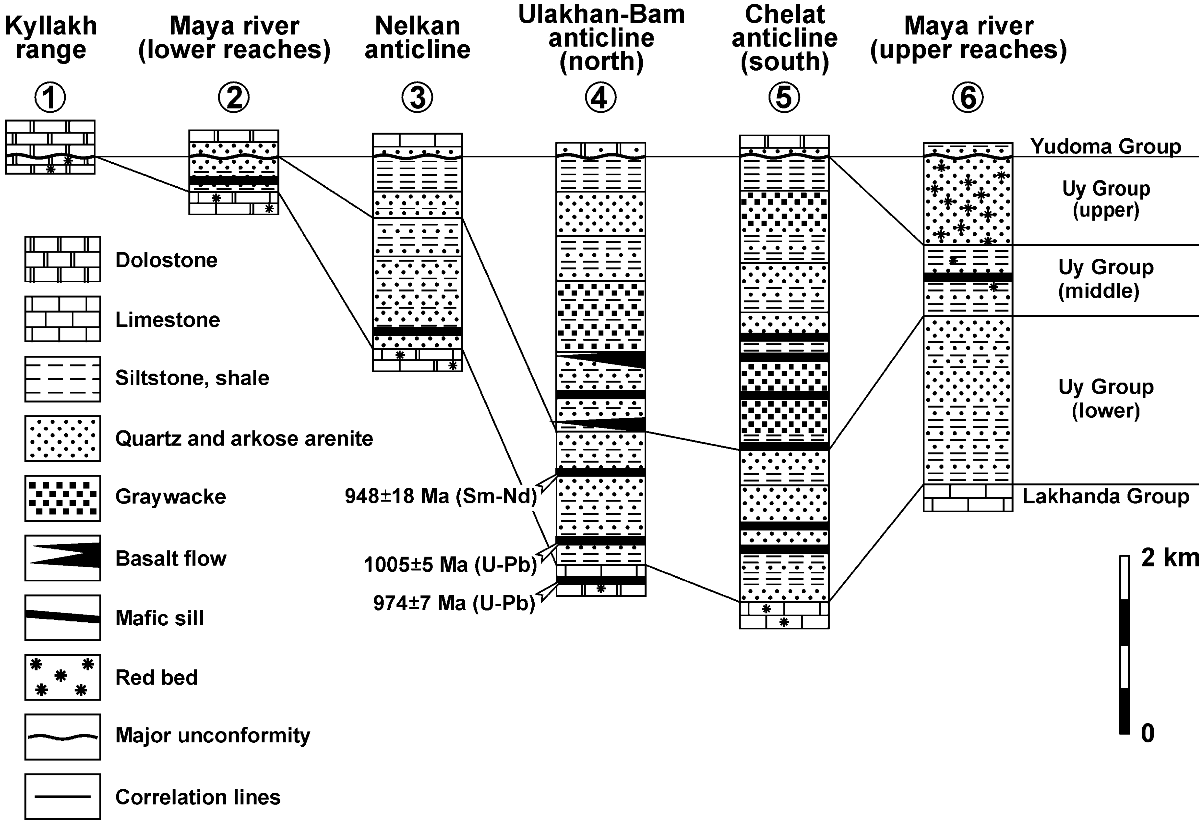


Fig. 7. Correlation chart for the upper Mesoproterozoic–lower Neoproterozoic Uy Group showing facies and thickness changes of rock units. Numbers in circles correspond to those in Fig. 3 and show locations of sections. Data source for compiled sections are unpublished observations of authors as well as data by Nevolin et al. (1978), Semikhatov and Serebryakov (1983), Yan-Zhin-Shin (1983), Sukhorukov (1986), Yakshin and Isakov (1991) and unpublished reports. Radiometric ages are from Pavlov et al. (1992, Sm–Nd), and Rainbird et al. (1998, U–Pb).

2001). Thus, most Mesoproterozoic successions consist of carbonates and mature terrigenous rocks that were deposited in a shallow epicontinental sea. They show very gradual lateral changes in lithology and thickness. However, the uppermost Mesoproterozoic to Neoproterozoic Uy Group is distinguished from underlying units by its terrigenous composition and abrupt facies and thickness variations. The Uy Group changes from less than 800 m in thickness with predominance of mature quartz sandstone in the west to a nearly 5-km-thick unit with wide distribution of immature sandstones and intercalated volcanic rocks in easternmost outcrops (Fig. 7) (Khudoley et al., 2001b). The middle part of the Uy Group is the only unit in the Precambrian succession that contains relatively deep-water sediments containing evidence of deposition by sediment gravity–mass flows. Although some changes in thickness of the Uy Group may be explained by pre-Vendian erosion, most units depositionally thin and give way to mature quartz arenite westward, towards the Siberian craton. Facies and thickness distributions of the Uy Group are controlled by faults, which are recognized as thrusts (Yan-Zhin-Shin, 1983; Khudoley et al., 2001b; Parfenov and Kuzmin, 2001). These thrusts also appears to have controlled magmatic activity; most of the sills and volcanics are located on hanging wall, close to the fault surface and abruptly decreases in volume both eastward and westward.

Abrupt thickness and facies variations of the Uy Group between different thrust sheets may be result of the Mesozoic orogeny that juxtaposed different structural units and hid transitions between them. Another possible interpretation is that some thrusts are reactivated normal faults that were active during deposition of the Uy Group. To test both options, we studied the structure of several major thrusts and restored cross-sections.

The map in Fig. 8 shows the general structure of the frontal Nelkan–Kyllakh thrust, which is typical for most major thrusts of the South Verkhoyansk sector. Here Mesoproterozoic rocks of the thrust-and-fold belt overthrusted onto the Cambrian and the uppermost Neoproterozoic rock units of the Siberian

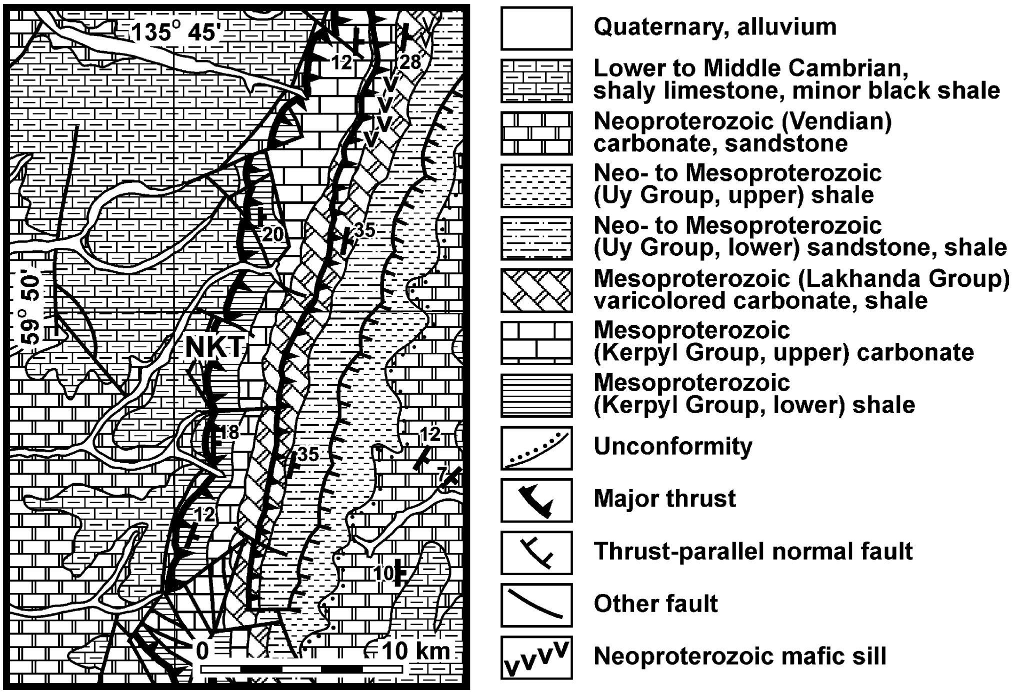


Fig. 8. Geologic map of the Nelkan–Kyllakh thrust, showing association of parallel thrusts and normal fault, after Potapov and Lobanova (1999), simplified and modified. See location in Fig. 3. Abbreviation: NKT—Nelkan–Kyllakh thrust.

craton sedimentary cover (Fig. 3), showing a set of parallel faults. Two frontal faults are thrusts that put older Mesoproterozoic units onto younger ones. However, the most internal fault separates the lower Uy Group in the footwall from the upper Uy Group in the hanging wall and is a normal fault. The normal fault is parallel to frontal thrusts and cuts bedding at a very low angle. Close proximity of parallel thrusts and normal faults in frontal ranges of thrust-and-fold belts is unusual, but can be explained if faults were syn-sedimentary normal faults and some of them were reactivated during Mesozoic compression.

Balanced and restored cross-sections are presented in Fig. 4. In the restored sections, the datum is the sub-Vendian unconformity and rocks above it are not plotted, to make variations in Mesoproterozoic unit thicknesses more apparent. Typically, the most complete sections of Mesoproterozoic strata are exposed in the hanging wall anticlines in the lower parts of thrust sheets near fault surfaces. However, where observable, facies and thickness changes in single thrust sheets are very moderate, and, to simplify construction of cross-sections, we hypothesize that the thickness of the entire succession is approximately constant within each thrust sheet, although total thickness of thrust sheets increases eastward. On the restored cross-sections, the basal detachments have several steps that reflect an eastward increase in the thickness of individual thrust sheets. However, for most thrusts, these steps may be averaged by a low-angle line that is approximately parallel to the surface of the Siberian craton basement (Fig. 4). It seems reasonable to conclude that this "averaged" detachment corresponds to its actual configuration during the Mesozoic orogeny. Furthermore, small steps on the restored cross-sections likely result from very gradual eastward thickening of Mesoproterozoic units across individual thrust sheets.

This explanation cannot be applied to the Nelkan–Kyllakh thrust, which is in direct structural contact with the Siberian craton, nor the Ulakhan–Bam and Chelat thrusts, which are located between platform and slope facies within the miogeocline. Here, steps in the detachment are too large to be accommodated by a gently dipping slope of the Siberian craton. We therefore infer that they are evidence of syn-sedimentary structures that caused local increases in the thickness distribution of the Uy Group. According to the restored cross-sections, during deposition of late Mesoproterozoic–early Neoproterozoic Uy Group these faults were normal faults with vertical offset about 2–3 km. This corresponds well with the interpretation of the Nelkan–Kyllakh thrust as a reactivated normal fault that resulted from existence of thrust-parallel normal faults (Fig. 8). However, sedimentation-controlled normal faults of the South Verkhoyansk were only reactivated during Mesozoic orogeny, approximately 850 My after their origin.

4. Neoproterozoic compression

Vendian sandstone and dolostone rock units are separated from underlying Mesoproterozoic to lower Neoproterozoic succession by an unconformity that is recognized throughout northeast Russia and Siberia (Semikhatov and Serebryakov, 1983). In the east margin of the Siberia craton and adjacent parts of the Kharaulakh segment and the South Verkhoyansk sector, a very low-angle unconformity gradually cuts progressively older Mesoproterozoic units, so that, in the Aldan and Anabar shields, Vendian dolostone lies directly on Archean and Paleoproterozoic crystalline rocks. An angular unconformity transecting older sedimentary rocks at up to 15° is only recognized in the easternmost exposures of the Maya–Kyllakh zone, where pre-Vendian rocks were affected by mild folding and thrusting (Arkhipov et al., 1981). The age of this event is poorly constrained—the youngest folded rock unit is the Uy Group, which is dated at about 1000 Ma, whereas overlapping Vendian rocks are younger than 650 Ma.

Neoproterozoic thrusts cut the Mesoproterozoic succession and are unconformably overlapped by uppermost Neoproterozoic (Vendian) rock units. A typical example is shown in Fig. 9. In the modern structure, this fault is a high-angle reverse fault that dips eastward with dip angle varying from 40° to 60°. However, it is a bedding-parallel fault with a hanging wall anticline that is typical of thrusts. The overlying Vendian rock units dip eastward as well, at an angle of 15–30°, and after rotation of Vendian rocks to a subhorizontal bedding attitude the fault transforms into east-dipping thrust. Similar thrusts were recog-

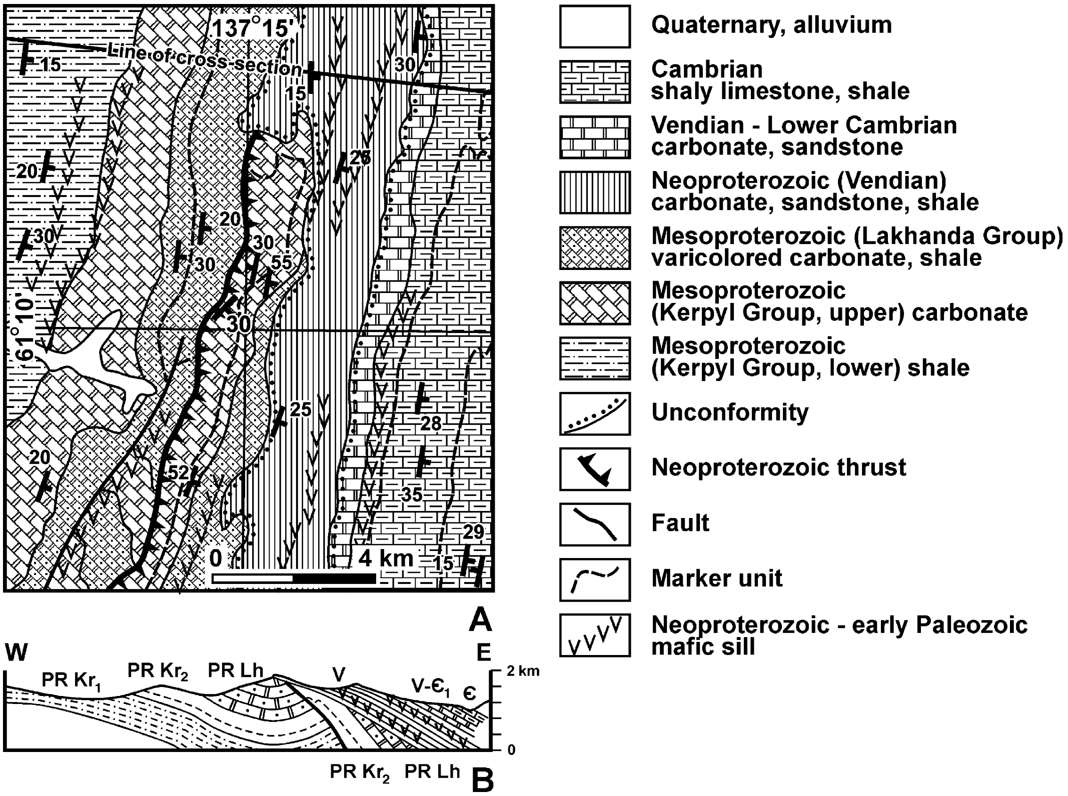


Fig. 9. Neoproterozoic (pre-Vendian) thrust. (A) Geologic map, after Starnikov (1993), (B) cross-section. See location in Fig. 3. Abbreviations (on cross-section): PR Lh—Lakhanda Group, PR Kr_2—upper Kerpyl Group, PR Kr_1—lower Kerpyl Group.

nized throughout the easternmost part of the Maya–Kyllakh zone.

The pre-Vendian paleogeological map (Fig. 10) shows the main features of the late Neoproterozoic structure. The area can be divided into two domains—an east domain with rare thrusts and gentle to open folds, and a west domain without compressional structures and very gentle bedding with dip angles typically less than 1°. In terms of structural setting, mapped Neoproterozoic thrusts are similar to the Mesozoic Nelkan–Kyllakh thrust, which separates the Siberian craton, with subhorizontal bedding, from the frontal ranges of the Verkhoyansk thrust-and-fold belt. However, there are no data about eastward and northward extension of the Neoproterozoic compressional structures as related areas are covered by the upper Paleozoic–Mesozoic Verkhoyansk Complex siliciclastics. Although Neoproterozoic thrusts in Fig. 10 seem to be an important structural feature, they do not correspond to any significant modern structure and are difficult to be recognized on the geological maps. They are located within units that are bounded by Mesozoic thrusts and do not show any evidence of reactivation during Mesozoic orogenesis.

5. Latest Neoproterozoic–early Paleozoic rifting

Although the ~ 950–1000 Ma rifting event was associated with significant normal faulting and significant volumes of basic magmatic rocks, Precambrian rock units of the South Verkhoyansk do not show evidence of the full-scale continental separation that probably occurred to the northeast of the South Verkhoyansk and Okhotsk massif (Khudoley et al., 2001b). Facies changes typical of modern passive margins with a transition from shelf carbo-

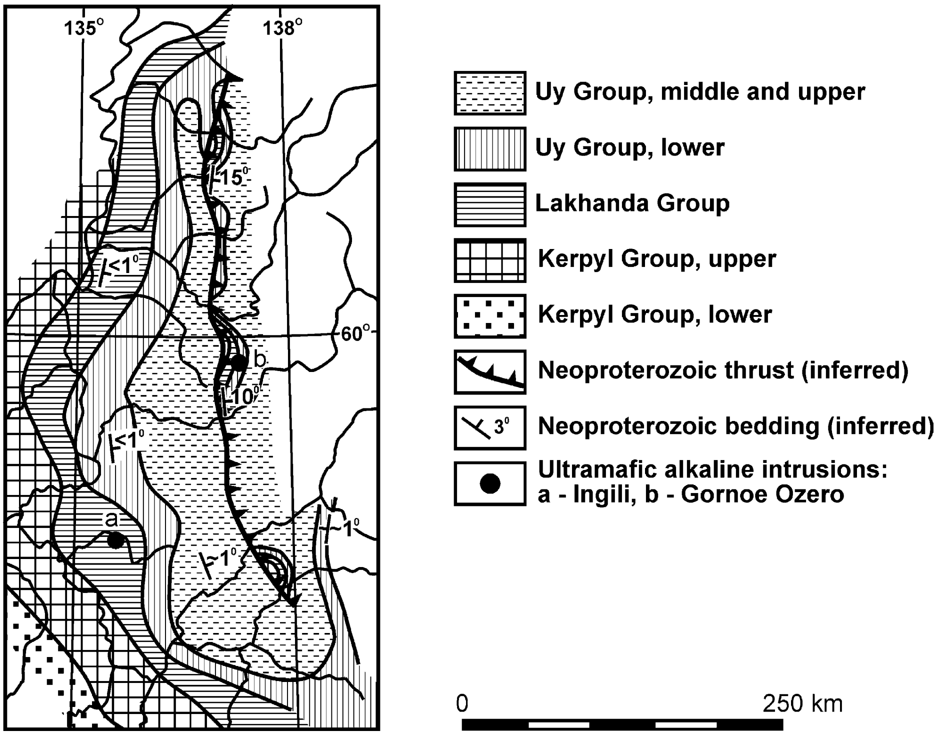


Fig. 10. Pre-Vendian paleogeological map, after Semikhatov and Serebryakov (1983), and Khudoley (1985).

nates to deep-water shales and carbonate turbidites are recognized both in the South Verkhoyansk and Kharaulakh areas only in Cambrian and younger rocks. The Neoproterozoic rifting event is approximately 450 My older than the beginning of passive margin sedimentation and, therefore, they cannot belong to a single tectonic cycle. Initiation of the Paleozoic passive margin sedimentation required a rifting event close to the beginning of the Paleozoic (Fig. 2).

The occurrence of the latest Neoproterozoic to early Paleozoic rifting is inferred from subsidence analysis (Khudoley and Serkina, 2002). Preliminary construction of tectonic subsidence curves points to several rifting events between 570 and 520 Ma. Rifting was accompanied by some magmatic activity as well. In the Kharaulakh segment, the Lower Cambrian rock units contain alkaline basalts that are located at the same stratigraphic level as volcanic breccia from the Olenek uplift dated by the U–Pb method at 544 Ma (Bowring et al., 1993). In the southern part of the Siberian craton, rift-related magmatism is probably represented by a few alkaline-ultramafic intrusions. One of them, the Ingili pluton, has discordant U–Pb age of 640 Ma that is approximately correlative with K–Ar dates from biotite of 640 and 660 Ma (Semikhatov and Serebryakov, 1983).

No structural evidence for occurrence of normal faults of latest Neoproterozoic–early Paleozoic age have been observed in the study area. Facies and thickness changes in Cambrian rocks usually are very gradual, although fault-related escarpments are hypothesized because of the abrupt appearance of breccia units. However, none of these assumed faults may be directly correlated with faults on the modern geological map. No structures are correlated with early Paleozoic alkaline basalt sills with discordant U–Pb age of 450 ± 12 Ma and alkaline ultramafic intrusions with Sm–Nd isochron age of 487 ± 29 Ma recently identified in the Sette–Daban zone (Fig. 2) (Khudoley et al., 2001a). Only a few normal faults separating Cambrian platform and slope facies, like those shown in the east part of cross-sections in Fig. 4, are probably related to early Paleozoic passive margin formation. Probably, the Burkhala fault, separating different Cambrian successions, is also of early Paleozoic origin. However, these faults cut younger Paleozoic rock units as well, and precise determination of their age requires more study.

6. Devonian rifting

A Devonian rifting event is widespread throughout the east margin of Siberian craton. Numerous tholeiite and alkaline basalt flows are intercalated with conglomerate, sandstone, evaporite and carbonate units in coarsening-upward cycles. These were deposited in continental to lagoonal and shallow-marine environments that are characteristic of rift successions. The earliest stage of the rifting event is Middle Devonian in age and is reported only in the Sette–Daban zone, whereas Upper Devonian rift-related strata are recognized in all parts of the east margin of the Siberian craton. Late Devonian rifting was accompanied by local compression, that is clearly identified in different localities of the Sette–Daban zone (Guriev, 1989; Khudoley and Guriev, 1994), especially in its southernmost part where Late Devonian granites (356 ± 2.8 Ma) were recently identified by Ar–Ar dating (Prokopiev et al., 2001). Devonian rifting is usually considered to be the most widespread extensional event that resulted in formation of a micro-ocean basin to the east of Siberian craton (Parfenov, 1995; Parfenov and Kuzmin, 2001).

Late Devonian normal faults are widespread in the east part of the Sette–Daban zone. The north part of the latter contains well-exposed mountain ranges where all relationships between rock units can be seen in outcrop. A typical example is shown in Fig. 11. Here Ordovician to Devonian rocks are conformably folded with adjacent siliciclastics of the Verkhoyansk Complex, indicating a Mesozoic age of deformation. In the west part of the cross-section, there are locally thick units of Famennian olistostromes exposed in the hanging wall of normal fault. To the east, the olistostrome units transform into sandy shales, indicating a provenance area just to the west of their present location. Most blocks in the olistostrome unit are of local origin and were derived from underlying Devonian to Ordovician rocks that were exposed on local highs during olistostrome deposition. According to sedimentary structures and distribution of olistostrome units, the predominant depositional environment is inferred to be slumps and slides in intermontane depressions (Kropachev et al., 1997). The interpretation shown in Fig. 11B assumes that a modern east-dipping normal fault separating Ordovician and Devonian rocks was formed in Famennian time during olistostrome unit deposition, as an east-dipping normal fault with a hanging wall half-graben basin that is typical for rift environments. Vertical offset along this normal fault was more than 2 km with correspondent block rotation of about 20°. A few west-dipping bedding-parallel faults within Middle Devonian are also interpreted as Devonian in age, and they were formed due to gravitational sliding along an evaporite unit during progressive development of a half-graben basin and corresponding increase in the dip of its slope.

More often Late Devonian faults are recognized on large-scale geological maps by abrupt changes in the upper Paleozoic stratigraphy. A typical example is shown in Fig. 12. Three fault-bounded stratigraphic domains are recognized in the map area. East and west domains contain Devonian and Silurian rock units, with total thickness of about 2 km, that are truncated by a pre-Carboniferous unconformity in a central domain. Overlapping Carboniferous units do not show any significant changes in thickness and lithology throughout the study area and domain-bounding faults juxtapose the upper part of the Lower Carboniferous limestone with the lower part of the Lower to Middle Carboniferous siliciclastics. According to changes in pre-Carboniferous stratigraphy, domain-bounding faults display vertical displacement of at least 2 km, whereas vertical displacement measured by offset of Carboniferous rocks is not more than 500 m. Therefore, at least 1.5 km of displacement occurred in pre-Carboniferous time. Another pre-Carboniferous structure is a strike-parallel fault within the central domain with at least 2 km of vertical offset of Silurian–Ordovician rocks, and tens meters of offset of the lower contact of Lower Carboniferous limestone. The age of these faults is inferred to be Late Devonian because Lower

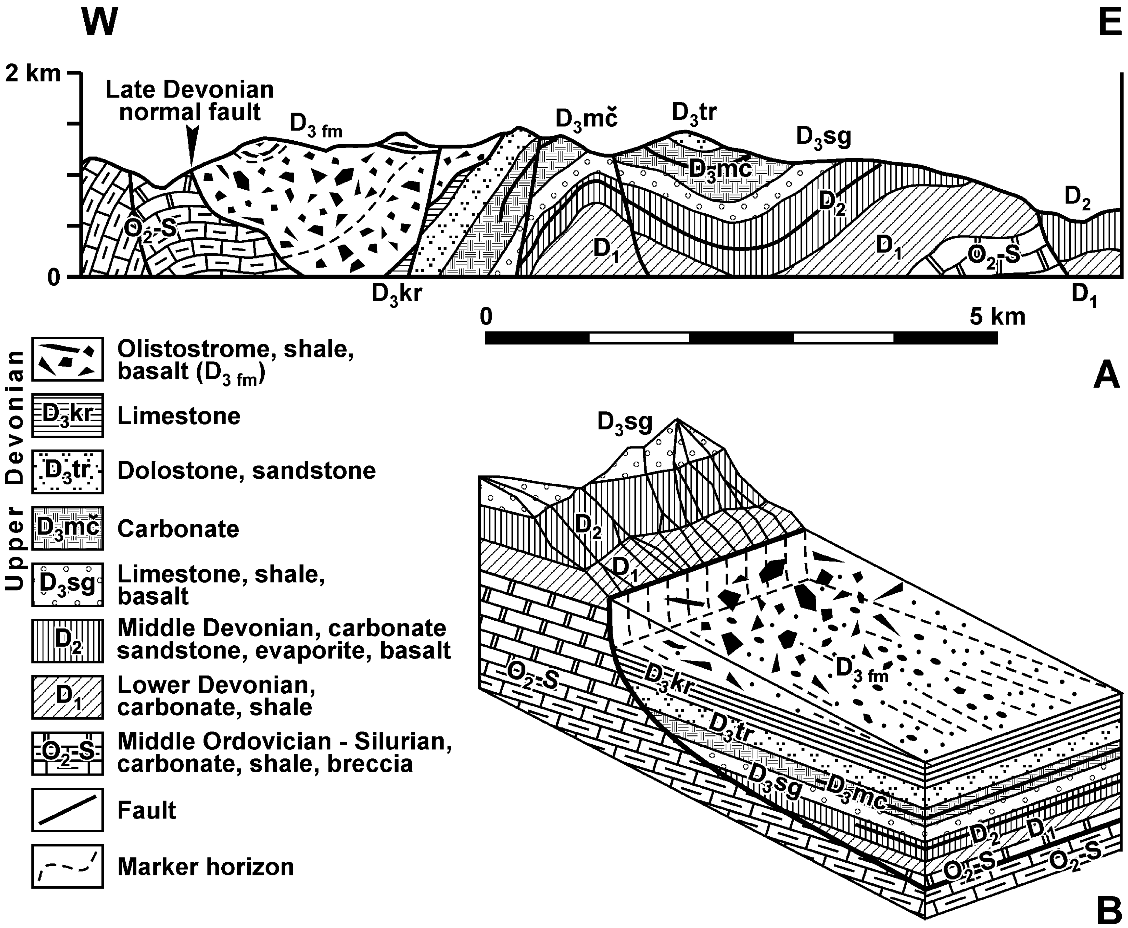


Fig. 11. Late Devonian normal fault: (A) cross-section through the Khurat syncline (northern Sette–Daban zone, after Kropachev et al., 1997, simplified), (B) its interpretation as a Famennian half-graben basin. See location in Fig. 3.

Devonian and older rock units are of marine origin with only gradual facial and thickness changes, whereas Upper Devonian rocks are partly of continental origin and contains coarse-grained clastics deposited close to uplifted highs (Khudoley and Guriev, 1994).

Late Devonian faults were only rarely reactivated during Mesozoic orogenesis, whereas many faults were passively involved in the Mesozoic structure. Thus, the Late Devonian normal fault shown in Fig. 11 still preserves its initial geometry and the step-like surface of the fault is probably the only influence of Mesozoic tectonics. A fault separating the west and central domains in Fig. 12 is now a west-dipping normal fault that does not show any influence of Mesozoic tectonics. Two other faults from Fig. 12 are now high-angle, close to vertical, west-dipping reverse faults. We interpret them as initially east-dipping normal faults similar to that in Fig. 11, which were passively rotated during the Mesozoic. Another example of a Late Devonian fault passively involved in the Mesozoic structure is presented in Fig. 13, which shows an overturned syncline containing fault-bounded Middle Ordovician to Carboniferous rocks in the core. The fault on the east side (Setaniya fault) was affected by several stages of deformation and has both sinistral strike-slip and thrust components of displacement. Faults on the west of syncline are parallel to each other and in their present day configuration are recognized as

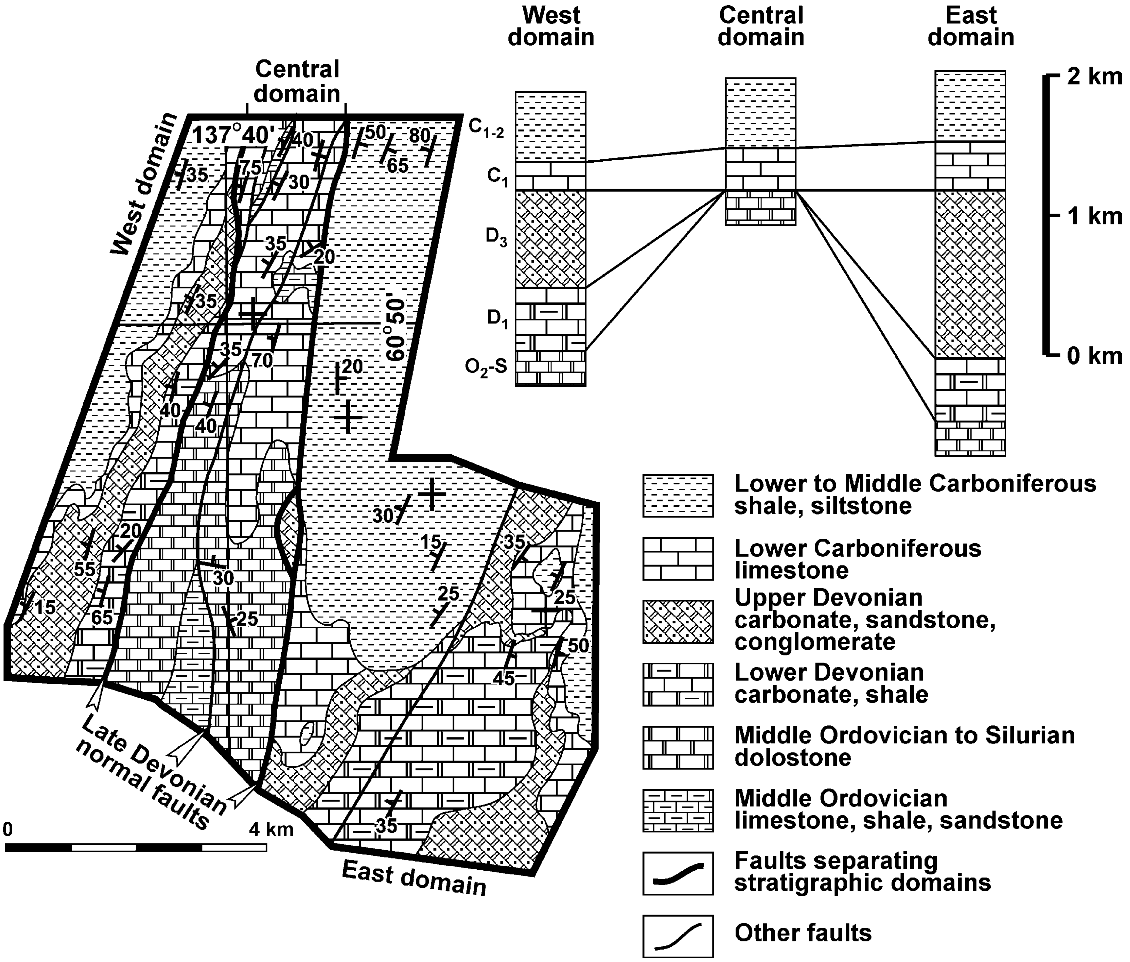


Fig. 12. Map and stratigraphic sections showing Late Devonian normal faults reactivated during Mesozoic orogeny. See location in Fig. 3.

west-dipping thrusts. The westernmost has typical thrust geometry with a hanging wall anticline and hanging wall bedding being approximately parallel to fault surface. However, the fault bounding the western part of the syncline does not contain a hanging wall anticline and cuts hanging wall bedding at a high angle. Available field observations show that in the footwall bedding is mainly parallel to the fault surface, but locally is truncated by the fault at a high angle. This geometry is not typical for thrusts, but may be explained as a result of clockwise passive rotation of a fault that was initially an east-dipping listric normal fault which locally cut bedding at a high angle, but mainly was subparallel to hanging wall bedding (Fig. 13B). This interpretation is also supported by the eastward thinning of Famennian rock units and paleocurrent measurements that show a southwestern provenance (Guriev, 1989). Rotation of the normal fault also led to folding of rocks in the hanging wall and transformation of the hanging wall into a footwall. This rotation resulted in a fault recognized in modern structure as a west-dipping reverse fault or thrust (Fig. 13C). According to differences in Ordovician stratigraphy, vertical displacement along this fault is about 1.5 km, which is typical for many Late Devonian normal faults and does not assume significant reactivation during Mesozoic orogeny. The main evidence of Mesozoic reactivation of some Devonian faults is the offset of Carboniferous and

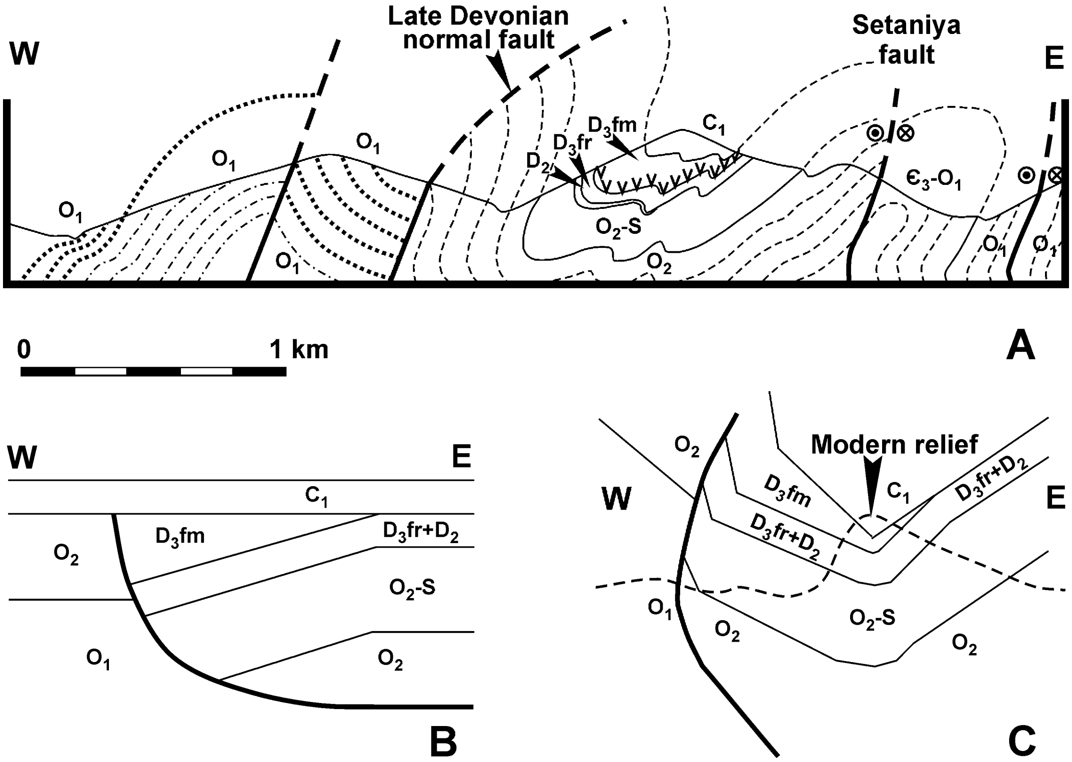


Fig. 13. West-dipping reverse fault (A), and its interpretation as east-dipping Late Devonian normal fault (B), passively rotated during Mesozoic orogeny (C). Dash and dot lines show different rock units in the Ordovician succession. See location in Fig. 3.

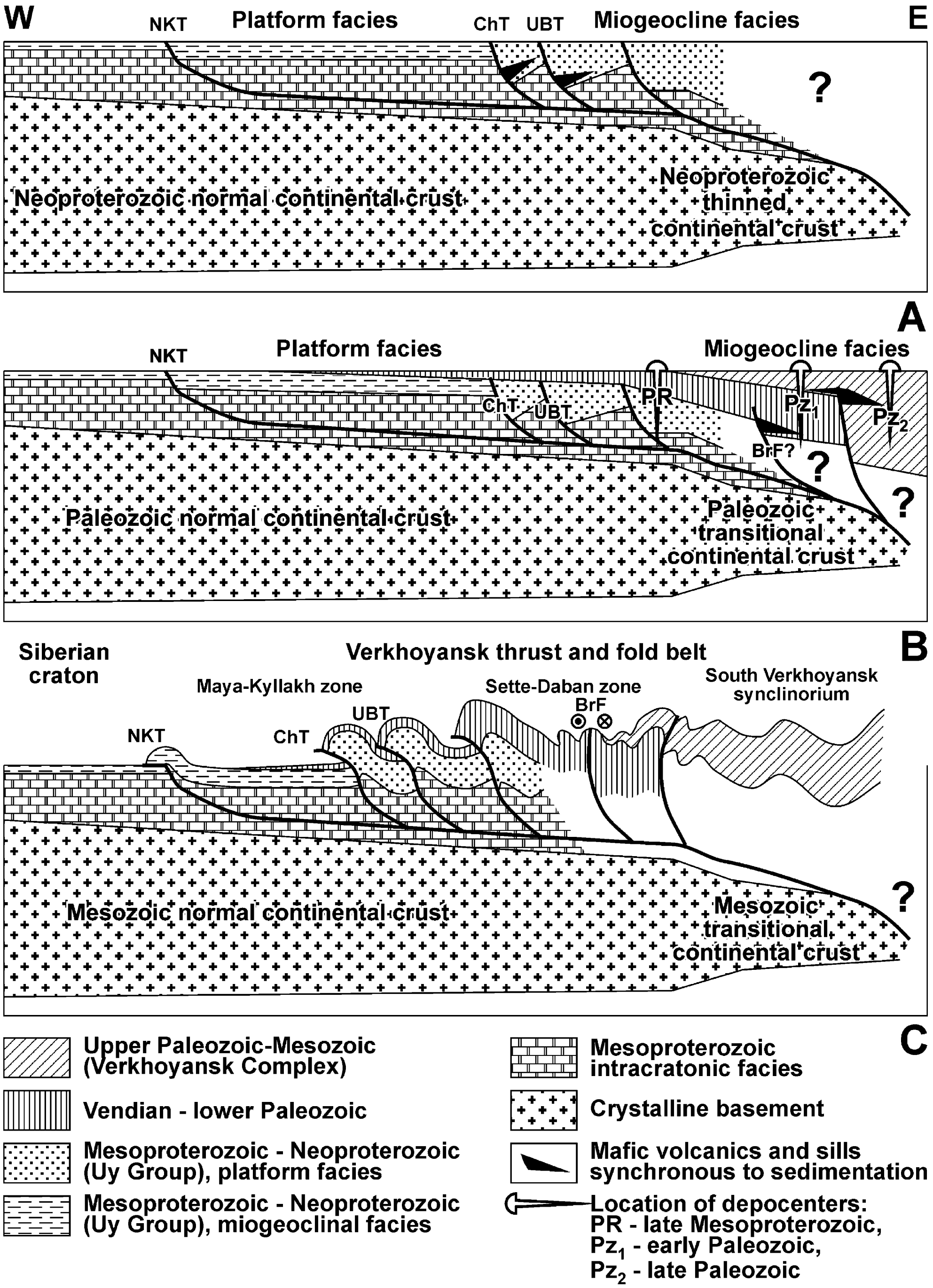
younger rocks across them. Typically this is very small, and for most faults is not greater than several hundred meters (Fig. 12).

7. Discussion

According to restored cross-sections in the southern part of South Verkhoyansk, the Siberian craton crystalline basement that underlies Mesoproterozoic intracontinental basin strata extended at least 40 km to the east from its present surface expression at the contact between the Maya–Kyllakh and Sette–Daban zones (Fig. 4). Its extension roughly correlates with the first occurrence of Neoproterozoic and early Paleozoic slope facies and synchronous rift-related mafic magmatic rocks. It was probably an ancient continental margin hinge zone at the beginning of the attenuated transitional continental crust. The width of the zone, including transitional continental crust, cannot be estimated. However, Middle Devonian to lowermost Carboniferous sedimentary

Fig. 14. Proposed model for the tectonic evolution of the east margin of the Siberian craton. (A) Rifting at 1000–950 Ma and formation of low-angle extensional detachment and high-angle normal faults (future Nelkan–Kyllakh, Chelat and Ulakhan–Bam thrusts) that controlled synchronous sedimentation and magmatic activity. (B) Latest Neoproterozoic (Vendian) to Triassic stage. Neoproterozoic normal faults are hidden under thin sedimentary cover of Vendian and Paleozoic rock units. To the east of Neoproterozoic normal faults, new normal faults control sedimentation and magmatic activity. Note eastward migration of sedimentary basin depocenter. (C) Mesozoic orogeny. Reactivation of Neoproterozoic normal faults as thrusts, formation of sinistral strike-slip fault as a result of oblique thrusting, passive rotation of Late Devonian normal faults to form west-dipping thrusts. Abbreviations: BrF—Burkhala fault, ChT—Chelat thrust, NKT—Nelkan–Kyllakh thrust, UBT—Ulakhan–Bam thrust.

rocks exposed on the east margin of the Sette–Daban zone are of shallow-marine to continental origin. Furthermore, some Devonian basalts display a distribution of trace and rare earth elements suggesting contamination by continental crust material (Khudoley, Kropachev, unpublished data). Because



Middle Devonian to Lower Carboniferous rocks are exposed about 30–40 km to the east of the first appearance of lower Paleozoic slope facies, and shortening of the Sette–Daban zone is more than 40% (Prokopiev, 1989), the width of the transitional zone is at least 60–75 km. This means that the inner zone of Neoproterozoic and Paleozoic rifts with oceanic crust was located at least 100 km to the east from modern boundary between Maya–Kyllakh and Sette–Daban zones. This area is now covered by siliciclastics of the Verkhoyansk Complex. Moreover, the zone of rift-related attenuated transitional crust is also covered by the Verkhoyansk Complex. This partly explains why structural evidences of some of the latest Neoproterozoic–early Paleozoic extensional tectonics events are so rare.

Data presented in this paper show significant influences on Mesozoic structures from faults initiated during late Mesoproterozoic–early Neoproterozoic (about 1000–950 Ma) rifting. These are the oldest faults recognized in the study area and they developed in an extensional environment. All younger faults ranging in age from Neoproterozoic to Devonian did not have significant influence on geometry of the Mesozoic thrust-and-fold belt, although some reactivation of Devonian normal faults is reported from the easternmost part of the Sette–Daban zone. During Mesozoic orogeny, the late Mesoproterozoic–early Neoproterozoic normal faults located in the Maya–Kyllakh zone were reactivated as thrusts, and in the modern structure the Maya–Kyllakh zone is a tectonically inverted counterpart of the late Mesoproterozoic–early Neoproterozoic Uy Group sedimentary basin. In modern structure, the most prominent hanging wall anticlines occur to the west of syn-sedimentary ramps. Thick successions of the Uy Group were displaced out of their depositional basins and juxtaposed over much thinner synchronous rock units deposited on the footwall of syn-sedimentary normal fault. Structural depressions, represented by wide synclines, occur above low-angle to subhorizontal basement of half-graben basins.

The structural style of the Maya–Kyllakh and Sette–Daban zone is similar to that of the Canadian Cordilleran foreland to the east of the Purcell anticlinorium (e.g. Fig. 2.6 from Price, 1994). Influence of strike-parallel sedimentation-controlled basement ramps or normal faults in the Canadian Cordilleran foreland was reported from the southern Rocky Mountains (Price, 1994; Price and Sears, 2000), northern Rocky Mountains (McMechan et al., 1991) and Mackenzie Mountains (Thompson et al., 1987; McMechan et al., 1991). As in the South Verkhoyansk sector, these syn-sedimentary structures are Mesoproterozoic to Neoproterozoic in age and are related to ancient rifting events. Reactivation of syn-sedimentary faults is also documented in thrust-and-fold belts with structural styles that are very different from that of the Verkhoyansk thrust-and-fold belt. For example, in the Alps many major thrusts separating tectonic and paleogeographic units in the Helvetic, Penninic and Austroalpine nappes are reactivated normal faults that bounded half-graben basins during initial stages of Mesozoic rifting (Lemoine and Trumpy, 1987; Froitzheim and Eberli, 1990). Some rift-related normal faults still preserve their initial geometry with extensional detachment, a splay of listric normal faults and tilted blocks in the hanging wall, whereas others were overturned, so that initially west-dipping normal faults are now recognized as an east-dipping thrust faults (e.g. Fig. 6 in Froitzheim and Manatschal, 1996). These overturned normal faults are structurally similar to those recognized in the easternmost part of the Sette–Daban zone (Fig. 13).

Despite similarities in reactivation history between Verkhoyansk and other thrust-and-fold belts, they differ in the involvement of basement on the rift margins. In both comparable areas, the Cordilleran foreland and the Alps, sedimentation was controlled by basement ramps or normal faults that displaced the basement surface. Available geophysical data from Verkhoyansk do not support 2–3 km of displacement of the basement surface that would be required to accommodate the Uy Group thickness changes. A possible tectonic model is presented in Fig. 14. During the 1000–950 Ma rifting a large extensional detachment was formed that attenuated continental crust in the internal part of rift system (Fig. 14A). In the outer part of rift, the detachment was developed along the weakest horizons within the sedimentary succession. Block rotation and transition from one weak horizon to another made steps in the basal detachment surface and caused significant thickness variation in the rift-related deposits (Uy

Group). In the South Verkhoyansk sector, the formation of transitional continental crust and oceanic crust occurred after the latest Neoproterozoic–early Paleozoic rifting event that is recognized on both the southeast (South Verkhoyansk) and northeast (Kharaulakh) margins of Siberian craton. However, the axial zone of the related rift system (as well as for Devonian rifting) was located to the east of the 1000–950 Ma rift zone that led to eastward migration of the sedimentary basin depocenter (Fig. 14B). As the result of eastward migration of the rift axial zone, latest Neoproterozoic–Paleozoic rifting events were less pronounced on the western margin of the 1000–950 Ma rifts, which approximately corresponds to the modern Maya–Kyllakh zone. In the late Paleozoic–Mesozoic, axial zones of more ancient rifts were covered by siliciclastics of the Verkhoyansk Complex. During the Mesozoic orogeny, thrusts propagated along horizons that were weakened during previous tectonic events (Fig. 14C). In the Maya–Kyllakh zone, the weakest horizon was an extensional detachment with a splay of normal faults that were reactivated as thrusts during Mesozoic deformation. In the Sette–Daban zone, ancient faults were passively rotated or, possibly, reactivated as sinistral strike-slip faults due to oblique displacement of crystalline blocks. No pre-Mesozoic faults are recognized in the South Verkhoyansk synclinorium, and this probably resulting in a fold-dominated structural style that greatly differs from structural styles of the Maya–Kyllakh and Sette–Daban zones.

8. Conclusions

The east margin of the Siberian craton is a typical passive margin with a thick succession of sedimentary rocks ranging in age from Mesoproterozoic to Tertiary. During the Mesozoic orogeny this succession was deformed and thrust onto the Siberian craton.

Several pre-Mesozoic tectonic events are recognized. In the South Verkhoyansk, intense rifting occurred about 1000–950 Ma. Sedimentation and magmatism associated with the 1000–950 Ma rifting event were controlled by syn-sedimentary listric normal faults that formed half-graben basins in the Maya–Kyllakh zone. These faults are localized within the sedimentary succession and do not affect crystalline basement. In today’s structure they are recognized as thrusts. Thrusts related to late Neoproterozoic compression event are reported from only the easternmost part of the Maya–Kyllakh zone. No extensional structures of latest Neoproterozoic–early Paleozoic rifting events are recognized throughout the study area. Late Devonian rifting events were accompanied by synchronous normal faults; half-graben basins are widespread in the eastern part of the Sette–Daban zone. Most of Late Devonian normal faults were passively rotated during Mesozoic orogeny and do not show significant reactivation.

During Neoproterozoic–early Paleozoic rifting events, the continental crust was attenuated and transformed into transitional continental crust. Incorporation of data on shortening of the Maya–Kyllakh and Sette–Daban zones show that the transitional crustal zone and assumed inner parts of rifts with oceanic crust are now hidden below late Paleozoic–Mesozoic siliciclastics of the Verkhoyansk Complex. However, the Neoproterozoic (1000–950 Ma) rifting event affected the margin of Siberian craton and led to formation of extensional detachments within the sedimentary cover. These weakened zones were reactivated during Mesozoic orogeny as thrusts that are characteristic of the structural style of the Maya–Kyllakh zone.

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References

Arkhipov, Yu.V., Volkodav, I.G., Kamaletdinov, V.A., Yan-Zhin-Shin, V.A., 1981. Thrusts of the western part of the Verkhoyansk–Chukotka fold belt. Geotectonics 15 (2), 81–98 (in Russian, translated into English).

Bowring, S.A., Grotzinger, J.P., Isachsen, C.E., Knoll, A.H., Pelechaty, S., Kolosov, P.N., 1993. Calibrating rates of Early Cambrian evolution. Science 261, 1293–1297.

Egorov, A.Yu., 1993. Avalanche sedimentation—the main process in the Verkhoyansk Complex formation. Dokl. Russ. Acad. Sci. 332, 346–351 (in Russian, translated into English).

Froitzheim, N., Eberli, G.P., 1990. Extensional detachment faulting in the evolution of a Tethys passive margin, Eastern Alps, Switzerland. Geol. Soc. Amer. Bull. 102, 1297–1308.

Froitzheim, N., Manatschal, G., 1996. Kinematics of Jurassic rifting, mantle exhumation, and passive-margin formation in the Austroalpine and Penninic nappes (eastern Switzerland). Geol. Soc. Amer. Bull. 108, 1120–1133.

Guriev, G.A., 1989. Middle Paleozoic syn-sedimentary tectonic folding of the North-East of USSR. Sov. Geol. 8, 67–73 (in Russian).

Khudoley, A.K., 1985. Unconformities in the Vendian–lower Paleozoic rocks of South Verkhoyansk. Sov. Geol. 7, 68–74 (in Russian).

Khudoley, A.K., Guriev, G.A., 1994. The formation and development of late Paleozoic basin on the passive margin of the Siberian paleocontinent. In: Beauchamp, B., Embry, A.F., Glass, D. (Eds.), Pangea: Global Environments and Resources. Canadian Society of Petroleum Geologists Memoir 17, Calgary, pp. 131–143.

Khudoley, A.K., Serkina, G.G., 2002. Early Paleozoic rifting of the east margin of Siberian craton: comparison of geological data and subsidence curves. In: Karyakin, Yu.V. (Ed.),Tectonics and Geophysics of Lithosphere. GEOS, Moscow, pp. 288–291 (in Russian).

Khudoley, A.K., Kropachev, A.P., Heaman, L., Zhuravlev, D.Z., Guriev, G.A., 2001a. Early Paleozoic magmatism of Sette–Daban (South Verkhoyansk, south-east Yakutia). Dokl. Russ. Acad. Sci. 378, 82–85 (in Russian, translated into English).

Khudoley, A.K., Rainbird, R.H., Stern, R.A., Kropachev, A.P., Heaman, L.M., Zanin, A.M., Podkovyrov, V.N., Belova, V.N., Sukhorukov, V.I., 2001b. Sedimentary evolution of the Riphean–Vendian basin of southeastern Siberia. Precambrian Res. 111, 129–163.

Kovalskiy, V.V. (Ed.), 1985. Structure and Evolution of the Earth Crust of Yakutia. Nauka, Moscow (in Russian).

Kropachev, A.P, Konovalov, A.L., Borkovaya, E.A., Murasheva, N.P., 1997. Paleozoic sedimentary rocks of the northern Sette–Daban, southeast Yakutia: a study of olistostrome units. In: Abramovich, I.I., Mezhelovskiy, N.V. (Eds.), Basics of Geodynamic Analysis During Geological Mapping. MPR, Moscow, pp. 477–486 (in Russian).

Kuzmin, V.V., Chukhonin, A.P., Shulezhko, I.K., 1995. Stages of metamorphic evolution of rocks of crystalline basement of the Kukhtui Uplift (Okhotsk Massif). Dokl. Russ. Acad. Sci. 142, 789–791 (in Russian, translated into English).

Layer, P.W., Newberry, R., Fujita, K., Parfenov, L.M., Trunilina, V.A., Bakharev, A.G., 2001. Tectonic setting of the plutonic belts of Yakutia, northeast Russia based on ^{40}Ar/^{39}Ar geochronology and trace element geochemistry. Geology 29, 167–170.

Lemoine, M., Trumpy, R., 1987. Pre-oceanic rifting in the Alps. Tectonophysics 133, 305–320.

McMechan, M.E., Thompson, R.I., Cook, D.G., Gabrielse, H., Yourath, C.J., 1991. Structural style: Part E. Foreland Belt. In: Gabrielse, H., Yourath, C.J. (Eds.), Geology of the Cordilleran Orogen in Canada. Geology of Canada, no. 4. Geological Survey of Canada, pp. 634–650 (Also Geological Society of America, The Geology of North America G-2).

Mezhvilk, A.A., Leonov, B.N., Nikolaeva, M.G., 1978. Geological Map of USSR, scale 1:1000000 (new Series), sheet R-(50)-52. Mingeo SSSR, Leningrad (in Russian).

Nevolin, B.S., Potapov, S.V., Stavtsev, A.L., 1978. Upper Proterozoic (Riphean) and Lower Cambrian of the south-east margin of Siberian platform, Yudoma–Maya depression and Okhotsk Massif. In: Khomentovsky, V.V. (Ed.), New Data on Stratigraphy and Paleontology of Late Precambrian of the East and North Regions of Siberia. IGG Press, Novosibirsk, pp. 21–63 (in Russian).

Nokleberg, W.J., (Ed.), 1994. Circum-North Pacific Tectonostratigraphic Terrane Map, scale 1:5,000,000. U.S. Geological Survey Open File Report 94-714.

Parfenov, L.M., 1995. Terranes and history of formation of Mesozoic orogenic belts of the eastern Yakutia. Pac. Geol. 14 (6), 3–10 (in Russian, translated into English).

Parfenov, L.M., Kuzmin, M.I. (Eds.), 2001. Tectonics, Geodynamics and Metallogeny of the Sakha Republic (Yakutia). MAIK Nauka/Interperiodica, Moscow (in Russian).

Parfenov, L.M., Prokopiev, A.V., Gaiduk, V.V., 1995. Cretaceous frontal thrusts of the Verkhoyansk fold belt, eastern Siberia. Tectonics 14, 342–358.

Pavlov, V.E., Manukyan, A.M., Sharkovsky, M.B., Levashova, N.M., 1991. First data on the Riphean paleomagnetism of the Okhotsk massif. Dokl. Russ. Acad. Sci. 317, 688–692 (in Russian, translated into English).

Pavlov, V.E., Burakov, K.S., Tselmovich, V.A., Zhuravlev, D.Z., 1992. Paleomagnetics of sills from the Uchur-Maya region and estimation of geomagnetic field intensity in late Riphean. Physics of the Earth 1, 92–101 (in Russian, translated into English).

Potapov, S.V., Lobanova, A.F., 1999. Geological Map of the Russian Federation, scale 1:200000, sheet O-53-X. VSEGEI, St. Petersburg (in Russian).

Price, R.A., 1994. Cordilleran tectonics and the evolution of the Western Canada Sedimentary Basin. In: Mossop, G.D., Shetsen, I. (Comp.), Geological Atlas of the Western Canada Sedimentary Basin. Canadian Society of Petroleum Geology and Alberta Research Council, Calgary, pp. 13–24.

Price, R.A., Sears, J.W., 2000. A preliminary palinspastic map of the Mesoproterozoic Belt–Purcell Supergroup, Canada and USA: implications for the tectonic setting and structural evolution of the Purcell Anticlinorium and the Sullivan Deposit. In: Lydon, J.W., Höy, T., Slack, J.E., Knapp, M.E. (Eds.), The Geological Environment of the Sullivan Deposit, British Columbia. Geological Association of Canada, Mineral Deposit Division Special Volume N1, pp. 61–81.

Prokopiev, A.V., 1989. Kinematics of the Mesozoic folding of the west part of South Verkhoyansk. Soviet Acad. Sci. Press, Yakutsk (in Russian).

Prokopiev, A.V., 1998. The Verkhoyansk–Chersky collisional orogen. Pac. Geol. 17 (5), 3–10 (in Russian, translated into English).

Prokopiev, A.V., Toro, J., Miller, E.L., Dumitru, T.A., Hourigan, J.K., 2001. Basic regularities of structure of the Verkhoyansk fold and thrust belt (north-east Asia). In: Goncharov, V.I. (Ed.), Problems of Geology and Metallogeny of Northeast Asia at the Millenium Threshold. Extended Abstracts, vol. 1. NESRI, Magadan, pp. 64–66 (in Russian).

Rainbird, R.H., Stern, R.A., Khudoley, A.K., Kropachev, A.P., Heaman, L.M., Sukhorukov, V.I., 1998. U–Pb geochronology of Riphean supracrustal rocks from southeast Siberia and its bearing on the Laurentia–Siberia connection. Earth Planet. Sci. Lett. 164, 409–420.

Semikhatov, M.A., Serebryakov, S.N., 1983. Siberian Hypostratotype of Riphean. Nauka, Moscow (in Russian).

Starnikov, A.I., 1993. Geological Map of the Russian Federation, scale 1:200000, sheet P-53-XXX. VSEGEI, St. Petersburg (in Russian).

Sukhorukov, V.I., 1986. The Upper Riphean type sections of the Ulakhan–Bam ridge. In: Khomentovsky, V.V. (Ed.), Late Precambrian and Early Paleozoic of Siberia. Siberian Platform and Outer Part of the Altai–Sayan Fold Belt. IGG Press, Novosibirsk, pp. 23–64 (in Russian).

Thompson, B., Mercier, E., Roots, C., 1987. Extension and its influence on Canadian Cordilleran passive-margin evolution. In: Coward, M.P., Dewey, J.F., Hancock, P.L. (Eds.), Continental Extensional Tectonics. Geological Society London, Special Publications, vol. 28, pp. 409–417.

Yakshin, M.S., Isakov, A.V., 1991. Uy group of the Yudoma–Maya depression. In: Khomentovsky, V.V. (Ed.), Precambrian and Lower Paleozoic of Siberia. UIGGM Press, Novosibirsk, pp. 65–82 (in Russian).

Yan-Zhin-Shin, V.A., 1983. Tectonics of the Sette–Daban Horst Anticlinorium. Soviet Acad. Sci. Press, Yakutsk (in Russian).