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GEOLOGY

Azimuthal Reorganizations of Structural Patterns in the Primorye Region as Reflection of Changes in Geodynamic Settings of the East Asian Margin

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Sinistral strike-slip faults, which resulted from submeridional compression along with their paragenetic system of NE-trending fold–thrust structures, are the dominant Mesozoic dislocations (Fig. 1) of the eastern Primorye region [1, 3]. They destroy or substantially complicate Paleozoic structures, fragments of which indicate their formation under sublatitudinal compression [4, 5]. This is evident from a submeridional system of folds established in the southwestern Primorye region (Khanka Massif) [6]. The analysis in [4–6] revealed that the azimuthal reorganization of the structural pattern in the Primorye region occurred at the Paleozoic–Mesozoic transition and likely reflected replacement of the sublatitudinal continental margin compression by the submeridional one. In order to substantiate these important inferences, reveal the time interval of submeridional compression, and define other probable changes in the stress regime and its role in azimuthal structural reorganization, we studied Proterozoic–Mesozoic tectonic dislocations. Primary attention was paid to the study of dynamic zones associated with long-living deep strike-slip faults, the kinematics of which is most sensitive to changes in compression vectors. The studies were carried out in areas located along the Ussuri strike-slip fault (Fig. 1).

The Ussuri strike-slip fault [5] represents a shear zone 30 km wide with a morphologically distinct main fault, which is traced almost continuously owing to straight segments of river valleys (Fig. 1). Two structural parageneses corresponding to sinistral and dextral displacement phases are recognized in the dislocation pattern of the strike-slip fault zone. Discordant superimposition of Mesozoic sinistral shear parageneses on the Paleozoic protostructure was thoroughly studied at the southern flank of the Ussuri strike-slip fault (Fig. 1) using the Barabash anticline (BA) composed of Permian rocks as an example (Fig. 2). The anticline represents a symmetrical fold approximately 10 km wide and up to 35 km long with usual dip angles of 5°–10° in the hinge area and up to 40°–50° at limbs. The submeridional strike of the fold corresponds to orientation of folded parageneses of the Ussuri dextral strike-slip fault, which formed under sublatitudinal compression. The second (superimposed) deformation pattern is evident from the BA axis bend (in plan view) and the development of small submeridional folded structures, which complicate limbs of anticlines and are marked by the limestone member (Fig. 2). Hinges of these folds dip in the ENE and WSW directions parallel to the dip of BA limbs. The penetrative Izvestkovaya syncline superimposed on the Barabash anticline includes fragments of Triassic sequences (Fig. 2). The Kedrovaya syncline composed of Triassic rocks diverges southwestward (in the centrocline) into a fan-shaped system of NE-trending folds complicating the eastern BA limb (Fig. 2). The western BA limb is deformed in the south into NE-trending folds with dip angles of limbs amounting to 40–60° (Fig. 2).

The different-rank folds discordantly superimposed on the protostructure reflect the onset of significant azimuthal reorganization of BA deformations due to the replacement of the submeridional compression by the submeridional one at the Paleozoic–Mesozoic transition. This is confirmed by development of sublatitudinal thrusts and conjugate NE-trending (sinistral) and NW-trending (dextral) strike-slip faults, along which BA limestone units are displaced over as much as 4 km (Fig. 2). The NE-oriented fold system (mostly brachyanticlines) in Mesozoic sequences (Fig. 2), which lack

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structures related to latitudinal compression, also formed in identical settings.

Like the synkinematic folding of the eastern Primorye region (Fig. 1), Mesozoic folds are oriented obliquely relative to the NE-trending sinistral strike-slip faults (Fig. 2) and can be considered as structural parageneses of the Ussuri fold zone, which activated in the Mesozoic synchronously with the entire system of sinistral strike-slip faults due to submeridional compression. The amplitude of the sinistral displacement along the Ussuri strike-slip fault is established in its central part south of Khanka Lake (Fig. 1) [5]. Here, the sinistral displacement of Cambrian beds over 50 km is marked by limestone bodies (Fig. 3). This area includes almost the entire Paleozoic section characterized by faunal and floral assemblages [2]. It is difficult to subdivide the Paleozoic section (except for the Cambrian) into individual structures because of the similar composition of different-age rocks (volcanogenic–terrigenous complexes). Judging from bed orientation, the entire Paleozoic sequence is deformed uniformly with formation of NNE-trending structures (Fig. 3). Consequently, it can be inferred that sublatitudinal compression dominated throughout the Paleozoic. Paleozoic structures were subjected to sinistral displacements (although without substantial internal reorganization) in the Mesozoic. At the same time, it is noteworthy that the reference limestone sequence is oriented in the meridional direction away from the Ussuri shear zone (Fig. 3). This orientation likely reflects the initial strike of Paleozoic structures, which rotated northwestward in the Mesozoic due to activation of the sinistral strike-slip fault zone.

The narrow Lower–Upper Proterozoic rock block is bordered by the Ussuri and West Sikhote Alin strike-slip faults (Fig. 1). Here, we mapped extended marker horizons of marbles, limestones, conglomerates, and amphibolites (Fig. 4), which made it possible to decipher the structure of the central part of the block and its flanks, as well as the dynamic influence zone of bordering strike-slip faults. The central part of the block is deformed into wide folds, which formed in the Proterozoic presumably under meridional compression (Fig. 4). The sinistral NE-trending strike-slip fault, which crosses the block diagonally, likely formed in the same settings (Fig. 4). In the Ussuri and West Sikhote Alin fault zones, folded structures (including those composed of Devonian rocks) are oriented in the NW direction. Their position corresponds to that of structural parageneses of these dextral strike-slip faults formed under submeridional compression (Fig. 4). The replacement of submeridional compression by sublatitudinal compression in the Paleozoic (prior to the Carboniferous) stimulated development of the Ussuri and West Sikhote Alin dextral strike-slip faults with clockwise rotation of Paleozoic latitudinal folded structures in the north-northwest direction corresponding to orientation of the Paleozoic fold system (Figs. 2, 3).

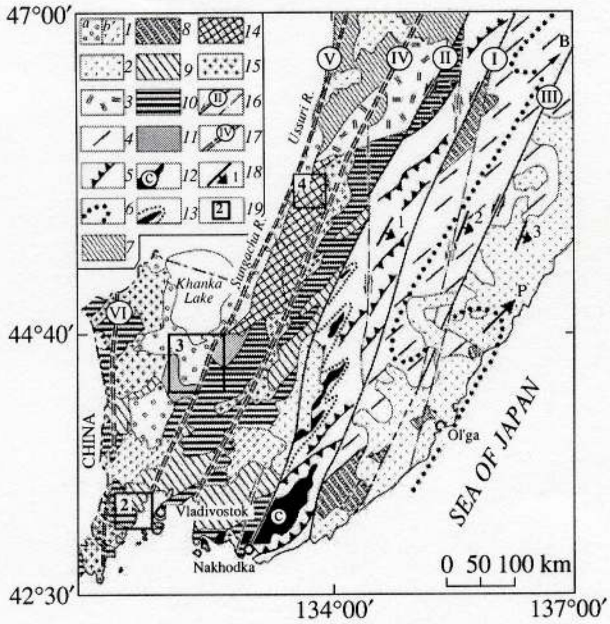

Fig. 1. General pattern of Mesozoic fold–thrust structures related to the strike-slip faults of the eastern Primorye region and lithotectonic complexes of the Khanka Massif. (*1*) Pliocene–Quaternary sediments (*a*) and Neogene basalts (*b*); (*2, 3*) Late Cretaceous volcanics (*2*) and Lower–Upper Cretaceous volcanogenic–terrigenous complexes (*3*); (*4, 5*) strikes of Mesozoic fold–thrust structures of the eastern Primorye region composed of (*4*) Lower Cretaceous (largely terrigenous) and (*5*) Jurassic (mostly terrigenous with olistrostromes) and imbricate Paleozoic–Triassic siliceous–terrigenous rocks; (*6*) generalized eastern boundary of Berriasian–Valanginian rocks with sinuous configuration determined by oblique erosional truncation of alternating large anticlines and synclines [3] (arrows indicate dips of the Pribrezhnaya (P) and Bikin (B) anticlines); (*7*) undivided Triassic–Lower Cretaceous siliceous–basaltoid–terrigenous rocks; (*8*) Jurassic–Lower Cretaceous (largely terrigenous) sequences with imbricate sheets of Paleozoic–Triassic carbonate–siliceous–terrigenous rocks; (*9–15*) lithotectonic zones of the Khanka Massif: (*9*) Triassic–Early Cretaceous continental coastal-marine, (*10*) Paleozoic volcanogenic-terrigenous (continental-riftogenic), (*11*) Cambrian carbonate–siliceous–terrigenous; (*12*) Early Proterozoic metagabbro–granitoid (Sergeevka) and (*13*) its fragments exposed in horst-anticlines, (*14*) Proterozoic metamorphogenic rocks, (*15*) Paleozoic granitoids; (*16*) sinistral strike-slip faults: (I) Sikhote Alin, (II) Arsen'ev, (III) East Sikhote Alin; (*17*) axes of strike-slip fault zones with sign-variable shear (sinistral and dextral) kinematics: (IV) West Sikhote Alin, (V) Ussuri, (VI) Primorsky; (*18*) dips of lithotectonic complexes (stages) constituting the eastern Primorye homocline [3]: (1) lower (Triassic–Jurassic), (2) middle (Early Cretaceous), (3) upper (Late Cretaceous); (*19*) areas studied in detail (numerals correspond to figure numbers).

As was mentioned, Paleozoic folded structures of the Khanka Massif were substantially complicated in the Mesozoic by discordantly superimposed folds (Fig. 2). In some areas (Fig. 3), the initial (presumably meridional) strike acquired a northwestern orientation

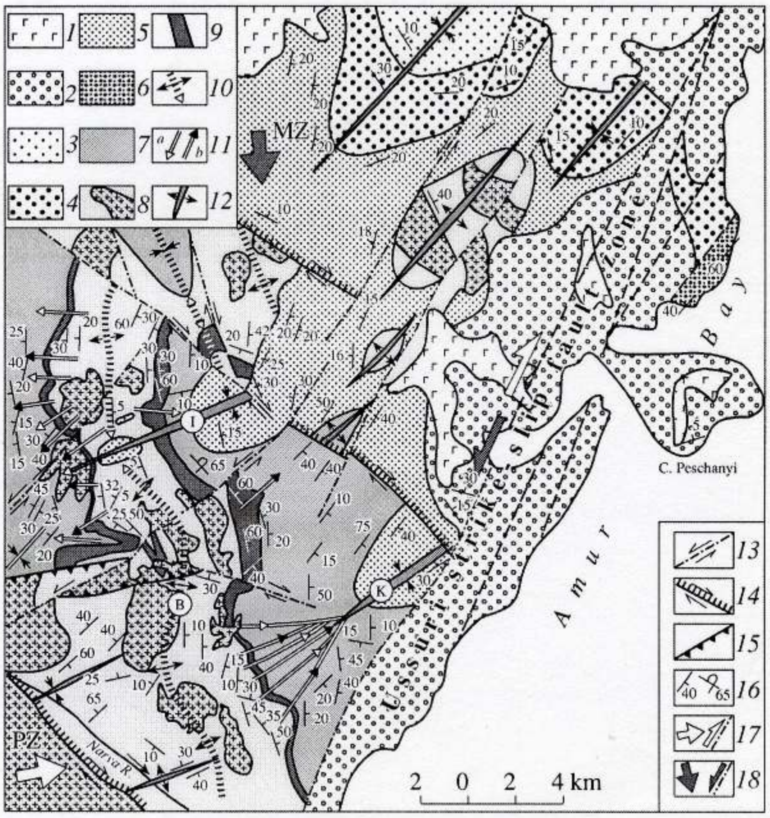

Fig. 2. Discordant superimposition of Mesozoic dislocations on Paleozoic protostructures. (*1*) Basalts (Neogene); (*2*) Pliocene–Quaternary sediments; (*3–6*) Mesozoic sedimentary complexes: (*3*) Lower–Upper Cretaceous terrigenous, (*4*) Lower Cretaceous terrigenous, (*5*) Upper Triassic, (*6*) undivided Triassic terrigenous and tuffaceous–terrigenous; (*7, 8*) complexes of the Barabash Formation: (*7*) terrigenous–basalt–rhyolite, (*8*) underlying terrigenous–basaltoid with numerous bodies of Late Permian granites (comagmatic to rhyolites); (*9*) reference member of Upper Permian limestones and calcareous sandstones; (*10*) axes of Paleozoic folds and direction of their undulations (white arrow); (*11*) axes of Mesozoic folds superimposed on limbs of the Paleozoic Barabash (B) anticline (arrows indicate dips of their axes: (*a*) synclines, (*b*) anticlines); (*12*) axes of large Mesozoic fold structures (synclines): (I) Izvestkovaya, (K) Kedrovaya; (*13*) strike-slip faults (dotted lines designate buried and assumed fractures); (*14*) strike-slip faults transformed into normal faults; (*15*) thrusts; (*16*) attitude elements; (*17, 18*) directions of regional compression: (*17*) presumed dextral (Paleozoic) and (*18*) proven sinistral (Mesozoic) displacements along the Ussuri strike-slip fault.

in sinistral strike-slip fault zones due to synchronous rotation. On the whole, the folds are not disguised by Mesozoic dislocations. Therefore, they reflect the distinctly submeridional orientation of the Paleozoic fold system. Mesozoic dislocations demonstrate different patterns in the eastern framing of the Khanka Massif: the long-term development of structures (primarily, the Central Sikhote Alin and Arsen'ev sinistral strike-slip faults) with a displacement amplitude up to a few hundred kilometers (Fig. 1) promoted the formation of the NE-extending East Sikhote Alin fold–thrust system in their dynamic influence zones, while pre-Mesozoic structures underwent a significant reorganization. The Barabash anticline exemplifies the initial stage of structural reorganization of Paleozoic folds in the Mesozoic (Fig. 2). At the eastern margin of the Khanka Massif, this process likely stimulated the complete transformation of Paleozoic structures and the development of penetrative (superimposed) NE-trending folds characterized by concordant relationships with Mesozoic folds (Fig. 1).

The presented material allows the following inferences: (1) meridional compression in the Paleozoic formed latitudinal compression-related structures; (2) at the Proterozoic–Paleozoic transition, meridional compression was replaced by latitudinal compression, which continued during the entire Paleozoic and produced the submeridional system of shear structures and NE-trending strike-slip faults, along which Proterozoic latitudinal folds were rotated to the northwest; (3) at the Paleozoic–Mesozoic transition, replacement of latitudinal compression by submeridional compression promoted the transformation of NE-extending dextral strike-slip faults into sinistral structures and the forma-

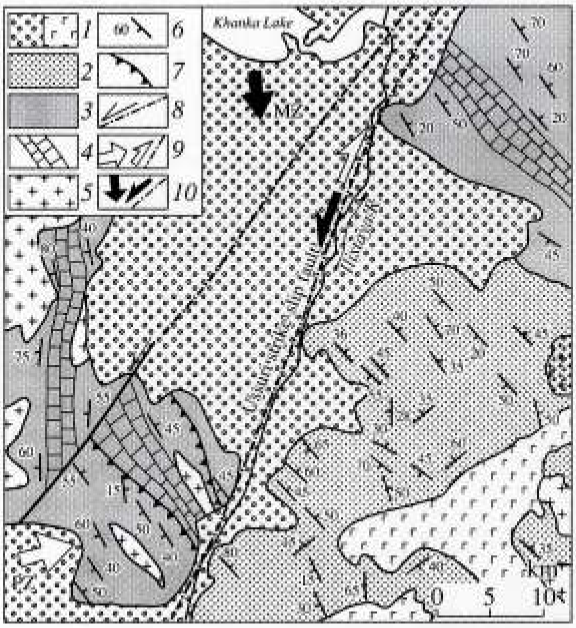

Fig. 3. Formation and displacement of Paleozoic fold structures along the Ussuri strike-slip fault under successive replacements of compression vectors. (*1*) Pliocene–Quaternary sediments and Neogene basalts; (*2*) undivided Paleozoic largely volcanogenic–terrigenous complexes; (*3, 4*) Cambrian volcanogenic–siliceous–carbonate–terrigenous complex (*3*) and its reference bodies mainly composed of limestones (*4*); (*5*) Paleozoic granitoids; (*6*) attitude elements; (*7*) thrusts; (*8*) strike-slip faults (dotted lines designate fractures buried under Quaternary sediments); (*9, 10*) vectors of compression and corresponding displacements along the Ussuri strike-slip fault in the Paleozoic (*9*) and Mesozoic (*10*).

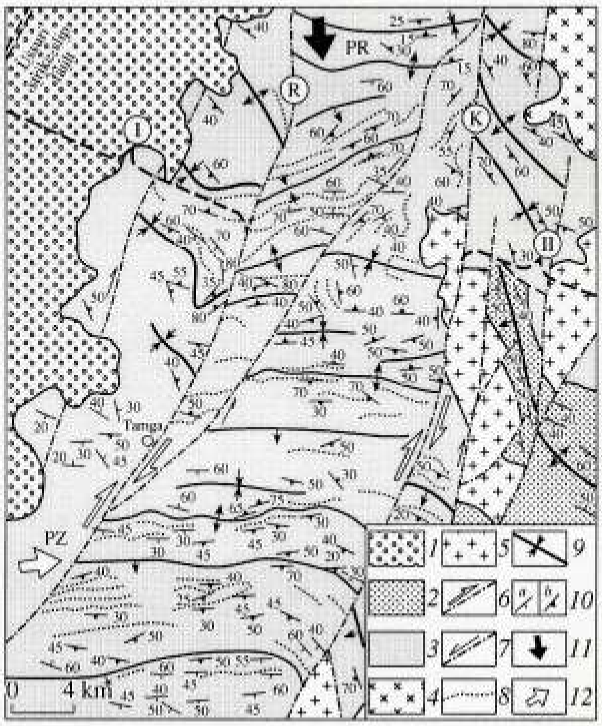

Fig. 4. Diverse deformations of Proterozoic rocks in the Khanka Massif. (*1*) Pliocene–Quaternary sediments; (*2*) Lower Devonian (phyllites, metasandstones, quartzites, shales, and limestones); (*3*) Proterozoic (sericite–chlorite, graphite, muscovite, and two-mica schists, biotite, amphibole–biotite, and garnet–cordierite gneisses, and graphite quartzites); (*4*) Early Cretaceous granites; (*5*) Early Paleozoic granites; (*6*) dextral strike-slip faults: (R) Rozhdestvenskii and (K) Kedrovyi bordering dynamic influence zones of the (I) Ussuri and (II) West Sikhote dextral strike-slip faults, respectively; (*7*) other strike-slip faults of higher orders; (*8*) reference members of marbles, limestones, and less common conglomerates and amphibolites; (*9*) anticlines, synclines, and homoclines; (*10*) attitude elements: (*a*) bedding, (*b*) metamorphic and gneissic banding; (*11, 12*) vectors of compression in the (*11*) Proterozoic and (*12*) Paleozoic.

tion of their structural parageneses (the Sikhote Alin fold–thrust system included). Structural reorganization of the Paleozoic submeridional fold system and development of superimposed (concordant with Mesozoic folding) NE-oriented folds proceeded in similar settings.

The change in directions of crustal compression and corresponding azimuthal reorganization of deformation patterns in the Asian continental margin reflect evidently repeated changes in lateral displacements of conjugate megablocks of the continental and (or) oceanic lithosphere. In our opinion, the dominant role in this process belonged to changes in direction of the Asian continent motion due to the Earth's rotation factor [4, 5], in addition to the probable (differently oriented) movements of the Pacific Plate in diverse geodynamic settings. The results of investigation are consistent with these concepts, because the meridional and latitudinal compression directions established correspond to the directions of the main rotation-related forces: forces directed from poles to equator and inertia forces oriented parallel to the equator. Their alternation is explained by the irregular velocity of Earth's rotation.

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